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# INTEGRATED CONTROL STRATEGIES FOR NON-IDEAL FORWARD CONVERTER

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THEAWARD OF THE DEGREE
OF

**MASTER OF TECHNOLOGY**

**In**

**POWER ELECTRONICS AND SYSTEMS**

Submitted by


**PRAGYA SHUKLA**

**(2K23/PES/09)**

Under the supervision of

**PROF. DHEERAJ JOSHI**

(Electrical Engineering Department, DTU)

**DEPARTMENT OF ELECTRICAL ENGINEERING**

**DELHI TECHNOLOGICAL UNIVERSITY**

(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042


JUNE, 2025

**DEPARTMENT OF ELECTRICAL ENGINEERING**

**DELHI TECHNOLOGICAL UNIVERSITY**

**(**Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

# DECLARATION

I, Pragya Shukla, Roll No. 2K23/PES/09 student of M. Tech (Power Electronics and Systems), hereby declare that the project Dissertation titled **"Integrated Control Strategies for Non-Ideal Forward converter"** which is submitted by me to the Department of Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original work and not previously used for the award of any Degree.

Place: Delhi **PRAGYA SHUKLA**

Date: 31th May 2025

**DEPARTMENT OF ELECTRICAL ENGINEERING**

**DELHI TECHNOLOGICAL UNIVERSITY**

**(**Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

# CERTIFICATE

This is to certify that the dissertation entitled ***"*Integrated Control Strategies for non-ideal forward Converter*"*** being submitted by PRAGYA SHUKLA (2K23/PES/09) in partial fulfillment of the requirements for the award of Master of Technology degree in "ELECTRICAL ENGINEERING" with specialization of "POWER ELECTRONICS & SYSTEMS" at the Delhi Technological University is an authentic work carried out by her under my supervision and guidance.To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma

Place: New Delhi

Date: 31th May 2025

**Prof. DHEERAJ JOSHI**
**(SUPERVISOR)**
Electrical Engineering Department
Delhi Technological University

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Date:31$^{th}$ May 2025

Place: DELHI (PRAGYA SHUKLA)

# ABSTRACT

This thesis sheds light on the rising demand for highly efficient power conversion electronics, putting emphasis on the role played by Forward converters. These stand out the primary objective of this scholarly thesis revolves around the comprehensive examination of the Non-ideal Forward converter through the application of small signal analysis, and the tailored design of its control techniques, ultimately aiming to elevate performance and ensure stability. The dc-dc isolated forward converter is a widely utilized power converter because of its great efficiency and ability to convert voltage both up and down. However, the efficiency and stability of the converter may be affected by the presence of parasitic elements such leakage inductance and diode junction capacitance. These components cause distorted waveforms and voltage spikes, which eventually affect the converter's performance and output voltage regulation. In order to overcome these difficulties and achieve voltage control in the forward converter. A minimal phase system that includes parasitic elements in a closed loop. This abstract investigates a variety of mitigating strategies. Analysis is done on the converter's stability using a PI controller and ANFIS controller which is inserted into the feedback path. Advanced control techniques, including feedforward compensation optimization, can be used to improve the forward converter's control loop performance and offset the impacts of parasitic elements.

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# CHAPTER 1
# INTRODUCTION

## 1.1 Overview

In modern times, the availability of electrical power has become an essential requirement for both household appliances and industrial operations They are capable of changing the form of electrical power as necessary. In addition to understanding their intricate mechanisms, it is critical to recognize the wide range of applications that power electronic converters find in various sectors. These converters are essential to many cutting-edge technologies because they make it possible to shift electrical power effectively and reliably to meet a variety of needs. Since they convert energy from sources like solar panels and wind turbines into electrical power that homes and businesses can utilize, power electronic converters are crucial parts of renewable energy systems. Electric power in various forms, such as AC (alternative current) or DC (direct current), constant or variable voltage, set or variable frequency, and so forth, is required for a variety of purposes. Customers usually receive electrical power in the form of AC with a constant frequency (either 50 or 60 Hz) and voltage magnitude. Many different types of power electronic converters have been created in order to meet the demands of various customers. When necessary, they are able to change the form of electrical power. Similar to this, converters in electric cars allow battery electricity to be converted into the energy required to power motors, guaranteeing smooth and efficient operation. Additionally, in portable electronics like laptops and smartphones, DC-DC converters regulate voltage levels to power sensitive electrical components, extending battery life and improving overall performance. By understanding the principles and control mechanisms of power electronic converters, researchers can enable new applications in emerging technologies and increase the efficiency and dependability of current systems. Similar to this, converters in electric cars allow battery electricity to be converted into the energy required to power motors, guaranteeing smooth and efficient operation. Additionally, in portable electronics like laptops and smartphones, DC-DC converters regulate voltage levels to power sensitive electrical components, extending battery life and improving overall performance. By understanding the principles and control mechanisms of power electronic converters, researchers can enable new applications in emerging technologies and increase the efficiency and dependability of current systems.

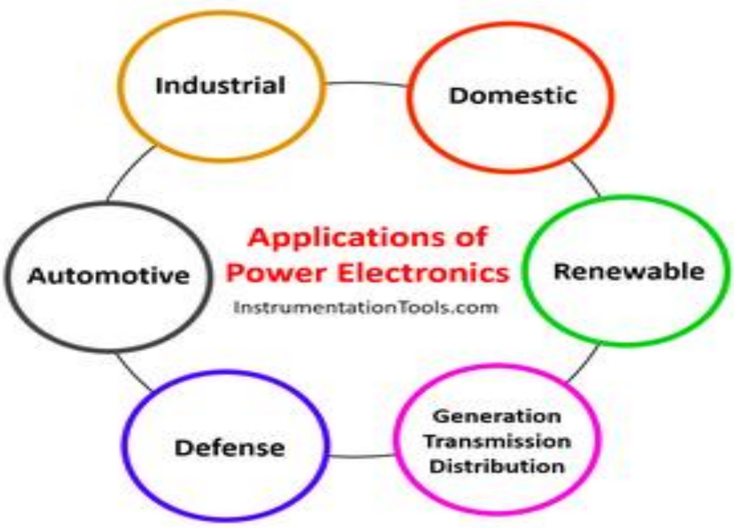


Fig.1. 1 Application of Power Electronics in different fields

**AC-DC Converters:** These converters transform AC voltage into either fixed or variable DC voltage in a precise and efficient manner. For example, diode rectifiers are highly efficient at converting AC into fixed DC. On the other hand, phase-controlled rectifiers are more advanced and allow for the regulation of variable DC voltage by modulating the conduction angle

**DC-AC Converters (Inverters):** Responsible for converting DC input into AC output, inverters ensure the provision of the desired voltage and frequency by precisely adjusting the switch-on time of the components. This allows them to efficiently operate a wide range of loads, including motors and appliances

**AC-AC converter:** A class of converters known as an AC-AC converter skillfully modifies fixed AC voltage to produce variable AC voltage, frequently with the option to change the frequency. While cyclo-converters have the special capacity to modify both voltage and frequency, making them appropriate for applications, AC voltage regulators, for example, maintain voltage levels without changing frequency.

**DC-DC Converters:** Specializing in the conversion of fixed DC voltage to variable DC voltage, these converters utilize meticulous control over switch-on timing to attain the desired output. Numerous types of converters exist, specifically engineered to effectively modify voltage levels for diverse uses. These converters are frequently utilized in portable electronics and renewable energy systems.

## 1.2 Motivation

Modern power electronic systems, notably those used in embedded systems, industrial automation, and telecommunications, need voltage management that is both efficient and dependable. People often utilize forward converters because they are easy to use, provide galvanic isolation, and work well in low- to medium-power applications. Because they are inherently nonlinear, these converters are nevertheless vulnerable to changes in input voltage and load. To keep the output voltage within acceptable limits in a lot of situations, closed-loop control solutions are needed. People like using a proportional-integral (PI) controller for regulatory tasks because it is simple and works well. It is possible to learn about the controller's strengths and weaknesses by simulating how it works. This will help in the future when creating more advanced or adaptable control systems. The goal of this research is to minimize the gaps of present understanding of DC-DC converter design procedures by taking consideration of the effects of non-idealities. Thorough research of the less-than-ideal variables, such as semiconductor switching and conduction losses, inductor core losses, and capacitor and inductor equivalent series resistance (ESR), should lead to improved converter efficiency designs. The mathematical modelling of DC-DC converters is another crucial step of this research, requiring a careful balancing act between accuracy and simplicity. This study aims to address the issue of representing converter non-idealities in a way that generates more accurate and practical models by addressing a significant area in modelling methodologies.

Analysing the feasibility of doing pulse width modulation (PWM) and other control methodologies for stabilising the output voltage is the agenda of this study. This study is also equipped in examining how non-ideal study methodologies help in the design of control strategies of the closed loop forward converters and other higher-order converters are extensively complicated. As long as the control system's effectiveness, this study aims to lower the cost of converter. The aim of this research is to address the difficulties raised and contribute significantly in the field by solving theoretical analysis with innovative practical approaches. By reducing the gap between theoretical models and practical application requirements, this work aims to enhance DC-DC converter design and control mechanisms, establishing new benchmarks for controlling the converters efficiency and effectiveness.

## 1.3 Objectives

The following are this thesis's primary goals:

1.To simulate a forward DC-DC converter that can be used in regulated, low-voltage applications.to create a closed-loop controller for output voltage regulation based on PI.

2. Use of MATLAB/Simulink to simulate the system and examine how it responds dynamically to the changes in input and output.

3. It assists the PI controller's efficiency in preserving voltage regulation using respective performance indicators like overshoot, fluctuations, settling time, and rising time.

## 1.4 Scope of Work

This thesis highlights on the closed-loop control analysis of a parasitic forward converter using a PI controller. The work includes:

Mathematical modelling and theoretical study of the closed loop parasitic forward converter circuit.

PI controller values are designed and tunned using standard techniques.

MATLAB/Simulink simulation model is designed for closed loop control system testing.

Evaluation of performance in various scenarios is analysed. The results and conclusions in this work are based on simulation-based analysis; hardware implementation is not included.

## 1.5 Thesis Organization

The thesis is organized as follows:

**Chapter 1-** introduces the research topic, motivation, objectives, scope, and thesis structure.

**Chapter 2** -presents a detailed literature review covering forward converters, control strategies, and relevant prior work.

**Chapter 3** -describes the design and role of all key components of the Non-Ideal Forward converter.

**Chapter 4** -outlines the Modelling of Forward Converter, state space model, average equations.

**Chapter 5** –lightens the designing of PI and ANFIS controller in closed loop.

**Chapter 6** – results and simulations

**Chapter 7** – conclusion and future scope

# CHAPTER 2
# DESIGN OF DC-DC CONVERTERS

## 2.1 Introduction

The DC-DC converters provide the effective operation of a variety of applications, from portable electronics like laptops and cell phones to renewable energy systems, automotive electronics, by supplying the voltage required for operation of electronic circuits. DC-DC converters come in a variety of topologies, each having special characteristics and functioning. These are the buck, boost, and buck-boost, cuk, sepic and forward converter. The output voltage is decreased with respect to a lower value in the buck converter. It comes out for its ability to provide a stable output voltage with minimal voltage fluctuations, which makes it good for applications requiring a dependable power source. The fact that the input current is not continuous, however, presents a challenge because smooth operation desires the application of a filter at the load side.

While on the other side, the input voltage is greater than the output voltage in case of the boost converter. The most advantageous feature of this converter is that it does not require an input filter because its input current flows continuously. However, it has disadvantages just like the buck converter which is, the output current in the boost topology is not continuous, meaning that it fluctuates over a period of time. A considerable value of filter is required to encounter the output voltage fluctuation and ripples in inductor current.

The DC-DC forward converter appears to be realistic approach of these three basic topologies with their advantages properly integrated. To change the output voltage to be equal to, lower than, or greater than the input voltage, as well as to change the current at the input and output sides.

In addition to the Forward converter, other DC-DC converters include the Zeta and SEPIC converters, which maintain the output voltage polarity equal to the input voltage. The SEPIC converter has a discontinuous output current, which is a disadvantage of the boost converter, even though the Zeta converter has a discontinuous input current, similar to the buck converter topology. Achieving the realistic goals demands precise converter design and parameter alterations. This necessitates an effective study of the forward converter's performance. Here, we go deeply into the Forward converter's non-ideal behaviour, leading to the creation of better design equations for the filter capacitors and inductors.

### 2.1.1 Control Techniques in Power Electronics

The performance of power electronics converter control systems is greatly affected by how well they work. Control strategies are necessary for them to work consistently, efficiently, and reliably under different loads and situations. These tactics improve the system's overall performance by optimizing the responsiveness, controlling the output voltage or current, and reducing fluctuations. This part covers a number of ways to regulate power electronics, from traditional linear controllers to modern smart and digital methods.

## 2.2 Classical Control Techniques

Classic control techniques denote the fundamental methodologies employed in control engineering to develop systems that exhibit specified behaviours. These methodologies are grounded in recognized mathematical frameworks and are generally used to linear time-invariant (LTI) systems. This is a summary of the principal classical control strategies

### 2.2.1 Open-Loop Control

The term "open-loop control" describes a configuration in which the controller doesn't use system output feedback. The predetermined control action is unaffected to disruptions or alterations in the system's characteristics. This method is straightforward and quick to use, but it is not accurate or robust enough for applications that need precision regulation.

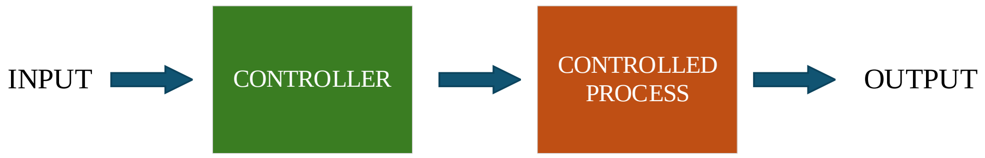


*Fig.2. 1 Block diagram of controlled process*

### 2.2.2 Closed-Loop Control

The majority of power electronic systems are built on closed-loop control, sometimes referred to as feedback control. In this setup, a feedback path is enclosed with forward path due to which the converter's output is continually observed contrasted and compared with a reference signal. The controller processes the received error signal to provide a stable and regulate the controller action that modifies the switching behavior of the converter.

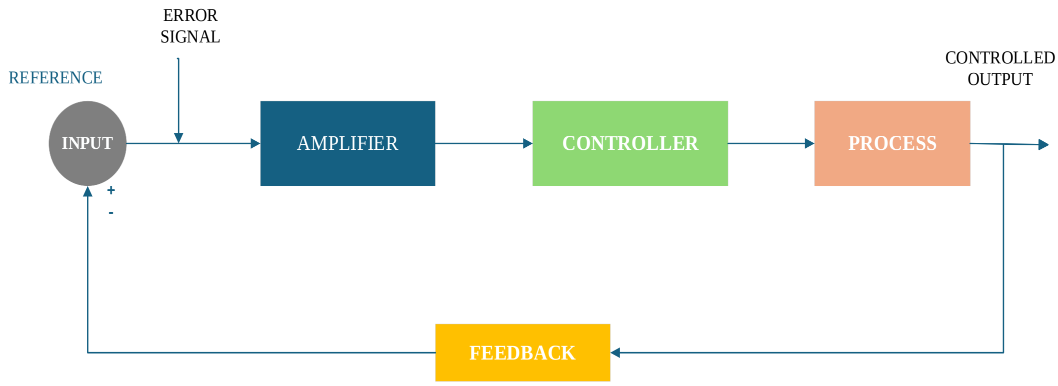


*Fig.2. 2 Close Loop System*

## 2.3 Modern Intelligent and Control Techniques

The nonlinear, time-varying nature of power electronic systems and their growing complexity may make classical control techniques insufficient. As a result, intelligent and contemporary control strategies that provide enhanced performance under uncertainty, robustness, and adaptability have been adopted. resilience to parameter changes and external disturbances. However, the main obstacles are implementation. These mythologies use artificial intelligence (AI), machine learning, and fuzzy logic to build systems that can learn, adapt, and make decisions in real time, going beyond conventional linear control techniques like PID or PI controllers

### 2.4 Types of Controllers

Various types of controllers are utilized in control systems, contingent upon the system's characteristics, requirements, and complexity. This is an overview of the primary categories of controllers, divided into classic types and certain contemporary extensions.

#### 2.4.1 Proportional (P) Controller

One type of control system used in automation and control engineering is a 'P' Controller, which stands for Proportional Controller. It responds to the error signal by adjusting the output in a way that takes into account the difference between the desired setpoint and the actual process value. Due to the lack of integral and derivative components, a P Controller alone is unable to eliminate steady-state errors. Improving response time by increasing 'Kp' could lead to instability or overrun in the system because the controller output is proportionate to the error signal.

#### 2.4.2 Proportional-Derivative (PD) Controller

A control system that integrates proportional and derivative control actions is referred to as a PD Controller (Proportional-Derivative Controller). The integration of the present error, through proportional action, alongside the rate of change of that error, via derivative action, enhances the stability and response time of the system. The derivative component improves the prediction of future error patterns by reducing overshoot and increasing dampening. Utilizes the present error and the velocity of its variation. Minimizes overshoot; however, it does not completely eradicate steady-state error.

### 2.4.3 Proportional-Integral (PI) Controller

A Proportional-Integral (PI) controller is frequently utilized in various engineering applications, especially in the realms of electrical, mechanical, and industrial systems. Its main function is to automatically reduce the difference (or error) between the desired and actual output of a system in order to minimize the difference between them. a PI controller combines proportional control with additional integral

### 2.4.4 Proportional-Integral-Derivative (PID) Controller

A PID controller is a widely used control system tool in engineering that helps maintain a process at its desired operating point. It works by continuously calculating the error between a desired setpoint and the actual system output, then applying a correction based on proportional, integral, and derivative terms.

This type of controller is significantly used in automation, power electronics, robotics, etc. PID controller consists of three control unit, The derivative term in it finds the rate of reduction of the error and uses that information to forecast future errors. It helps decrease overshoot and provides steadiness.

## 2.5 Previous Work on PI Control in Forward Converters

Power converters may be integral to modern electrical systems, ensuring efficient energy conversion while maintaining voltage stability. Among various converter topologies, forward converters stand out due to their simplicity and effectiveness in low-to-medium power applications. However, maintaining voltage stability and transient response remains a challenge, prompting extensive research into control strategies such as PI control.

PI controllers help minimize steady-state errors while providing adequate transient response improvements. Unlike proportional controllers alone, PI controllers integrate past errors, ensuring stability even under fluctuating load conditions. Researchers have dedicated considerable efforts to refining PI control techniques, improving efficiency, and adapting them to complex power system requirements.

### 2.5.1 Early Implementation of PI Controllers

Initial studies on PI control in forward converters focused on implementing basic proportional-integral mechanism to regulate output voltage. Early approaches emphasized fixed-gain PI control, where parameters were predefined based on system design considerations. While effective in maintaining steady-state voltage levels, these methods lacked adaptability in dynamic operating conditions.

### 2.5.2 Adaptive and Optimized PI Control Strategies

Recognizing the limitations of fixed-gain PI controllers, subsequent research introduced adaptive control methods. Adaptive PI control techniques dynamically adjust controller parameters based on real-time system behavior. Studies demonstrated that self-tuning controllers significantly improved transient performance, minimizing overshoot and settling time.

Optimization algorithms such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) were employed to fine-tune PI controller parameters. These approaches enhanced the efficiency of forward converters by ensuring optimal gain values under diverse load conditions.

## 2.6. Combining With Digital Control Methods

The advancement of digital control systems revolutionized PI control applications in forward converters. Researchers explored the integration of microcontrollers and Digital Signal Processors (DSPs) to execute real-time PI control strategies. Digital implementation offered greater precision, adaptability, and reliability, enabling forward converters to operate efficiently in fluctuating environments.

Moreover, studies highlighted the benefits of hybrid control approaches, where PI controllers were combined with fuzzy logic or model predictive control (MPC)**.** These hybrid systems demonstrated superior performance compared to conventional PI controllers alone, particularly in complex load scenarios.

# CHAPTER 3
# FUNDAMENTALS OF FORWARD CONVERTER

## 3.1 Fundamentals of Forward DC-DC Converters

DC-DC converters are very important for regulating voltage and converting energy efficiently in current power devices. The forward converter is one of the most popular topologies because it is simple, reliable, and works well for low- to medium-power applications. This converter is very useful in fields like telecommunications, electronics for cars, and systems that use renewable energy. The forward converter is a non-isolated switching converter that lowers down DC voltage quickly while keeping the input and output electrically separate. It works by moving energy through a transformer, which makes sure that the voltage stays stable and safe.

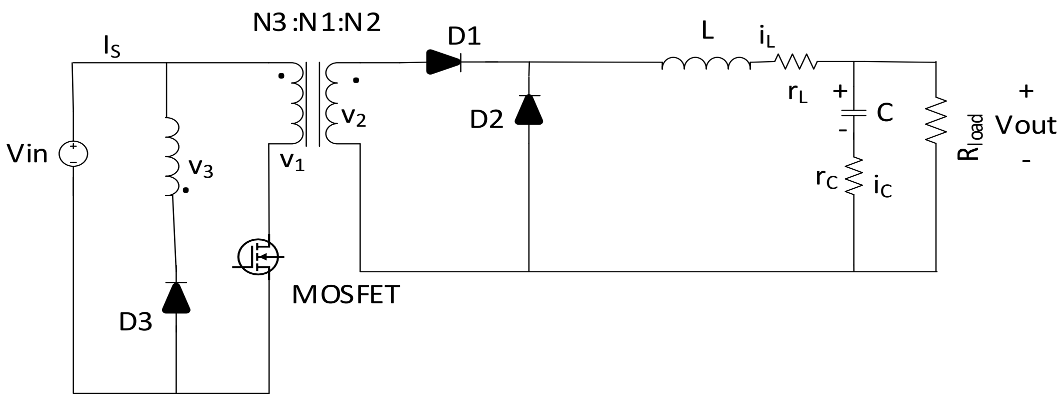


*Fig.3. 1 Forward Converter*

## 3.2 Converter Topologies

The forward converter is a DC-DC isolated power conversion topology, known for its efficiency and ability to provide electrical isolation. It utilized in industrial, telecommunication, and automotive applications where stable voltage is required. The basic structure consists of many components, each playing important role in its operation

### 3.2.1 Mode of Operations of Forward converter

Forward converter operates using a transformer and a switching device (MOSFET) and MOSFET controlled by a PWM signal. The operation occurs in two main modes, mode-1 switch is ON and mode-2 switch OFF.

#### 3.2.1.1 Switch ON (Active Mode)

When the switch in a forward converter turns on, current flows from the input source through the primary winding of the transformer. This action creates a magnetic field that induces a voltage in the secondary winding due to electromagnetic coupling. As a result, current is driven through a diode, followed by a filter inductor and capacitor, which together smooth the output and supply power to the load. During the switch-on period, energy is transferred directly from the input to the output. Although the transformer core stores some magnetic energy, the forward converter differs from a flyback converter in that it does not depend on releasing this stored energy during the off-state. Instead, energy transfer occurs primarily during the on-state, making the forward converter more efficient for continuous power delivery.

#### 3.2.1.2 Switch OFF (Freewheeling Mode)

Upon deactivating the switch in a forward converter, the current flowing through the primary winding of the transformer stops suddenly. A freewheeling diode in the output circuit is activated to maintain a constant current supply to the load. This diode enables a gradual release of energy stored in the output inductor, ensuring a steady current supply to the load. Additionally, to prevent transformer core saturation and effectively dissipate the magnetic flux gathered during the on-state, a demagnetizing or reset winding is incorporated. This winding aids in the resetting of the transformer core during the off period, thereby ensuring reliable and consistent performance in the following switching cycles.

## 3.3 Components and their Roles

### 3.3.1 Transformer

The transformer is one of the most important components in a forward converter. It performs two functions: voltage scaling and electrical isolation. Voltage scaling refers to the converter's ability to either step down or step up the input voltage based on the requirements of the application. This feature makes the forward converter suitable for a wide range of load conditions. Additionally, the transformer used in the converter provides electrical isolation between the input and output sides. This isolation preventing direct electrical connection and protecting sensitive components and users from faults or voltage spikes.

### 3.3.2. Switch (MOSFET)

The forward converter utilizes a MOSFET (Metal Oxide Semiconductor Field-Effect Transistor) for the regulation of power transmission.

Roles of the Switching Device

- Controls the ON and OFF cycles of the converter.
- Operates at higher switching frequencies, reducing the size of filter components like inductors and capacitors.
- Regulated by Pulse Width Modulation (PWM), which adjusts the duty cycle of the switching device to maintain a stable output voltage.

### 3.3.3. Rectification Mode (Diode)

In order to convert the AC voltage of secondary winding of the transformer into a DC voltage rectifier circuit is essential. Diodes and freewheeling diode are used in a forward converter to accomplish this rectification and use LC filter which ensures constant current flow and lowers voltage fluctuation. Rectifier diodes play an important role in the operation of a forward converter by ensuring unidirectional current flow. Their main function that to convert the AC transformer's output into a pulsating DC

### 3.3.4 Freewheeling Diode

When the switching device MOSFET turns OFF, there is a risk of voltage collapse. This is where the freewheeling diode comes into picture, ensuring that current continues to flow smoothly through circuit. freewheeling diode in a forward converter is essential for sustaining constant current flow and guaranteeing voltage stability during the switching process. Energy is moved from the transformer to the output when the power switch (MOSFET) is turned on, and some of this energy is stored in the output inductor. The inductor, which resists abrupt changes in current, tries to keep the current flowing when the switch is turned off. Abrupt output voltage collapse are possible without a suitable channel for current, which could harm circuit components and impair functionality. By giving the inductor current a different route when the switch is off, the freewheeling diode solves this problem.

### 3.3.5 Output Filter Components

The output filter plays a crucial role in ensuring a smooth and stable DC voltage across the load. The two key components of the output filter may be inductors and capacitors, which work together to minimize voltage ripple and regulate current flow. Their combined operation can be essential for maintaining efficient energy conversion and protecting connected devices.

#### 3.3.5.1 Inductor

The output filter inductor in forward converter plays a crucial role in smoothing the output current and storing energy. During the ON state, the inductor stores energy as current flows through it. During OFF state, the inductor gradually releases this stored energy, maintaining a continuous flow of current to the load. This process helps in avoiding sudden spikes or drops in current, ensuring a stable operation.

#### 3.3.5.2 Capacitor

The output filter capacitor complement capacitor stabilizing the voltage and reducing high-frequency noise. Since switching converters inherently produce pulsed voltage, the capacitor an important role in filtering out ripple and maintaining constant DC output. It absorbs sudden voltage fluctuations and helps provide a constant voltage to the load.

## 3.4 Analysis of Forward DC-DC Converter

The schematic diagram of a Forward DC-DC converter as shown in Fig.3.2 show that a unique arrangement design to regulate voltage. It consists of one inductor, one capacitor, a SiC diode, and a switch MOSFET. The forward converter can be derived from the buck converter by adding the transformer and diode D1 between the switch and the diode D2. its capability to work in two modes: Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM). For the purpose of this study, the focus is narrowed to its operation in CCM. This mode is critical for understanding how the converter performs under steady conditions, with particular emphasis on the duty cycle (D) and the switching frequency ($f_s$). The duty cycle, which is the ratio of the switch's active time to the total cycle time, plays a pivotal role in controlling the converter's output, making it a key factor in our analysis.

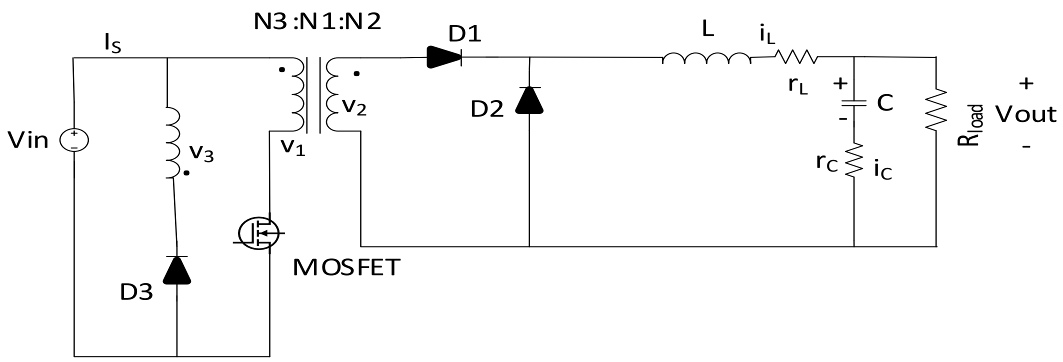


*Fig.3. 2 schematic diagram of forward converter*

The analysis of the forward PWM converter of Figure 3.2. is based on the following assumptions, described below;

1. The power MOSFET and the diode are ideal switches.

2. The value of transistor output capacitance, the diode capacitance, and the lead inductances are zero, which implies zero switching losses.

3. The transformer leakage inductances and stray capacitances kept neglected.

4. Passive components of the circuit are linear, time-invariant, and frequency-independent.

5. The output impedance of the input voltage source is zero for both ac and dc components.

**3.4.1 Mode 1 of operation: Switch- ON, Diode-OFF ($0 < t \leq DT$)**

In this time interval, $0 < t \leq DT$, the switch and the diode D1 are turned ON, and the diodes D2 and D3 turned OFF. An ideal equivalent circuit for this time interval is shown in Figure(a).

The actual transformer is modeled by an ideal transformer and the magnetizing inductance

Lm (shown in cicuit). The relationship in the transformer voltages and the transformer turns ratio is given below;

$$v_1 : v_2 : v_3 = N_1 : N_2 : (-N_3) \quad (3.1)$$

Where, $N_1 : N_2 : N_3$ are the numbers of turns of the primary, secondary, and tertiary winding

of the transformer. The voltage ratio can also be expressed as-

$$v_1 : v_2 : v_3 = \frac{N_1}{N_2} : 1 : (\frac{-N_3}{N_2}) \quad (3.2)$$

Where,

$$\frac{N_1}{N_2} = n_1, : n_3 = \frac{N_3}{N_2} \quad (3.3)$$

When the switch is turned on, the transformer's primary voltage and the magnetising inductance Lm are

$$v_1 = V_1 = v_{L_m} = L_m \frac{di_{Lm}}{dt} \quad (3.4)$$

$$v_1 = V_{in} \quad (3.5)$$

$$v_2 = v_1\left(\frac{N_2}{N_1}\right) = V_{in}\left(\frac{N_2}{N_1}\right) \quad (3.6)$$

Applying KVL, KCL in fig (2);

$$v_2 - L\frac{di_L}{dt} - i_L r_L - R\left(i_L - C\frac{dv_C}{dt}\right) = 0 \tag{3.7}$$

$$C\frac{dv_C}{dt} = i_c \tag{3.8}$$

$$-v_C - Cr_C\frac{dv_C}{dt} + R\left(i_L - C\frac{dv_C}{dt}\right) = 0 \tag{3.9}$$

### 3.5.2 Mode 2 of operation: Switch- OFF, Diode-ON (DT≤ t< T)

During this time interval, the switch and diode D1 are turned OFF due to reverse voltage applied across them, and the diodes D2 and D3 are turned ON. In mode 2, the switch S is open, For the transformation from winding 1 to 3, current out of the dotted terminal of winding forces current into the dotted terminal of winding 3. Diode *D*3 is then forward-biased to provide a path for winding 3 current, which must go back to the source. When *D*3 is on, the voltage across winding 3.The voltage across the inductor L is

$$v_3 = -V_{in} \tag{3.10}$$

$$v_2 = v_3\left(\frac{N_2}{N_3}\right) = -V_{in}\left(\frac{N_2}{N_3}\right) \tag{3.11}$$

$$v_1 = v_3\left(\frac{N_1}{N_3}\right) = -V_{in}\left(\frac{N_1}{N_3}\right) \tag{3.12}$$

Using KVL, KCL in mode 2;

$$-L\frac{di_L}{dt}-i_L r_L - R\left(i_L - C\frac{dv_C}{dt}\right)=0 \tag{3.13}$$

$$C\frac{dv_C}{dt}=i_C \tag{3.14}$$

$$-v_C - Cr_C\frac{dv_C}{dt}+R\left(i_L - C\frac{dv_C}{dt}\right)=0 \tag{3.15}$$

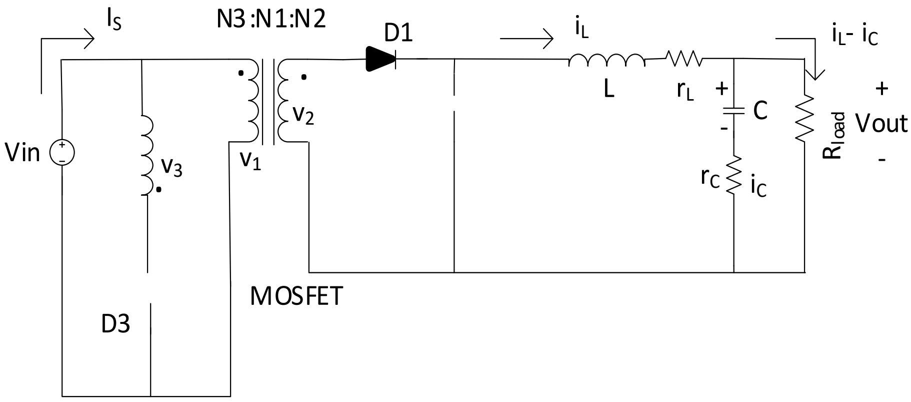


*Fig.3. 3 Mode 1 of Operation*

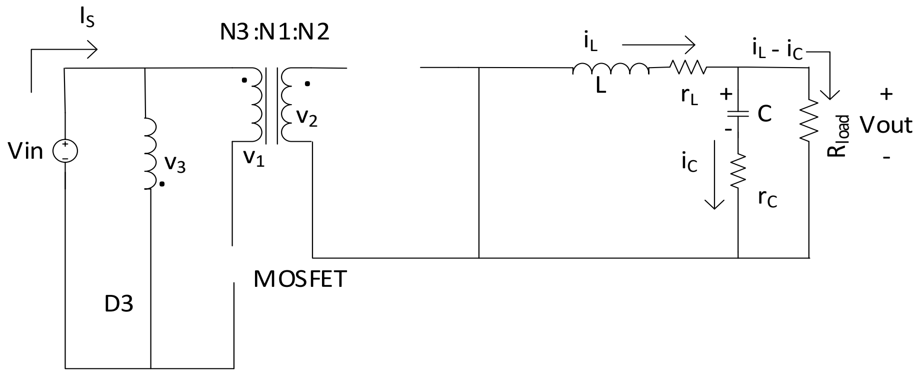


*Fig.3. 4 Mode 2 of Operation*

Table 3. 1 Design Specification of Forward Converter

| **Parameter Description** | **Notations** | **Nominal value** |
|---|---|---|
| Input voltage(V) | $V_{in}$ | 187 |
| Desired Output Voltage(V) | Vo | 5 |
| Capacitance(μF) | C | 200e-6 |
| Capacitive resistance(mΩ) | $r_C$ | 25e-3 |
| Inductive resistance(mΩ) | $r_L$ | 43 |
| Inductance(mH) | $L$ | 65e-6 |
| Desired switching frequency (Khz) | $f_S$ | 100 Khz |
| load resistance(Ω) | $R_L$ | 0.25 |
| Duty ratio | D | 0.24 |
| Primary to secondary ratio | $\left(\frac{N_1}{N_2}\right)$ | 8 |

| | | |
|---|---|---|
| Primary to tertiary ratio | $\left(\frac{N_1}{N_3}\right)$ | 1 |
| Resistance(Ω) and inductance of primary winding (mH) | $r_{T1}$ , $l_1$ | 50e-3, 10e-4 |
| Resistance(Ω) and inductance(mH) of secondary winding | $r_{T2}$ , $l_2$ | 10e-3, 10e-5 |
| Resistance(Ω) and inductance(mH) of tertiary winding | $r_{T3}$ , $l_3$ | 5e-3, 10e-6 |
| Magnetization resistance(Ω) and inductance(mH) | $r_{Lm}$ , $l_m$ | 1e6, 2.01e3 |

## 3.5 Inductor design

The efficiency of DC-DC converters is significantly influenced by the design of the inductors. It affects their size, effectiveness, and ability to regulate voltage swings. The performance of the converter is decided by inductors, which are essential for storing and transferring of energy. Therefore, concentrating on developing innovative inductor design is crucial for producing DC-DC converters that are more resilient, compact, and efficient.

Refer to equation no. (3.4),(3.7) and (3.13)

Finally ,

$$v_L = (\frac{N_2}{N_1}).V_{in} - V_0 \tag{3.16}$$

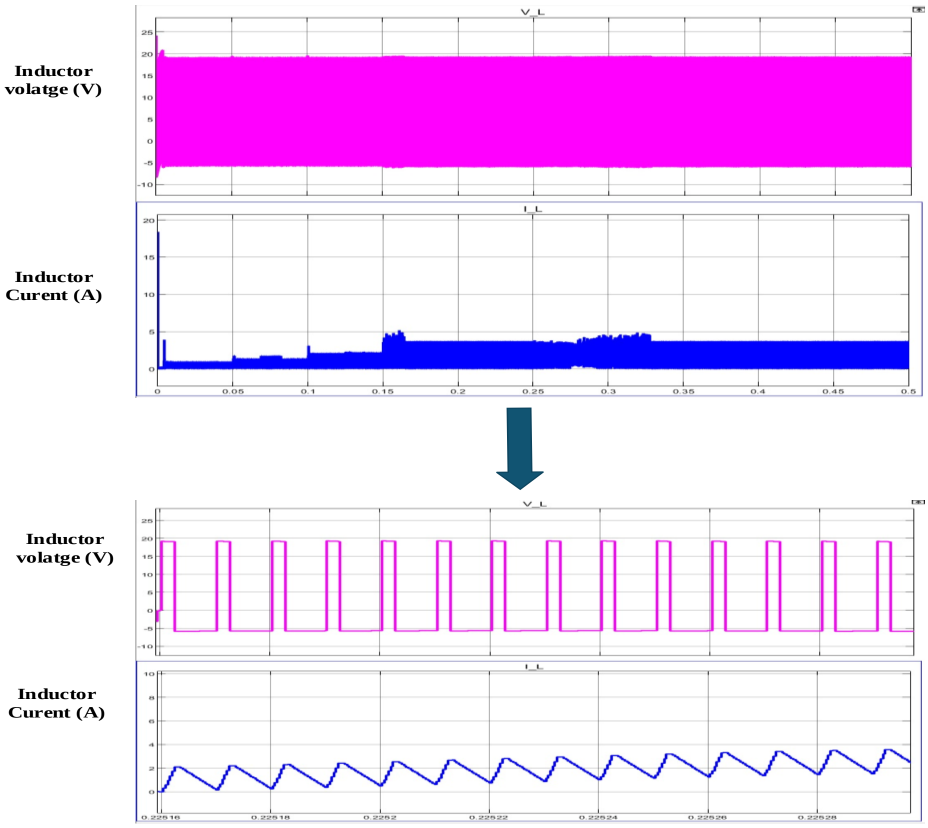


*Fig.3. 5 Graph of inductor voltage and inductor current*

Here, switching frequency is, $f_s = 100$Khz

Step1: On time-period,$T_S = \frac{1}{f_S} = 10\mu s \rightarrow t_{ON} = D.T_S = 0.214 \times 10 \approx 2.14\pi s$

Step2: Inductor Voltage During ON Time,

$v_L = (\frac{N_2}{N_1}).V_{in} - V_0$=$0.125\times 187 - 5 = 18.37V$

Step3: Calculate Ripple Current, $\Delta I_L$.Well, this is about 30% ripple for a 2 A output current.

$$\Delta I_L \approx 0.3 \times 2 \approx 0.6$$

Step4: Value of filter inductor,

$$L = \frac{V_L.t_{ON}}{\Delta I_L} = \frac{18.375\times 2.14\times 10^{-6}}{0.6} = 65.6\mu H \quad (3.17)$$

Value of peak current,$I_{peak} = I_0 + \frac{\Delta I_L}{2} = 2 + 0.3 \approx 2.3A$ (3.18)

## 3.6 Capacitor design

The overall performance and efficiency of the converter are significantly decided by the design of filter capacitor. A well-designed capacitor reduces voltage ripples and improves power stability by ensuring the smooth passage of energy between circuits. This crucial part smoothest the output voltage by storing and releasing electrical energy. The capacitor's design specifications, such as its physical dimensions, voltage rating, and capacity, must be carefully calculated to satisfy the converter's unique needs. It makes it possible to attain great levels of efficiency, operational dependability, and converter longevity, highlighting the need for accurate capacitor design in the creation of the well-suited Forward DC converter

Step-1: Understand Ripple Generation, i.e. In a forward converter, the inductor current ripple flows into the filter capacitor. The capacitor must withstand half the ripple current during each switching cycle:

$$I_C = \frac{\Delta I_L}{2} \tag{3.19}$$

Step 2: Capacitor Ripple Voltage Equation;

$$\Delta V_0 = \frac{\Delta I_L}{4 f_S C}$$

$$C = \frac{0.0605}{4 \times 100 \times 10^3 \times 0.05} \geq 60\mu F \tag{3.20}$$

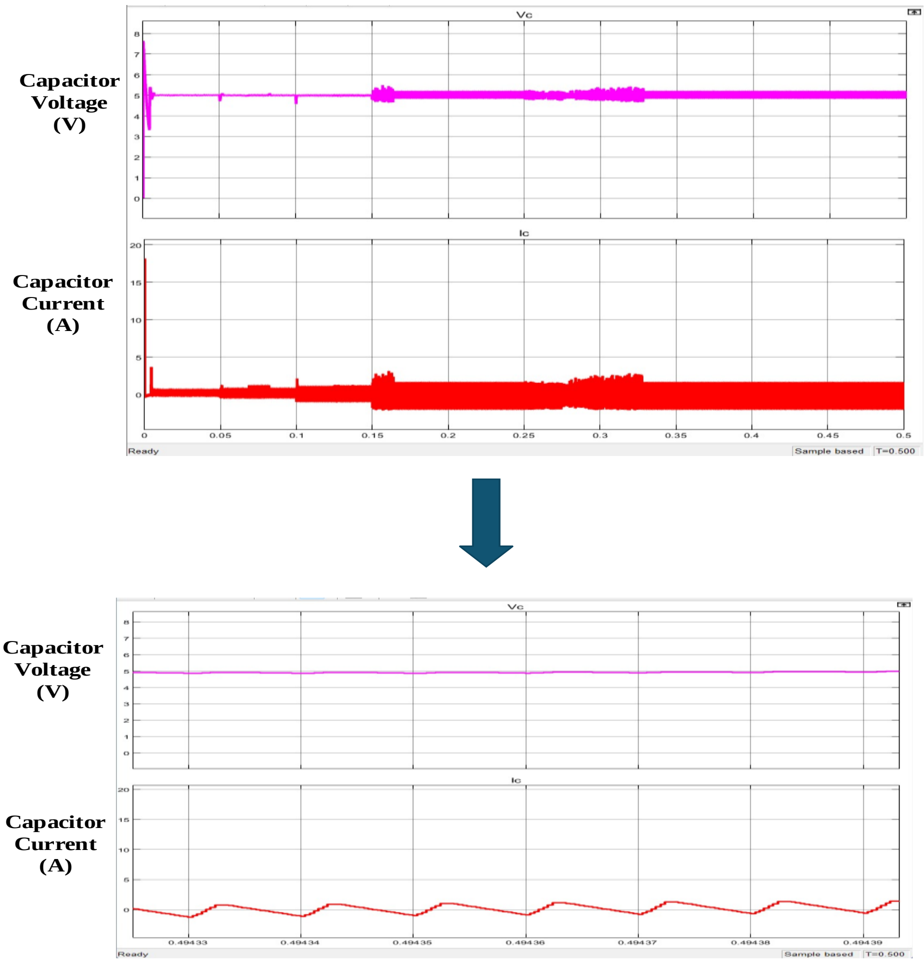


*Fig.3. 6 Voltage across the capacitor and capacitor current*

## 3.7 Voltage across the switch

The graph displays a forward converter's diode current and voltage waveforms. The diode current in the first set of waveforms (top) is quite variable and heavily distorted. In continuous conduction mode, the diode current displays a distinct, repeating triangle pattern.

Likewise, the diode voltage lacks the anticipated pulsed nature that characterizes typical converter operation, appearing flat and irregular waveform as shown in plot two. In continuous conduction mode, the diode current shows a distinct, repeating triangle pattern. This demonstrates that the converter operates with steady switching cycles. In contrast, the diode voltage exhibits a distinct, square waveform that alternates between high and low levels.

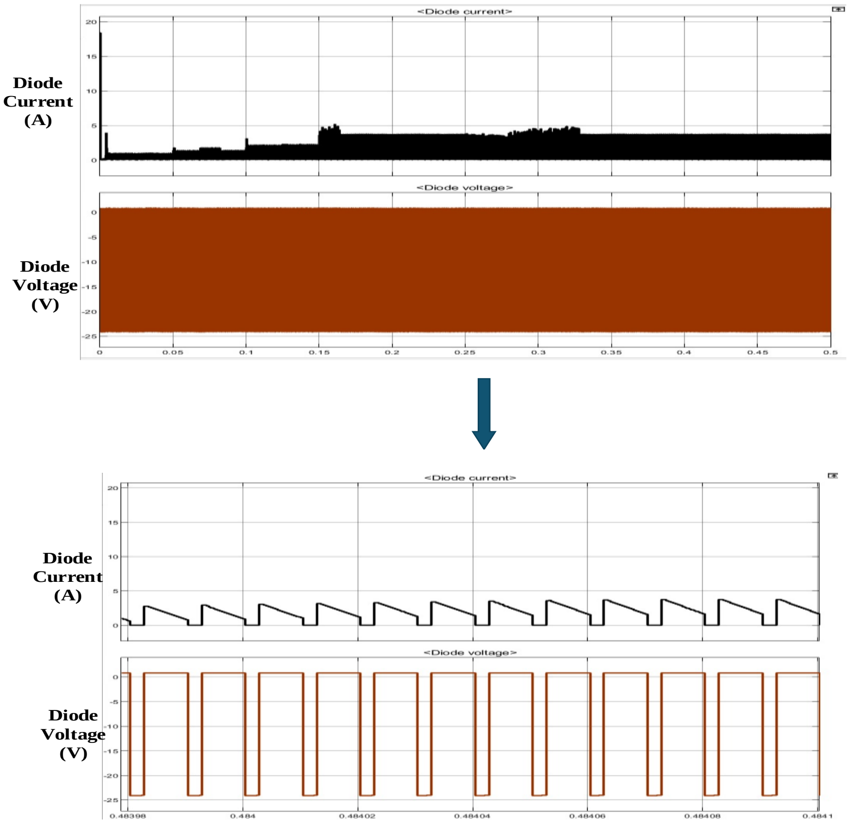


*Fig.3. 7 Voltage across the capacitor and capacitor current*

# CHAPTER 4
# MODELLING OF FORWARD CONVERTER

## 4.1 Introduction

It is very important to model both ideal and non-ideal DC-DC converters early on in the design process for power converters. It lets you guess how the system will act as the load, input voltage, and ambient variables change, which leads to better performance, efficiency, and reliability. Models that are correct are also very important for making controllers that keep things stable, control output, and react to problems in a good way. This thesis uses the state-space averaging method because it strikes a good mix between being simple and accurate. This makes it a good choice for creating and analyzing control systems in power electronics.

## 4.2 State Space Model

The dynamic behaviour of power converters can be modelled and analysed using the state-space technique. In this method, nonlinear characteristics are reduced to linear time-invariant (LTI) systems over a switching period. It makes it possible to develop and analyse converter controllers using linear control theory, which is far simpler and takes less time than working directly with nonlinear-systems. There are multiple steps in the technique, such as its on and off states, are first identified, and the circuit equations for each state are modelled in state-space form. Taking into account the duty cycle of the converter, it computes the average of these state-space equations for a single switching period.

By combining the electrical components and dynamics of the control system into a single framework, the state-space averaging technique offers a smooth understanding of the converter's behaviour, which is one of its important advantages. This comprehensive approach is crucial for increasing reliability, performance, and converter design optimisation. Ideal and non-ideal DC-DC converters by employing the state-space averaging technique. This makes it easier to build reliable, effective power conversion systems and associated controllers.

### 4.2.1 Step 1: Identify System States

In state space technique various operational states of the converter is present. Such states correlate to the switching component as like MOSFET and diodes being in either on or off state for a conventional switched-mode power supply. Every operational state of the converter is characterised by a unique set of system equations in the analysis of DC-DC converters. The voltage across capacitors and the currents passing through inductors are the state variables for modelling. As a result, the number of inductors and capacitors in the circuit directly affects the overall number of state variables.  A state variable vector, represented by the notation x(t), contains these state variables. For Continuous Conduction Mode (CCM), the state equations for the two operational circuit states can be expressed as follows:

$$\dot{x} = Ax + Bu \tag{4.1}$$

$$y = Cx + Eu \tag{4.2}$$

A is the state matrix, B is the input matrix, C is the output matrix, and E is the output coupling matrix.

**(A) Mode-1   Switch- ON, Diode-OFF**

After Solving above equations (3.5), (3.6), (3.7) and (3.8) matrix form is obtained in

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} -\frac{r_C R + r_L r_C + R r_L}{L(R+r_C)} & -\frac{R}{L(R+r_C)} \\ \frac{R}{C(R+r_C)} & -\frac{1}{C(R+r_C)} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} [v_2] \tag{4.3}$$

Value of output voltage from mode 1:

$$v_0 = R(i_L - C\frac{dv_C}{dt}) \tag{4.4}$$

$$v_0 = \begin{bmatrix} \frac{r_C R}{(R+r_C)} & \frac{R}{(R+r_C)} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} \tag{4.5}$$

Matrix form obtained after solving above equation (3.10) ,(3.11),(3.12),(3.13) and(3.14)

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} -\frac{r_C R + r_L r_C + R r_L}{L(R+r_C)} & -\frac{R}{L(R+r_C)} \\ \frac{R}{C(R+r_C)} & -\frac{1}{C(R+r_C)} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} [v_2] \tag{4.6}$$

Value of output voltage from mode 2:

$$v_0 = R(i_L - C\frac{dv_C}{dt}) \tag{4.7}$$

$$v_0 = \begin{bmatrix} \frac{r_C R}{(R+r_C)} & \frac{R}{(R+r_C)} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} \tag{4.8}$$

### 4.2.2 Step 2: State Space Averaging equation

Average the state equations for each state variable across a single switching period while accounting for the duty cycle. The circuit equations are averaged over a single switching period in order to eliminate the switching ripple component. The 'on' state equations are multiplied by (D), while the 'off' state equations are multiplied by (1-D). The results are then sum up. The model is successfully linearised in this step, allowing linear control theory to be used for analysis and design. To remove the switching ripple component from the circuit equations, averaging over one switching period is done. The averaged switching model is obtained by averaging these equations over one switching period:

$$
\begin{aligned}
A &= A_1 d + A_2(1-d) \\
B &= B_1 d + B_2(1-d) \\
C &= C_1 d + C_2(1-d) \\
E &= E_1 d + E_2(1-d)
\end{aligned}
\tag{4.9}
$$

$$
\begin{aligned}
L_m \frac{d\bar{i}_{Lm}}{dx} &= D_1 V_{in} - D_2 \frac{n_1}{n_2} V_{in} \\
L_m \frac{d\bar{i}_{Lm}}{dx} &= \bar{d}_1 V_{in} - \bar{d}_2 \frac{n_1}{n_2} V_{in}
\end{aligned}
\tag{4.10}
$$

$$L \frac{d\bar{i}_L}{dt} = \bar{d}_1 \frac{n_3}{n_1} V_{in} - \bar{d}_1 \bar{v}_c - \bar{d}_2 \bar{v}_c - \bar{d}_3 \bar{v}_c \tag{4.11}$$

$$C \frac{d\bar{v}_c}{dt} = \bar{d}_1 \bar{i}_L - \bar{d}_1 \frac{\bar{v}_c}{R} + \bar{d}_2 \bar{i}_L - \bar{d}_2 \frac{\bar{v}_c}{R} + \bar{d}_3 \bar{i}_L - \bar{d}_3 \frac{\bar{v}_c}{R} \tag{4.12}$$

To derive the small signal model of the Isolated Forward converter, the nonlinear averaged state-space model needs to be linearized around an operating point. This is achieved by applying perturbations to the state variables, x ($i_{La}, i_{Lb}, V_{ca}, V_{cb}$) input variables, x ($\square_{S}$), output variables, y ($\square_{O}$) and duty cycle, d:

### 4.2.3 Step 3: Perturbation and Linearization of averaged state space model

Perturbation and linearisation techniques are frequently used to investigate and control systems with nonlinear dynamics, as seen in the averaged state-space models. In order to have a linear approximate idea of the system's behaviour, this includes minor fluctuations around a steady operational point. This procedure makes system analysis and control strategy design easier, more prominent, particularly in the field of power electronics.

The small ac perturbation introduced around steady state values are as follows:

$$\begin{aligned} \overline{i}_L &= I_L + \hat{i}_L \\ \overline{v}_c &= V_c + \hat{v}_c \\ \overline{d}_1 &= D_1 + \hat{d}_1 \\ \overline{d}_2 &= D_2 + \hat{d}_2 \\ \overline{d}_3 &= D_3 + \hat{d}_3 \end{aligned}$$

$$L_m \frac{d\overline{i}_{Lm}}{dt} = (D_1 + \hat{d}_1)v_{in} - (D_2 + \hat{d}_2)\frac{n_1}{n_2}v_{in} \tag{4.13}$$

$$L\frac{d(I_L + \hat{i}_L)}{dt} = (D_1 + \hat{d}_1)\frac{n_3}{n_1}v_{in} - (D_1 + \hat{d}_1)v_c - (D_2 + \hat{d}_2)\overline{v}_c - (D_3 + \hat{d}_3)\overline{v} \tag{4.14}$$

$$C\frac{d\overline{v}_c}{dt} = (D_1 + \hat{d}_1)(I_L + \overline{i}_L) - (D_1 + \hat{d}_1)\frac{\overline{v}_c}{R} + (D_2 + \hat{d}_2)(I_L + \overline{i}_L) - (D_2 + \hat{d}_2)\frac{\overline{v}_c}{R} + (D_3 + \hat{d}_3)(I_L + \overline{i}_L) - (D_3 + \hat{d}_3)\frac{\overline{v}_c}{R} \tag{4.15}$$

**Small Signal Part**

$$L\frac{d\hat{i}_L}{dt} = \hat{d}_1 v_{in} - \hat{d}_2\frac{n_1}{n_2}v_{in} \tag{4.16}$$

$$C\frac{d\hat{v}_c}{dt} = D_1\hat{i}_L + \hat{d}_1 I_L - D_1\frac{\hat{v}_c}{R} + D_2\hat{i}_L + \hat{d}_2 I_L - D_2\frac{\hat{v}_c}{R} + D_3\hat{i}_L + \hat{d}_3 I_L - D_3\frac{\hat{v}_c}{R} \tag{4.17}$$

To determine the different transfer functions, we apply the Laplace transform to the State-space model, yielding the following expression;

$$\frac{\hat{v}_0}{\hat{d}} = \frac{\frac{v_2}{LC}(1+sCr_C)}{s^2 + s\left[(\frac{r_C + r_L}{L}) + \frac{1}{RC}\right] + \frac{1}{LC}} \tag{4.18}$$

After putting values of parameters (table.) in above equation (4.18), final value of transfer function of forward converter obtained is :-

$$T(s) = \frac{6250s+50}{s^2+2000s+10} \tag{4.19}$$

## 4.3 Conclusions

In conclusion, considerable progress in comprehending the behaviour of forward converters has been made by the use of the state space averaging technique in modelling. An improved model for the non-ideal parasitic forward converter was made possible by this technique, providing more accuracy in both steady-state and transient analysis. A detailed study of the dynamics of these converters was attained by looking at the transfer functions associated with input voltage to output voltage.

The improved transfer functions that produced, crucial for controller design because transfer function provide information that guarantees the dependability and strong performance of forward converters in practical applications. Therefore, using state space averaging for modelling helps to advance power electronics design and analysis.

# CHAPTER 5
# CONTROL OF DC-DC CONVERTERS

## 5.1 Need of Controllers

In a DC-DC converter, Changes in load conditions have a direct impact on the output voltage. if the load abruptly drops, it reduces the current demand. If the converter continues to supply the same amount of energy, the output voltage may overshoot before the controller adjusts the duty cycle to bring it back to the desired level. These temporary deviations, known as voltage transients, can severely affect the output and efficiency in sensitive electronic systems. The voltage variations, which are frequently transient in nature, might affect a system's stability and performance, particularly in electronic applications like phones, chargers etc. Maintaining a steady and controlled output depends on the converter's control system's capacity to react swiftly to these variations.

PID and PI controllers are frequently employed in industrial settings due to their broad variety of applications and robust performance. These controllers effectively attenuate overshoots and swiftly resolve transients. The simple mathematical formulas allow for easy application with parameters that can be adjusted to meet specific application needs.

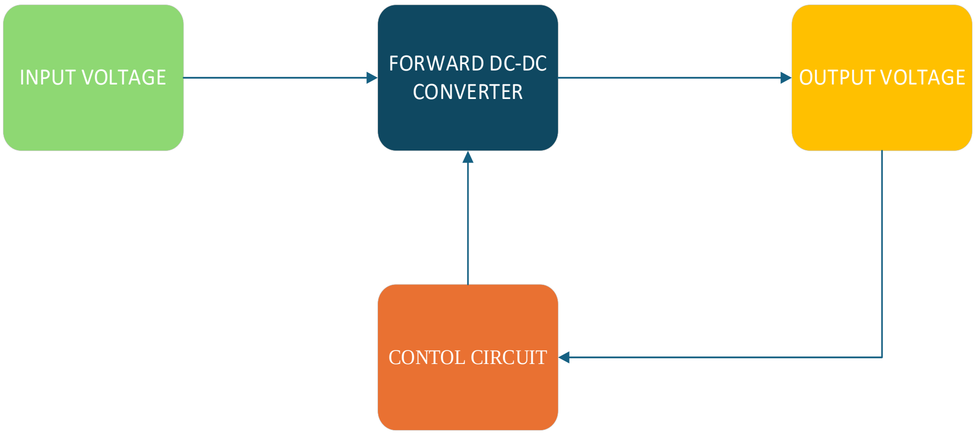


*Fig.5. 1 Block diagram of a Closed loop controller circuit*

## 5.2 Proportional-Integral (PI) Controller Structure and Operation

PI controller is widely used in control systems due to its simplicity and effectiveness in eliminating steady-state error and transient error. It operates by continuously adjusting the control input to a system based on the error between a desired output and the actual output. The controller combines two corrective actions: the proportional part reacts instantly to the present error, providing a control signal that is directly proportional to the magnitude of the error. On the other hand, the integral part accumulates the error over time and addresses any residual steady-state error that the proportional part cannot eliminate. Together, these two actions ensure both fast response and accurate regulation.

The complicated process of managing suboptimal forward converters pose distinct issues. Non-ideal converters demonstrate inefficiencies attributable to the Equivalent Series Resistance (ESR) of capacitors and inductors, which creates supplementary dynamics that a controller must manage. These encompass variations in response time and output ripple, which are less problematic in ideal converters compared to suboptimal ones. The efficacy of closed-loop controllers in forward converters has been shown by significant modeling experiments. These studies illustrate that diverse control techniques are helpful in managing standard deviations and enhancing performance across multiple operational situations. Thus, the application of advanced control techniques in DC-DC converters guarantees operational dependability and improves the efficiency of these essential components.

The overall control signal is the sum of these two components and is used to drive the system toward its desired output.

The proportional integral controller is represented mathematically as follows:

$$m(t) = K_p[e(t) + \frac{1}{T_i}\int K_i e(t)dt] \quad (5.1)$$

where,

$K_p$ = proportional gain constant

$K_I$ = integral gain constant

$e(t)$ = value of error

$E(s)$= laplace transform of error signal

In Laplace transform notation, the PI controller's transfer function is given in below equation: -

$$M(s) = E(s)[K_p + \frac{K_I}{s}] \quad (5.2)$$

$$Y(s) = [K_p + \frac{K_I}{s}] \quad (5.3)$$

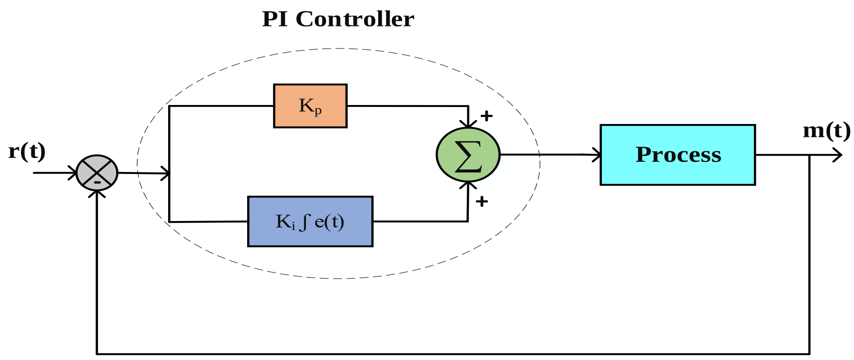


*Fig.5. 2 Block diagram of a PI controller*

## 5.3 Tunning of PI controller

The performance of a PI controller depends greatly on the correct selection of its gain parameter proportional gain ($K_p$) and integral gain ($K_i$). Tuning refers to the process of determining these values to achieved a desired value with fast response, stability, and accuracy. Several methods are mainly used to tune PI controllers, each with its own advantages and limitations:

### 5.3.1 Manual Tuning of a PI Controller

In manual tuning is a straight forward method of adjusting the PI controller gains through hit and trial. The process begins by setting the integral gain ($K_i$) to a low value, preferred is zero and gradually increasing the proportional gain ($K_p$) until the system responds with a quick rise time but without excessive overshoot. Once a suitable ($K_p$) is found, the integral gain ($K_i$) is slowly increased to reduce steady-state error. The process is repeated by observing the system's step response and adjusting the gains until a balance is achieved between reference value and desired value.

### 5.3.2 Ziegler–Nichol's Method

The Ziegler–Nichol's method is a popular and systematic method for tuning PI controllers. It starts by setting the integral gain ($K_i$) to zero and gradually increasing the value of proportional gain ($K_p$) until the system output exhibits continuous and stable oscillations. The value of  at this point is called the ultimate gain, and the time period of oscillation is the ultimate period. Based on these values, the PI controller gains are set using standard formula:

$$K_p = 0.45 \cdot K_u,\ K_i = 1.2\frac{K_p}{P_u} \tag{5.4}$$

$$(T \cdot F)_{OL} = \frac{(6250s+50)}{s^2+2000s+10} \tag{5.5}$$

Finally,

$$(T \cdot F)_{CL} = \left[\frac{(6250s+50)\cdot k}{s^2+s(6250k+2000)+50k+10}\right] \tag{5.6}$$

So, characteristic equation is,

$$s^2+50k+10 \tag{5.7}$$

Using Routh-Herwitz criteria, value of $K_u = 0.2$

Replacing, ‘s’ from ‘jw’ gives equation,

$$s^2 + 20 = 0 \tag{5.8}$$

$$w^2 = 20, w = 0.894$$

$$\begin{aligned} T_u &= \frac{2\pi}{0.894} \\ T_u &= 7.024 \\ K_u &= 0.2 \end{aligned} \tag{5.9}$$

For the PI controller, value of $K_p$ and $K_i$ can be given as;

$K_p$ = (0.45) $K_u$ = (0.45)*(0.2)= 0.09

$$K_i = \frac{(0.54)K_u}{T_u}$$
$$K_i = \frac{(0.54)(0.2)}{7.024} = 0.0153 \tag{5.10}$$

## 5.3 Non-ideal Forward Converter Voltage Regulation using PI controller

In a forward converter, maintaining a stable and accurate output voltage is essential, especially when the input voltage or load conditions are varied. The PI controller operates by measuring the error between the reference voltage ($V_{ref}$) and the actual output voltage ($V_0(t)$. This error signal, defined as:

$$e(t) = V_{ref} - V_0(\mathrm{t}) \tag{5.11}$$

This error fed to PI Controller to generate the appropriate pulse width. By modifying the duty cycle of the switching element in response to voltage feedback, the PI controller in a forward converter controls the output voltage. This guarantees that even when there are variations in the load or at the input side, the output will stay stable and constant. Because of its simplicity of use, minimal processing demands, and consistent ability to maintain voltage stability, the PI controller is particularly preferred in these kinds of applications. In real-world applications, the load connected to a DC-DC converter such as a forward converter often changes continuously due to varying power demands. These load changes affect the output voltage, which can lead to instability or poor performance if not properly regulated. When the load increases, more current is drawn from the output, causing the output voltage to drop. Conversely, a sudden decrease in load may cause a temporary rise in output voltage due to excess energy stored in the inductor. In both situations, the PI controller detects the deviation of the output voltage from the reference value through an error signal.

Since the output voltage of the forward converter is given by:

$$V_0 = D \cdot V_{in} \cdot \frac{N_2}{N_1} \tag{5.12}$$

changing the duty cycle alters the energy delivered to the output as shown in equation (5.12). If the voltage drops due to an increased load, the PI controller increases the duty cycle to compensate. If the voltage rises due to a decreased load, it reduces the duty cycle accordingly.

## 5.4 Non-ideal Forward Converter Voltage Regulation using ANFIS controller

### 5.4.1 Introduction

ANFIS, an acronym for Adaptive Neuro-Fuzzy Inference System, is a control methodology that integrates the flexibility of neural networks with the logical reasoning of fuzzy systems. ANFIS is distinguished by its capacity to manage systems that do not adhere to a straightforward, predictable pattern. It acquires knowledge from data and modifies itself according to the system's performance—capabilities that conventional controllers such as PI or PID are not inherently equipped to perform. This versatility is particularly advantageous in real-time control tasks, such as maintaining a stable output voltage in power converters. In the scenario of a forward converter, ANFIS receives inputs such as the discrepancy between the actual and desired voltage, as well as the rate of change of that discrepancy, to determine adjustments to the switch's duty cycle. What is the outcome? Regardless of variations in load or fluctuations in input voltage, the output remains near its intended level. The learning capability of ANFIS provides a significant benefit in scenarios where fixed-rule controllers may be inadequate.

### 5.4.2 PI controllers Limitations

PI controllers are dominantly used in power electronic systems. They do have certain disadvantages, though, particularly when working with nonlinear or time-varying systems in DC-DC converters. Their fixed gain settings, which are adjusted according to certain operating conditions, are a significant disadvantage. Longer settling times and more overshoot may result in this. Conventional PI controllers frequently underperform in systems subjected to rapid fluctuations. Due to their operation within defined parameters, they are incapable of adapting or learning from system behavior. This complicates their ability to respond efficiently to shifts in system dynamics, including load variations, component alterations, or unforeseen disturbances. They often encounter difficulties with nonlinear systems, where established norms may not be applicable. Due to these constraints, PI controllers may not be optimal for applications requiring rapid reactions and great accuracy. Consequently, there has been an increasing interest in more sophisticated control techniques, such as ANFIS, which provide enhanced adaptability and are more appropriate for dynamic, real-world environments.

### 5.4.3 Objective for designing an ANFIS controller

Designing and testing an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller for efficient voltage regulation in a forward DC-DC converter is the main goal of this thesis. In dynamic load settings, when quick variations in load demand might affect system performance, the emphasis is on preserving a steady output voltage.

The objective is to create a control system that reacts smooth and fast to these fluctuations, guarantee precise and dependable voltage regulation in a variety of operating and situations. Designing and implementing an ANFIS based forward converter controller with a particular emphasis on voltage regulation under dynamic load situations

## 5.5 ANFIS Controller Design

ANFIS controller is a hybrid intelligent controller that integrates the learning capabilities of neural networks with the rule-based reasoning of fuzzy logic. It is particularly effective for nonlinear and intricate systems where accurate mathematical models are challenging to formulate.

### 5.5.1 Implementation of ANFIS in the Forward Converter System

This study investigates the application of an Adaptive Neuro-Fuzzy Inference System (ANFIS) as a closed-loop controller for regulating output voltage in a non-ideal forward DC-DC converter. The objective is to attain accurate and responsive voltage regulation, particularly during variations in load resistance or input supply—situations when conventional controllers like as PI frequently fail to operate effectively. The ANFIS controller seeks to mitigate voltage fluctuations, reduce response time, and preserve overall system stability amid abrupt disruptions by reacting to system changes in real time. This controller's usefulness will be demonstrated by comparing its performance to that of a standard PI controller under analogous settings, illustrating how ANFIS provides more robust control in dynamic, real-world scenarios.

### 5.5.2 Role of Membership Functions

Membership functions are a key feature of all fuzzy logic systems. They connect the fuzzy reasoning that is similar to how people think with the real numbers that a system gets. These capabilities assist the controller better understand changing conditions in the case of a forward converter, where accurate control of output voltage is critical. In short, a membership function tells you how strongly an input value belongs to a certain fuzzy collection. For example, a voltage mistake of 0.2 volts can fit into both the "Low Error" and "Medium Error" sets, depending on how those sets are defined. These functions usually use forms like triangles, trapezoids, or Gaussian curves. There are pros and cons to each shape. For example, triangular and trapezoidal functions are easy to use and ubiquitous, whereas Gaussian curves are preferable for applications that need more accuracy since they make transitions smoother.

A fuzzy controller gives each input, like the error and its rate of change, a set of membership functions that break the input range into usable groups, such as "Negative Large," "Negative Small," "Zero," "Positive Small," and "Positive Large." The shape and location of these functions determine how a certain input is categorized. These membership functions are not fixed in an ANFIS controller. They are set up at the design phase, but they are fine-tuned during training utilizing neural network learning methods. This lets the controller change and get better based on data it gets in real time.

## 5.3 Layers of the ANFIS Model:

The Adaptive Neuro-Fuzzy Inference System (ANFIS) works in various levels for a forward converter. Each layer has its own job of processing data and generating control decisions. The input layer is where the system starts by comparing the reference voltage to the actual output. This creates two signals in real time: the voltage error (e) and the change in error (Δe). There is no change made to these data before they are sent to the next stage. Using membership functions, which are commonly triangular or Gaussian in shape, the fuzzification layer turns these numbers into fuzzy phrases like "Negative," "Zero," or "Positive." This lets the same input belong to more than one set, which makes the control more flexible and fluid in how it reacts. The next layer is the rule layer, which uses a set of fuzzy logic rules on the inputs. A common rule can be, "If the error is positive and the change in error is negative, then the output is decrease." There is a rule for each node in this layer, and the system checks all conceivable combinations of inputs at the same time. After that, the outputs from these rules go to the defuzzification layer. This element of the system turns the imprecise decisions into a clear control signal with numbers. It does this by adding up the outputs of the rules, giving them different weights based on how relevant they are. This clear output is used to change the duty cycle of the converter's switch, which closes the loop.

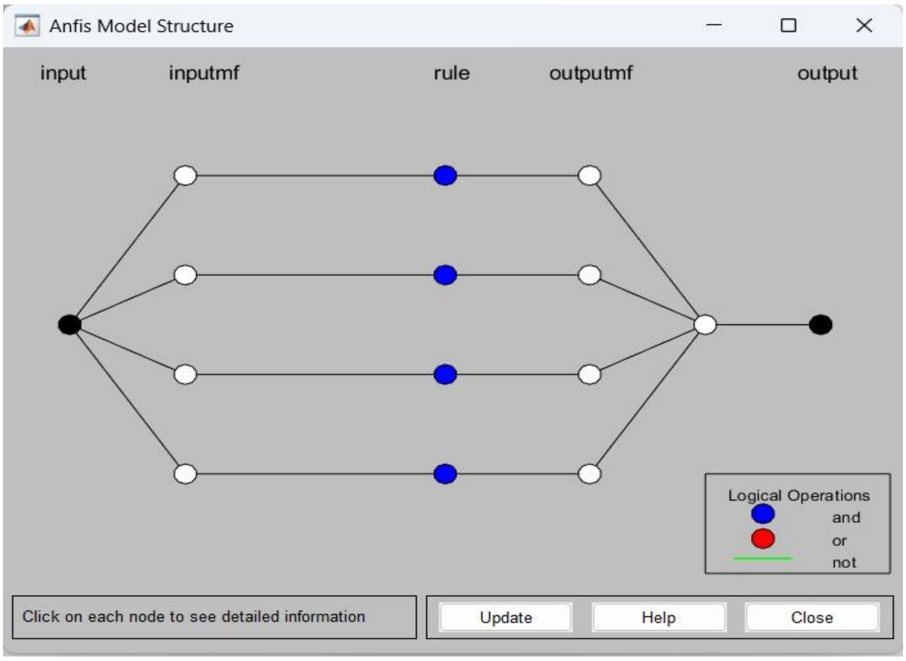


*Fig.5. 3 Structure of the different layers of the ANFIS controller in forward converter*

The output layer then figures out the system's final reaction and sends a precise control action that keeps the voltage stable, even when the conditions vary.

## 5.4 Training and Evaluation of ANFIS Model

The Adaptive Neuro-Fuzzy Inference System (ANFIS) model's training procedure using a sizable dataset of 1,438,129 input-output data pairs is depicted in fig.5.2. The consistency and distribution of the data during the learning phase are shown by the training graph, which graphs the output values against the dataset index. Accurate fuzzy categorization is made possible in this configuration by processing a single input via four membership functions. The grid partitioning approach is used to create the fuzzy inference system (FIS), which creates the corresponding fuzzy rules by uniformly dividing the input space. For model training, a hybrid optimization algorithm is employed, combining the strengths of gradient descent and least squares estimation to improve both convergence speed and accuracy.

The number of training epochs is chosen at 200 to guarantee that the model is well-trained, providing enough iterations to reduce training error and improve system

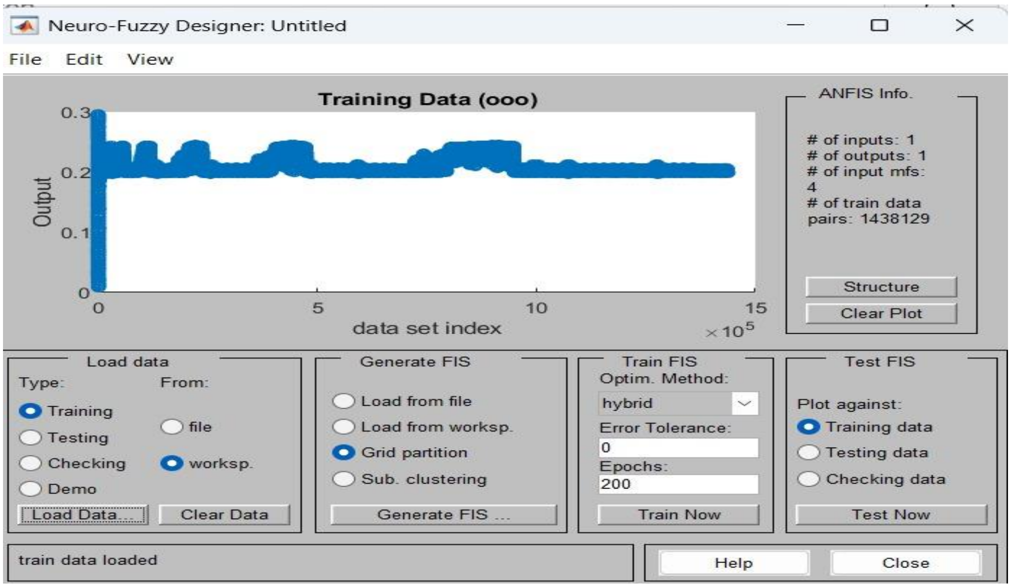

*Fig.5. 4 Training interface of the ANFIS model*

performance. The output fluctuates at first, but stabilizes as training goes on, signifying good learning and convergence. By comparing its performance using distinct testing and validation datasets, this trained ANFIS model may now be verified under various nonlinear forward converter load situations.

## 5.5 Training Error Analysis of ANFIS Model for non-ideal Forward Converter Voltage Regulation

The performance of an ANFIS model used to control a parasitic forward converter's output voltage under various load conditions is shown in the fig.5.3 The training error trend during the ANFIS model training for controlling a forward-converter's output voltage is represented by the graph: X-axis: Number of epochs (0 to 200); Y-axis: Corresponding training error. The hybrid learning method with grid partitioning was used for the training process, and the model was trained using one input variable, one output, and four membership functions (MFs). The error steadily decreased as training went on, indicating good model convergence and effective learning. At epoch 200, the

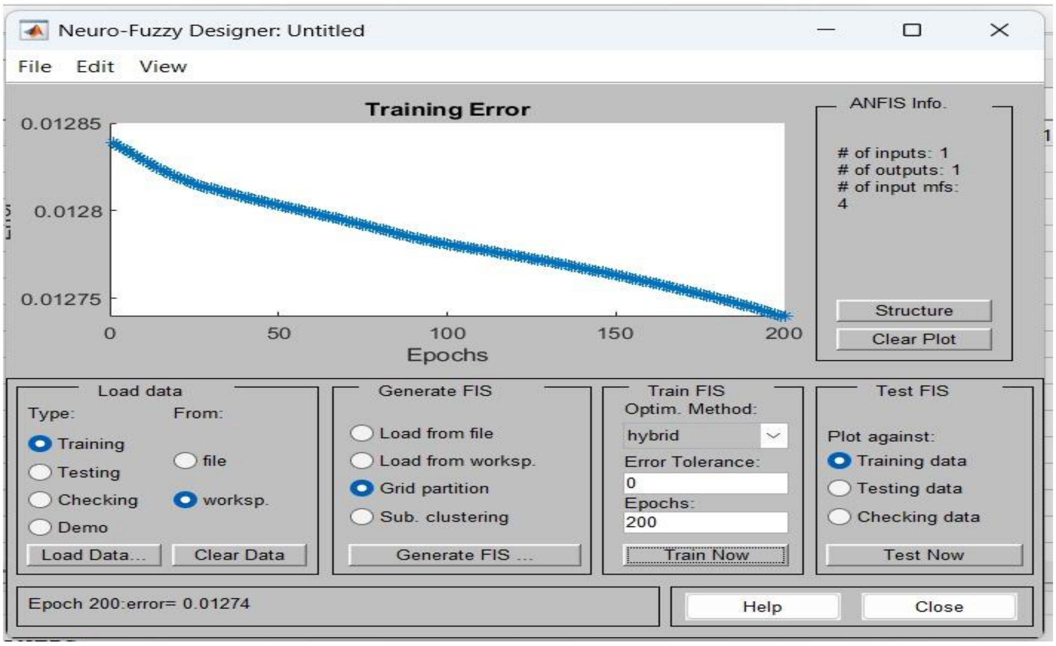


*Fig.5. 5 Graph of Training Error Analysis of ANFIS Model*

final training error was around 0.01274, demonstrating a high level of accuracy for output prediction. The error reduction indicates that the ANFIS controller successfully learnt the input–output relationship for voltage regulation and hence goal achieved.

## 5.6 Membership Function Analysis for Input Variable in Forward Converter Fuzzy Inference System

The membership function graph for the input variable "input1" in the fuzzy inference system (FIS) governing the forward converter is illustrated in Fig. 5.4. Four triangular membership functions in1mf1, in1mf2, in1mf3, and in1mf4 characterize "input1" in this setup. These algorithms facilitate smooth and uninterrupted transitions among fuzzy sets by including a specific range of the input variable. The overlap of adjacent membership functions ensures adaptable interpretation of input variations and facilitates uncertainty management. The degree of membership, ranging from 0 to 1, facilitates precise mapping of input values to corresponding fuzzy rules. This framework enhances the responsiveness and adaptability of the fuzzy control system

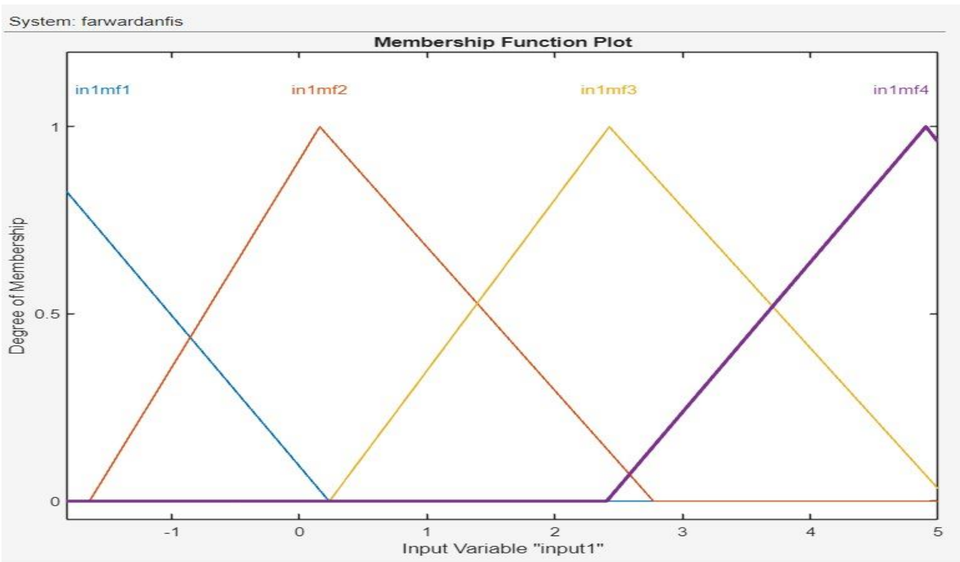


*Fig.5. 6 Graph of membership function generated during ANFIS Modelling*

by identifying subtle variations in the input signal. This membership function arrangement enhances the FIS's efficiency in processing input signals, which is crucial for achieving precise and consistent regulation in the forward converter.

## 5.14 Output Voltage Response of non-ideal Forward Converter using ANFIS controller

The fig shows the waveform of voltage regulation of the parasitic forward converter: the switch voltage (top plot) and the output voltage (bottom plot). The switch voltage exhibits the characteristic waveform of a forward converter with periodic switching and transformer reset behavior. The output voltage remains consistently regulated around 5 V even after load variations, demonstrating effective voltage control under the given operating conditions.

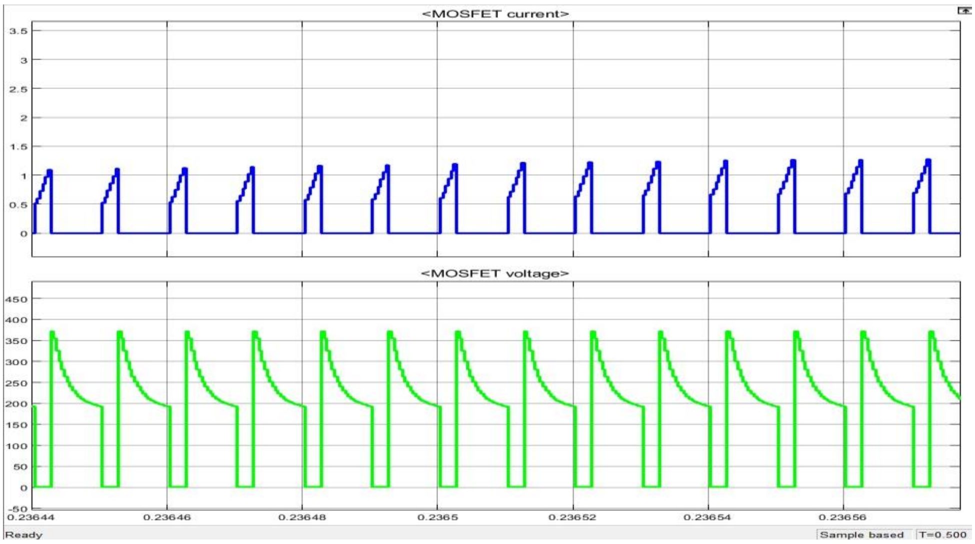


*Fig.5. 7 Graph of voltage and current across switch*

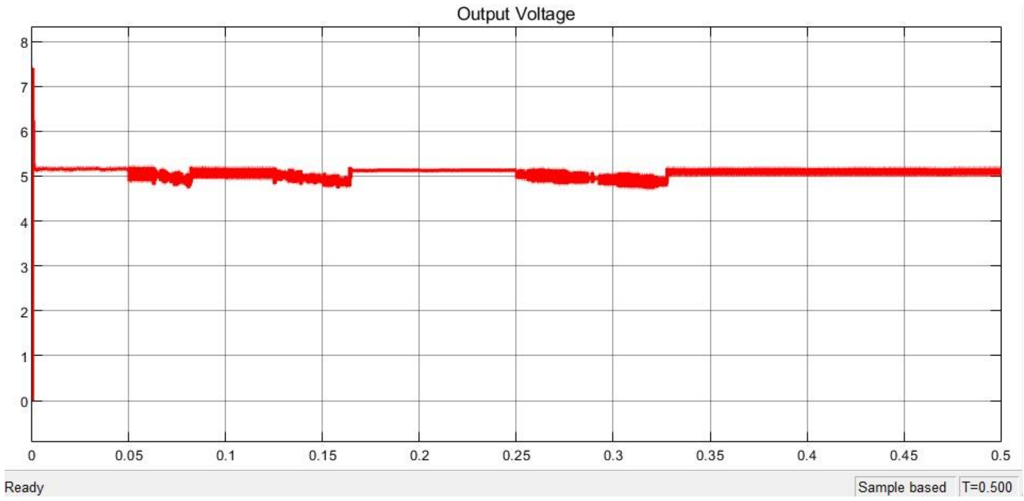


*Fig.5. 8 Graph of output voltage regulation at various load conditions*

### 5.14.1 Results and Observations

The switch voltage waveform continues to follow the anticipated pattern, which is an exponential decline when the switch is in OFF mode and attains a square shaped waveform during the turn ON period.

Peak switch voltage reaches approximately 370 V, which is within safe operational limits for the switching device.

The waveform is constant under all load situations, suggesting that the converter's core switching behavior is consistent and unaffected to changes in load.

Proper transformer demagnetization through the reset winding is confirmed by the voltage spike at the beginning of the OFF period.

The feedback control loop successfully maintains voltage regulation since the output voltage is almost constant at 5 V with little ripple.

The output voltage is kept extremely near to 5 V with little ripple when the load is 20 Ω, indicating a light-load state with low output current requirement.

The output current rises as the load reaches 10 Ω, yet the controller adapts to maintain the output voltage controlled with very little transient variation.

The output voltage briefly dips under the 5 Ω load condition (heaviest load) because of the higher demand, but the control system quickly corrects to bring the output back to the nominal 5 V level.

The smooth regulation across different load levels highlights the effectiveness of the feedback control system (PI or ANFIS, depending on implementation).

The transient response is minimal, with no significant overshoot or oscillation, indicating well-tuned controller parameters and adequate phase margin.

## 5.15 Conclusion

The simulation results of ANFIS controller in a non-ideal forward converter, shows that under a variety of load circumstances, the forward converter maintains stable output voltage regulation. The output current rises as the load drops from 20 Ω to 10 Ω and finally to 5 Ω. Only minor transients are seen during load transitions, and the output voltage continuously stays near the desired value of 5 V inspite of this variation. This shows that the control technique used, whether it be ANFIS or PI, is trustworthy and effective at adapting to dynamic changes.

Furthermore, proper switching behaviour and transformer reset operation are confirmed by the switch voltage waveform remaining stable and within acceptable operating limits. All things considered, the converter exhibits stable, robustness and good dynamic performance, which makes it appropriate for applications with variable load conditions.

Furthermore, when it comes to tracking a reference voltage, closed loop has demonstrated superior accuracy and speed, effectively adapting to rapid fluctuations in reference signals, it shows better stability than PI Control under changing conditions.

# CHAPTER 6

# SIMULATION RESULTS AND DISCUSSION

## 6.1 Result of Simulation:

For Voltage Regulation,in a closed-loop system, it has been observed that when loading is increased by decreasing the load resistance, the output voltage stabilizes after a few transient fluctuations (fig.11). In this case, the output voltage is set at 5V, and as loading increases, it stabilizes at roughly 5V. Hence effective controlling is achieved by using a PI controller, which the graph makes evident. The graph shown in fig. shows the simulation results that how the forward converter performs dynamically under various load conditions. The output voltage (Vo) is displayed in the upper plot, while the matching output current (Io) is displayed in the lower plot. The output current rises when the load resistance is gradually reduced from 200 Ω to 2.5 Ω. The output voltage stays well-regulated around the intended 5V level during these transitions, demonstrating the controller's efficient voltage regulation.

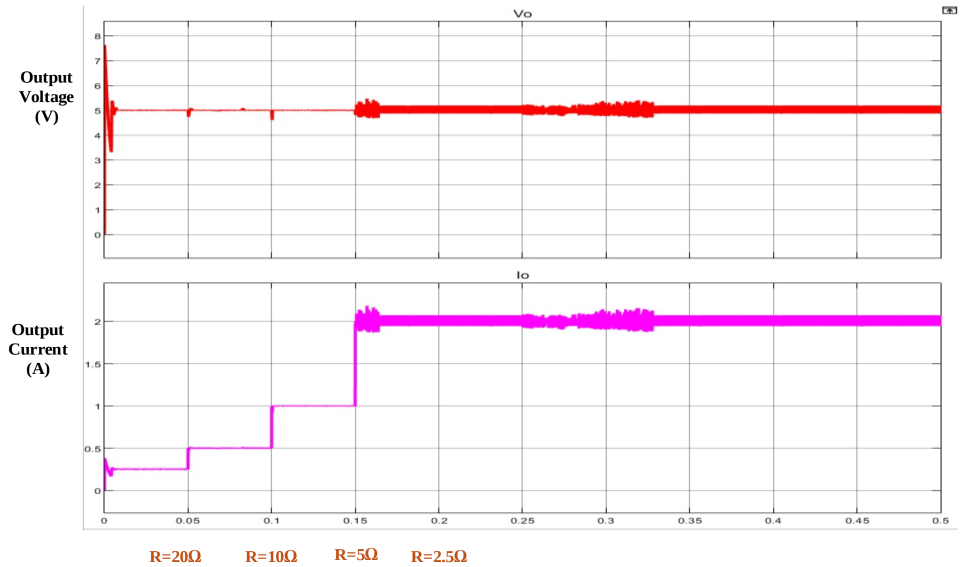


*Fig.6. 1 Graph of voltage regulation at different load conditions in closed loop PI controller*

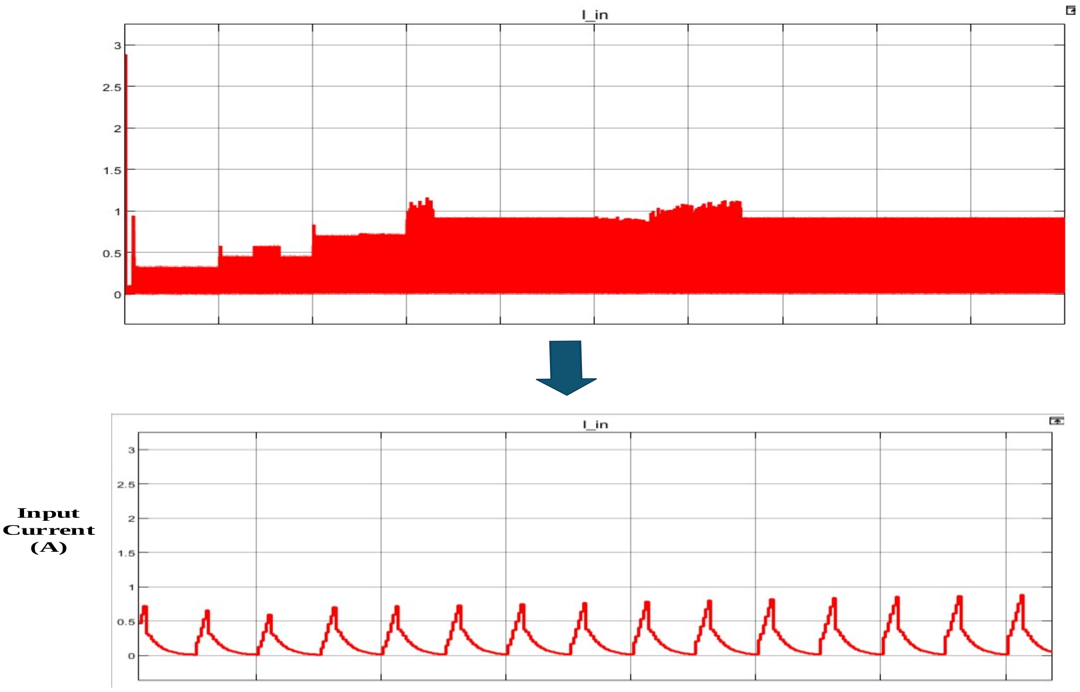


*Fig.6. 2 Graph of Input Current*

The forward converter's input current characteristics are shown in the figure. The main cause of this fluctuations is the converter's high-frequency switching, which adds harmonics and abrupt changes to the input current.

## 6.2 Comparison of Output Voltage Response in Open-Loop and Closed-Loop Control of Forward Converter

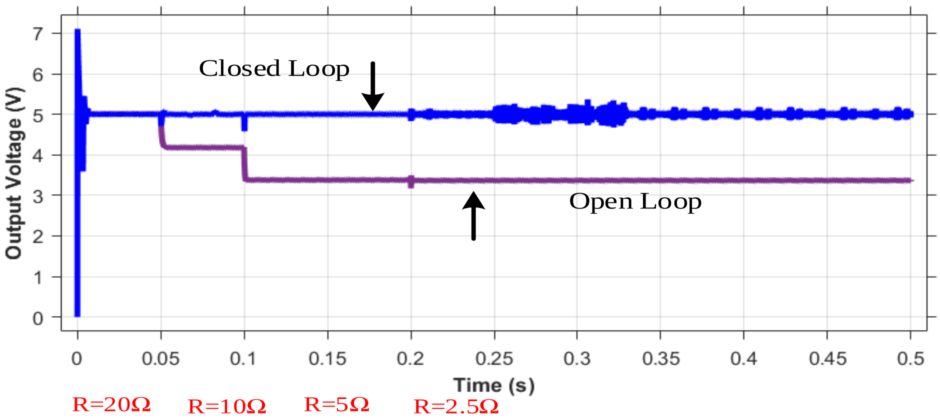


*Fig.6. 3 Comparison of output voltage in open loop and close loop at transient stage*

The output voltage response of a forward DC-DC converter under various load situations is illustrated on the graph shown in fig.6.3. After the startup transient, the converter output voltage in close loop (shown in blue) quickly increases to about 5V and stabilizes even after change in loading conditions. The matching dips in the purple curve, which represents the load voltage fluctuations in open loop, shows that as loading increases output voltage stats dropping. The regulated output voltage stays near the desired 5V in spite of these abrupt load variations, indicating the controller's ability to maintain voltage regulation under shifting load conditions, which shows a perfect controlling and tunning of the PI controller.

Table 6. 1 Comparison of open Loop and close Loop

| **SYSTEM** | **MAXIMUM PEAK OVERSHOOT (%M$_P$)** | **SETTLING TIME (ms)** |
|---|---|---|
| Open Loop System | 8.59 V | 1.57-2 |
| Close Loop System Using PI Controller | 5.27 V | 0.55-0.57 |

The performance of a non-ideal forward converter was analysed quantitatively in two different configurations: open-loop control and closed-loop control with a PI controller. Primary focus of comparisons are settling time ($t_s$) and maximum peak overshoot ($\%M_p$) as shon in table of (6.1). The output voltage in the open-loop system peaked at approximately 8.59V as shown in fig.6.3, suggesting a rather significant overshoot. The system takes longer to stabilise following a disturbance, as clearly shown by the settling time of fig.6.3, which was found to be between

$1.57 - 2ms$. This behaviour is a reflection of the absence of feedback control, which leads to inadequate voltage regulation and poor dynamic response of the parasitic forward converter. On the other hand, the closed-loop system that used a PI controller performed better. The settling time was much shorter, ranging from $0.55 - 0.57$ ms and the highest peak overshoot was decreased to 5.27 V. This demonstrates that how adding feedback and having a well-tuned controller enables the system to react to changes faster and more precisely by reducing the deviations from the reference voltage. Overall, the findings demonstrate that the closed-loop control system boosts both the transient and steady-state performance of the converter, ensuring faster stabilization and lower voltage variances, which are critical for maintaining consistent power delivery under different load situations

## 6.3 Comparative Analysis of PI & ANFIS Controllers

Performance differences for managing a forward converter are shown by the comparison of PI and ANFIS controllers. A conventional linear control technique, the PI controller modifies the output in response to errors and current conditions. ANFIS can manage system non-linearities better. It can react more effectively under dynamic and unpredictable operating settings by automatically modifying control rules based on input-output data as shown in fig.6.2. ANFIS offers enhanced stability, quicker settling time, and smoother output regulation, particularly in systems for forward converters that encounter abrupt changes in input or load circumstances as shown in fig.6.4.

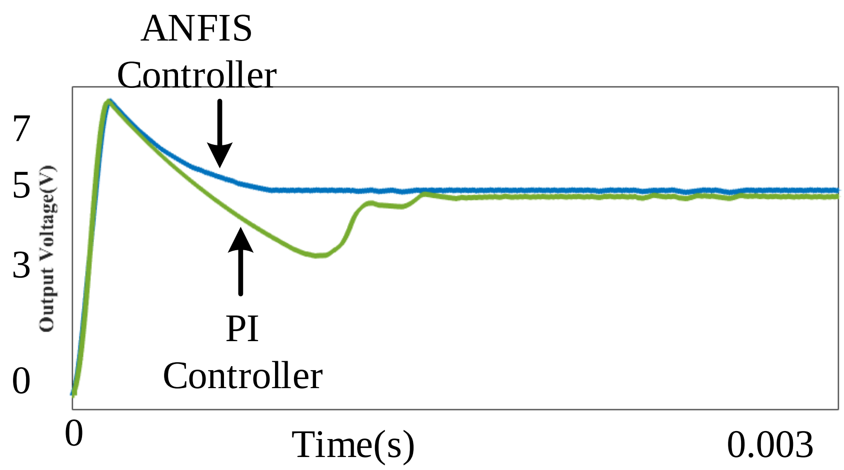


*Fig.6. 4 Voltage regulation in close loop using PI and ANFIS in close loop*

The graph shown in fig.6.4, shows the response of the output voltage of a non-ideal forward converter controlled by two different controllers: an ANFIS-based controller and a PI controller. Before progressively stabilizing at the target voltage level of 5V the PI controller (shown by the green curve) shows a peak overshoot. On the other hand, the ANFIS controller (shown by the blue curve) reacts more effectively, exhibiting less oscillation and overshoot, and reaching steady-state faster and more smoothly after load transitions. This comparison demonstrates how the ANFIS controller performs better under dynamic load settings, with faster settling time and better voltage regulation.

Table 6. 2 Comparison of PI Controller and ANFIS Controller

| **Controller** | **Maximum Peak Overshoot (%$M_P$)** | **Settling Time ($t_s$) (ms)** |
|---|---|---|
| PI | 7.61 | 1.497 |
| ANFIS | 7.30 | 0.781 |

Table 6. 3 Losses and Efficiency of Forward Converter Using PI and ANFIS Controllers

| Sl. No. | Controller | Load Resistance (Ω) | Conduction Losses (W) | Diode Losses (W) | Switching Losses (W) | Total Losses (W) | Efficiency (%) |
|---|---|---|---|---|---|---|---|
| 1. | PI | 2.5 | 0.215 | 1.064 | 0.234 | 1.513 | 86.8 |
| | | 5 | 0.0538 | 0.532 | 0.117 | 0.703 | 87.7 |
| | | 10 | 0.0135 | 0.266 | 0.058 | 0.338 | 88.1 |
| | | 20 | 0.0034 | 0.133 | 0.029 | 0.165 | 88.3 |
| 2. | ANFIS | 2.5 | 0.215 | 1.064 | 0.187 | 1.466 | 87.2 |
| | | 5 | 0.0538 | 0.532 | 0.094 | 0.679 | 88.0 |
| | | 10 | 0.0135 | 0.266 | 0.047 | 0.326 | 88.5 |
| | | 20 | 0.0034 | 0.133 | 0.029 | 0.165 | 88.3 |

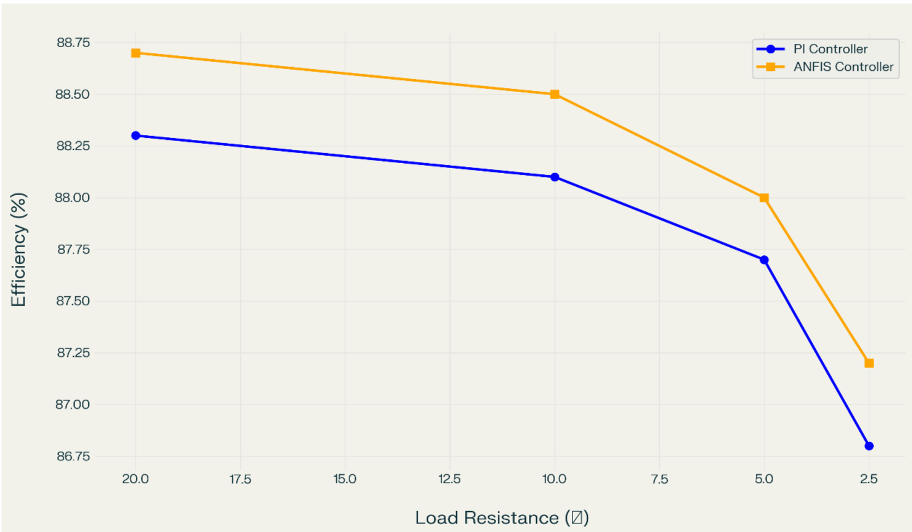


*Fig.6. 5 Graph of efficiency at variable load conditions for PI and ANFIS Controllers*

The efficiency performance of a forward converter using two distinct control strategies one is PI controller and another is ANFIS controller is analysed here under various load resistances is displayed on the graph. The y-axis shows efficiency in percentage (%), and the x-axis shows load resistance in ohms (Ω). Both controllers exhibit a decrease in efficiency as the load resistance drops. Under all load circumstances, the ANFIS controller continuously have more efficiency than the PI controller. Both controllers function almost similarly at greater load resistances (lighter loads), but the PI controller's efficiency drastically decreases at lower resistances (heavier loads), making the difference quite noticeable. This illustrates that, particularly in load variations, the ANFIS controller performs better and stable in closed loop conditions.

## 6.4 Efficiency Analysis in open loop, closed loop using PI and ANFIS controller

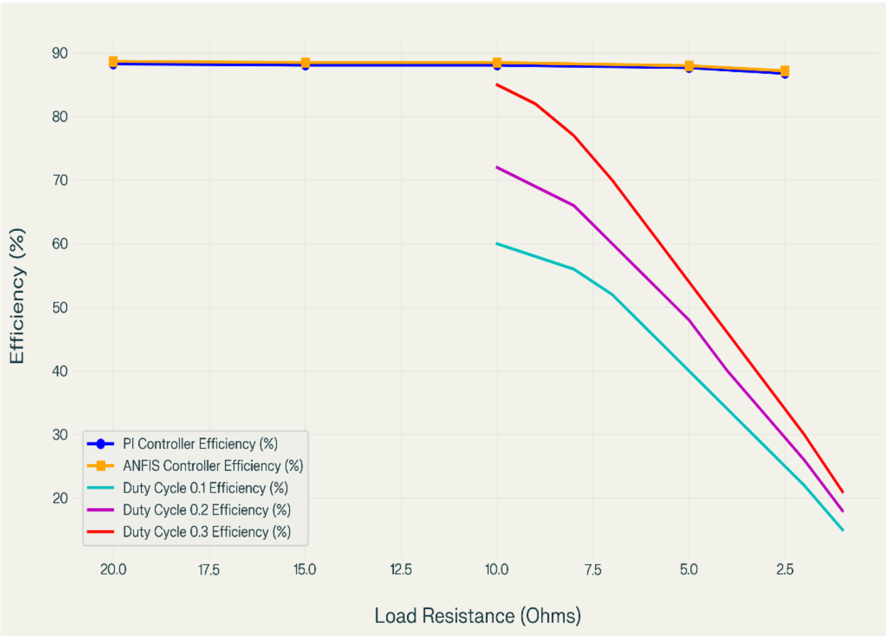


*Fig.6. 6 Plot showing the variation of efficiency with load resistance for different duty cycles in open loop and closed loop using PI and ANFIS.*

The graph compares the efficiency of a forward converter under different load conditions, under various control methods and duty cycles. The ANFIS controller performs marginally better, particularly at lower resistances, although both controllers maintain excellent and almost constant efficiency throughout all load fluctuations. On the other hand, as the load resistance drops, duty cycles (0.1, 0.2, and 0.3) exhibit a steep drop in efficiency. All duty cycles have comparatively good efficiency at higher resistances, but under heavy load conditions,the efficiency drastically decreases, with the lowest duty cycle (0.1) exhibiting the sharpest fall over.

# CHAPTER 7
# CONCLUSION AND FUTURE SCOPE

## 7.1 Conclusion

The design, mathematical modelling, and control issues associated with non-ideal Forward converters have been seriously examined in this thesis. The research study's conclusions about design, modelling, control and stability issues can be summed up as follows It was found that, Power dissipation across the converter's many resistive parts is blamed on the voltage drop. The parasitic components of the converter are taken into considerations in these computations, the formulas used to calculate the size of capacitors and inductors were also done to better consideration for circumstances in which these non-ideal conditions arise. It has been discovered that in order to meet design requirements, non-ideal systems require larger component values.

The non-ideal forward converter was evaluated using the state-space averaging approach to examine the links between input voltage and output voltage, load current and output voltage, and duty cycle and output voltage. To construct a more precise and reliable model, non-ideal factors—including the equivalent series resistance (ESR) of inductors and capacitors, along with losses from switches and diodes—were considered. This facilitated a more profound understanding of both the steady-state and dynamic characteristics of the system. The resultant transfer functions, when juxtaposed with ideal models, exhibited significant discrepancies in both transient responsiveness and steady-state performance. Employing these non-ideal transfer functions, diverse control strategies were formulated to manage the converter's output voltage across varying operating situations. Proportional-Integral (PI) and Adaptive

Neuro-Fuzzy Inference System (ANFIS) controllers were utilized. The PI controller was calibrated utilizing the Ziegler–Nichols method, and simulations indicated that although it effectively regulated voltage, it produced increased overshoot and extended settling periods. Analogous behavior was noted during the real-time evaluation of the PI controller. The ANFIS controller exhibited enhanced efficacy in voltage regulation, especially under fluctuating load situations. Simulation results indicated that the ANFIS methodology resulted in expedited settling, less overshoot, and enhanced adaptability. These findings validate that ANFIS enhances accuracy and provides more robust and dependable control than traditional approaches such as PI, particularly in dynamic load conditions.

## 7.2 Future Scope

There are numerous chances to advance the study of DC-DC converters, building on the foundation established by this research. Other DC-DC converter types can readily be designed, modelled, and controlled using the same techniques as DC-DC Forward converters. Additional research in important areas could be very beneficial for a variety of applications, increasing the understanding and efficacy of these systems.

It is simple to adapt and modify the design, modelling, and control approaches for DC-DC converters to other DC-DC converter types. Despite offering insightful information, the small-signal averaged model employed in this thesis falls short in capturing fully capture how converter switching frequency affects system dynamics. The creation of mathematical models that specifically take the influence of converter switching frequency into account could be the focus of future study. Consistent converter parameters were taken into account when developing control strategies in this thesis. Nevertheless, by taking into account the differences in converter settings, these methods can be further enhanced.

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