Abstract

This paper focuses on the hardware implementation of boost converter control techniques for renewable and EV application using real-time control dSpace MicroLabBox RT (1202) platform. The Output voltage of boost converter is regulated using Proportional-Integral (PI) control or Fuzzy Logic Control (FLC) at various applications like solar energy integration in agriculture, DC microgrid and Electrical Vehicle (EV) or space craft power system. The simulation of boost converter is built in MATLAB software. The control techniques including to regulate the output voltage, two control strategies Proportional-Integral (PI) and Fuzzy Logic Control (FLC) are implemented to achieve precise output voltage regulation to charge the batteries and other application. The experimental results are captured on 100watt boost converter laboratory prototype. The dSpace is powerful real time controller used to study power electronics devices and electrical drives in laboratories. The proposed work, both PI and FLC techniques are implemented and compared through simulation and experimental hardware results. This paper presents a comparative analysis highlights the performance, response time, steady-state accuracy, robustness and suitability of each control strategy for various real-world applications.

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Chapter 1
Introduction

1.1 Introduction to DC-DC converters

DC-DC converters are essential components in modern power electronics, responsible for converting one level of direct current (DC) voltage to another. The primary function of a DC-DC converter is to step up (boost) or step down (buck) the input voltage to meet the requirements of the load or to interface with other components in the system. They are widely used in a variety of applications, including renewable energy systems, electric vehicles, consumer electronics and industrial power supplies, where voltage stepping up is necessary to meet specific operational requirements.

The performance of boost converters is largely determined by the control techniques employed, which play a critical role in ensuring stability, efficiency and performance under varying load conditions. In recent years, advancements in real-time control technologies, such as dSpace MicroLabBox have enabled enhanced control strategies that improve the operation of boost converters.

Moreover, The integration of advanced control techniques into power electronics has become a transformative approach for improving converter performance. Methods such as Fuzzy Logic Control (FLC) provide adaptive capabilities that enhance boost converter operation under dynamic conditions. These techniques adjust control parameters in real time, enabling more robust and efficient performance. By evaluating both traditional methods, such as PI control with PWM, and modern techniques like FLC, this study aims to identify the strengths and weaknesses of each approach. The findings will highlight the effectiveness of combining the dSpace platform with advanced control strategies and provide guidance for future research and development in power electronics.

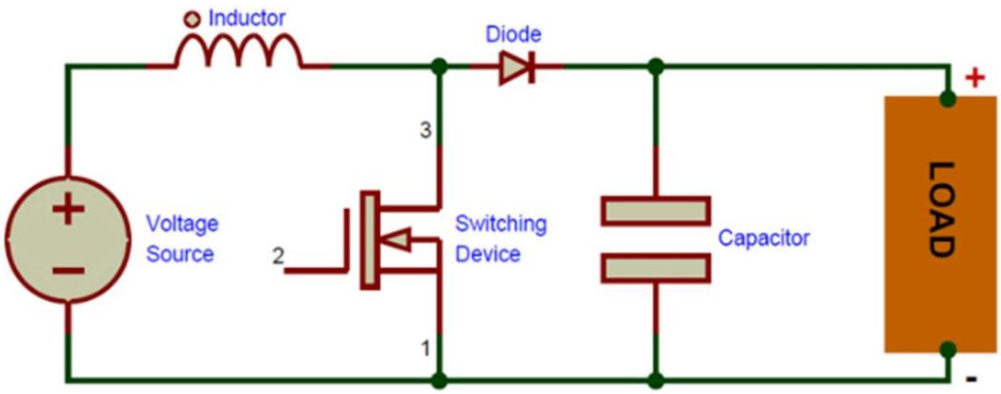

Fig.1.1 DC-DC Boost Converter Circuit Diagram

This project aims to compare and analyses different control techniques implemented on a boost converter using dSpace MicroLabBox and real-time control systems. dSpace MicroLabBox provides a robust platform for real-time simulation and control, enabling precise implementation and testing of various control strategies in a hardware-in-the-loop (HIL) environment. The integration of Propagational Integration Control (PI) and artificial intelligence (AI) based of Fuzzy Logic Controller (FLC) techniques further enhances control performance by enabling adaptive and intelligent decision-making.

1.2 Literature Reported

These Converters Various control strategies have been proposed to improve their performance, efficiency, and robustness under varying operating conditions. In advance the control technique Fuzzy Logic Controllers (FLCs) offer robust control even on low-cost platforms.

A study demonstrates the implementation of a fuzzy logic controller (FLC) on a low-cost 8-bit microcontroller for DC–DC converters, achieving effective voltage regulation without complex mathematical models. The design of membership functions, rule bases and programming is presented with experimental results showing improved dynamic response, reduced overshoot and better load variation handling compared to PI controllers. This cost-effective approach proves the feasibility of intelligent control for enhancing converter performance even with limited hardware resources [1].

Many researchers focus on systematic methods for designing PI and PID controllers to meet specific transient performance requirements, such as settling time, overshoot and steady-state error. These studies provide mathematical formulations and practical guidelines that bridge theoretical control design with real-world implementation. Using time-domain specifications, the controller parameters are directly tuned to ensure predictable and reliable performance. This approach is particularly effective for applications like DC–DC converters where precise voltage regulation and fast transient response are essential. Overall, the work serves as a valuable reference for optimizing controller design in both educational and industrial contexts [2]

Fuzzy Logic Controller (FLC) techniques are applied to a DC–DC boost converter to improve its dynamic and steady-state performance. The design process includes defining input and output membership functions, constructing an appropriate rule base and implementing inference mechanisms. Simulation and experimental results demonstrate faster settling time, minimal overshoot and improved disturbance rejection compared to traditional PI control methods. The study emphasizes FLC's adaptability in handling non-linearities inherent in power electronics systems [3].

A 12 V to 24 V closed-loop boost converter is developed for low-power applications using dSpace for real-time control implementation. The system integrates power circuit hardware with MATLAB/Simulink-based control algorithms executed on the dSpace platform. Performance evaluation shows stable voltage output under varying loads, quick transient response, and reliable operation. The approach highlights the effectiveness of combining digital control platforms with hardware prototypes for precise and flexible converter operation [4].

A detailed performance comparison between PI and Fuzzy controllers is conducted for a solar-powered DC–DC boost converter. Using MATLAB/Simulink simulations, the study evaluates parameters such as rise time, overshoot, settling time and efficiency under fluctuating solar irradiance and load variations. Results indicate that Fuzzy Logic Control provides superior adaptability, faster transient response and better voltage regulation in dynamic conditions, while PI control offers simpler implementation but less robust performance [5].

Presents the design of Robust Sliding Mode Controller (SMC) and Fuzzy Logic Controller (FLC) for boost and buck–boost converters. The study focuses on enhancing system robustness against input voltage variations and load disturbances. Both controllers are designed, simulated, and compared, with results showing that SMC offers better robustness while FLC provides smoother control and reduced overshoot [6].

The research investigates the performance of fuzzy logic-controlled DC–DC converters under varying load and supply conditions, focusing on parameters such as overshoot, steady-state error, and settling time. The analysis reveals that the Fuzzy Logic Controller demonstrates superior adaptability and responsiveness to dynamic operating conditions compared to conventional controllers. It offers faster transient response, improved stability and better voltage regulation with minimal oscillations, even in the presence of load disturbances or input variations. Overall, the study highlights FLC as an effective control strategy for enhancing the dynamic performance of DC–DC converters [7].

The most research focuses on optimizing fuzzy logic controllers for second-order DC–DC converters by adjusting membership functions, linguistic variables, and rule bases. It evaluates performance through parameters like voltage ripple, rise time, and overshoot, showing that proper tuning enhances stability, efficiency, and transient response, and provides guidelines for effective FLC design. Simulation results highlight how proper tuning of fuzzy parameters improves stability, efficiency, and transient response. The work also offers a systematic approach for selecting fuzzy rules to achieve desired performance objectives. Overall, it serves as a guide for engineers to develop robust and efficient FLC designs for power electronics applications [8].

Some study implements of fuzzy logic control on a DC–DC buck converter and compares it with conventional control techniques. It shows that FLC achieves faster voltage regulation and improved adaptability to varying operating conditions. The controller effectively minimizes overshoot and steady-state error under load and input fluctuations. Simulation results confirm better dynamic performance compared to traditional controllers. Overall, FLC enhances efficiency and robustness in DC–DC buck converter operation [9].

Research compares the performance of Fuzzy Logic Control (FLC), Proportional-Integral (PI) control, and Sliding Mode Control (SMC) for a boost converter operating with a variable input voltage source. It evaluates parameters such as output voltage regulation, transient response and robustness under changing load and source conditions. Results indicate that SMC provides the highest robustness, PI offers simplicity in design, and FLC ensures smoother control with reduced overshoot. The study uses simulation analysis to highlight the strengths and trade-offs of each control strategy. Overall, it provides valuable insights for selecting suitable controllers in renewable energy and power electronics applications [10].

A fuzzy controller design for a boost converter using the current slope as the primary control variable. The approach focuses on improving transient response and reducing voltage overshoot by dynamically adjusting the duty cycle based on inductor current changes. Simulation and experimental results show that the proposed method enhances system stability under varying load and input voltage conditions. The controller demonstrates faster recovery from disturbances compared to conventional control methods. Overall, it offers an effective and adaptive control strategy for high-performance boost converters [11].

The implementation of a 200 kHz PWM Field-Oriented Control (FOC) system using RTLib and C programming on a dSpace MicroLabBox platform. It focuses on achieving high-speed, real-time control for electric drives and power electronics applications. The detail the integration of hardware and software, emphasizing the advantages of dSpace tools for rapid prototyping. Experimental validation confirms the system's capability to maintain precise control under fast switching conditions. The work serves as a practical reference for developing high-frequency FOC systems in research and industrial settings [12].

1.3 Motivation

Power electronics form the backbone of modern energy conversion systems, with DC–DC boost converters being widely used in applications such as electric vehicles, solar and wind energy systems and industrial automation. While conventional controllers like Proportional-Integral (PI) are simple and reliable, they often struggle to maintain optimal performance under rapidly changing operating conditions, nonlinearities and disturbances. Fuzzy Logic Controllers (FLC) offer better adaptability, but their performance depends heavily on expert rule design. Recent advancements in Artificial Intelligence (AI) and real-time control platforms like the dSpace MicroLabBox present a unique opportunity to combine the strengths of traditional and AI-based control methods. This project is motivated by the need to develop a control strategy that delivers high efficiency, fast transient response, robustness and adaptability for boost converters. By integrating PI, FLC and validating them through dSpace platform real-time testing, this work aims to address the limitations of existing methods and pave the way for smarter, more efficient power conversion systems suitable for next-generation energy applications.

1.4 Problem Statement

To study control strategies implemented to regulate output voltage of DC-DC boost converter and analyze robustness and performance of converter in dynamic conditions. Real-time implementation of advanced control algorithms on hardware platforms such as dSpace MicroLabBox is complex and requires optimization.

1.5 Objectives

I. Implement Various Control Techniques on a Boost Converter design and implement multiple control strategies namely Proportional-Integral (PI), Artificial Intelligence (AI)-based Fuzzy Logic Control (FLC) method on a DC–DC boost converter. The implementation will be carried out using the dSpace MicroLabBox real-time control system, enabling precise experimentation and comparison between classical and modern control approaches.

II. The project seeks to integrate PI and Fuzzy Logic control strategies into the dSpace MicroLabBox platform, enabling real-time implementation and validation of control algorithms for a DC–DC boost converter. By leveraging the platform's high-speed processing and flexible I/O capabilities, the system will be tested under realistic operating scenarios with a dc input source, simulating conditions typical in renewable energy and electric vehicle applications.

III. This work implements **Proportional-Integral (PI)** and **Fuzzy Logic Controller (FLC)** techniques on a DC–DC boost converter and performs a comparative analysis based on key performance parameters, including transient voltage response, settling time (ts), steady-state output voltage, output ripple, rise time (tr) and error (e) under both steady-state and dynamic operating conditions to determine the most suitable control method for achieving optimal performance. A comparative analysis will be conducted to identify the most effective control method for optimizing converter performance. This study targets applications in renewable energy systems and electric vehicles, ensuring reliable and efficient power conversion.

IV. To design, implement and validate a real-time control system for a DC-DC boost converter using the dSpace platform. The project aims to achieve precise voltage regulation, improved dynamic response and enhanced system stability by integrating advanced control algorithms such as PI and Fuzzy Logic controllers. The real-time implementation on the dSpace hardware will enable hardware-in-the-loop (HIL) testing, ensuring reliable performance under varying input conditions and load disturbances. This approach will demonstrate the practical feasibility and efficiency of advanced control techniques in power electronics applications.

Chapter 2
Design of DC-DC Boost Converter

2.1 Introduction to DC-DC Boost Converter

A DC-DC boost converter is a power electronic circuit designed to step up a lower input DC voltage to a higher output DC voltage, making it essential for applications such as renewable energy systems and electric vehicles.

The basic operation involves an inductor, a switch (typically a MOSFET), a diode and a capacitor. During the switch ON period, energy is stored in the inductor; when the switch turns OFF, the inductor releases its energy to the output, boosting the voltage.

2.2 Working Principle

The boost converter operates in two main switching states:

1. **Switch ON (Charging Phase):** When the switch is closed (ON), the input voltage (Vin) is applied across the inductor, causing the inductor current to increase linearly and store energy in its magnetic field. During this phase, the diode is reverse biased, isolating the output from the input.
2. **Switch OFF (Discharging Phase):** When the switch is opened (OFF), the inductor current cannot change instantaneously and flows through the diode into the output capacitor and load, releasing its stored energy. This adds to the input voltage, resulting in a higher output voltage (Vout).

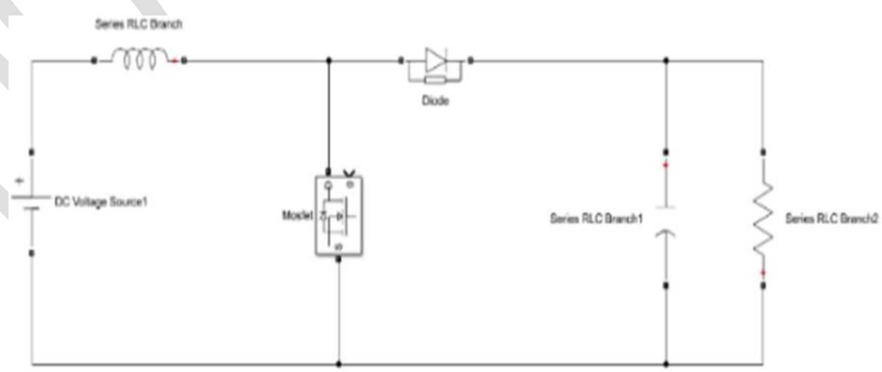

Fig.2.1 Boost Converter circuit

The output voltage depends on the duty cycle D (the fraction of the switching period when the switch is ON) and is given by the ideal formula:

Vout = Vin / 1−D

Where,
Vout = output voltage,

Vin = input voltage,

D = duty cycle ($0 < D < 1$).

As D increases, the output voltage rises, allowing the converter to boost the voltage above the input level. Efficient control of the duty cycle is essential for maintaining a stable and regulated output voltage under varying input and load conditions.

2.2.1 Operating Modes

1. Continuous Conduction Mode (CCM): The inductor current never falls to zero during the switching cycle. This mode occurs at higher load currents and is preferred for stable operation with lower current ripple.

2. Discontinuous Conduction Mode (DCM): The inductor current falls to zero for a portion of the switching cycle. This occurs at light loads or high duty cycles and generally leads to higher current ripple and more complex control.

- **Duty Cycle = (Ton-Toff)/Total Time**

i. **Output Voltage (Vout): -**

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

where:

- Vin = input voltage
- Duty cycle (ratio of switch ON time to total switching period)

ii. **Inductor Value (L): -**

$$L = \frac{V_{in} \times D}{\Delta I_L \times f_s}$$

(L= Input Voltage* Duty Ratio/ Ripple Current* Switching frequency)

Where,

- K = Duty Ratio
- ΔIL = peak-to-peak inductor current ripple
- fs = switching frequency

iii. Inductor Current (Average): -

$$I_L = \frac{I_{out}}{1 - D}$$

where $I_{out} = \frac{V_{out}}{R}$

iv. Output Current: -

$$I_{out} = \frac{V_{out}}{R}$$

v. Capacitor Value (C): -

$$C = \frac{I_{out} \times D}{\Delta V_{out} \times f_s}$$

(C= Output Current * Duty Ratio/Ripple Voltage* Switching Frequency)

Where,

- ΔVout = peak-to-peak output voltage ripple

vi. Load Resistor (R):-

$$R = \frac{V_{out}}{I_{out}}$$

vii. Power (P): -

a. Input Power (Pin)

$$P_{in} = V_{in} \times I_{in}$$

b. Output Power (Pout)

$$P_{out} = V_{out} \times I_{out}$$

c. Power Through Load Resistor (R)

$$P_{out} = \frac{V_{out}^2}{R}$$

d. Efficiency (η)

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

Chapter 3

Comparison and Analysis of Control Techniques Implemented on Boost Converter for Renewable and EV Application

3.1 Block diagram

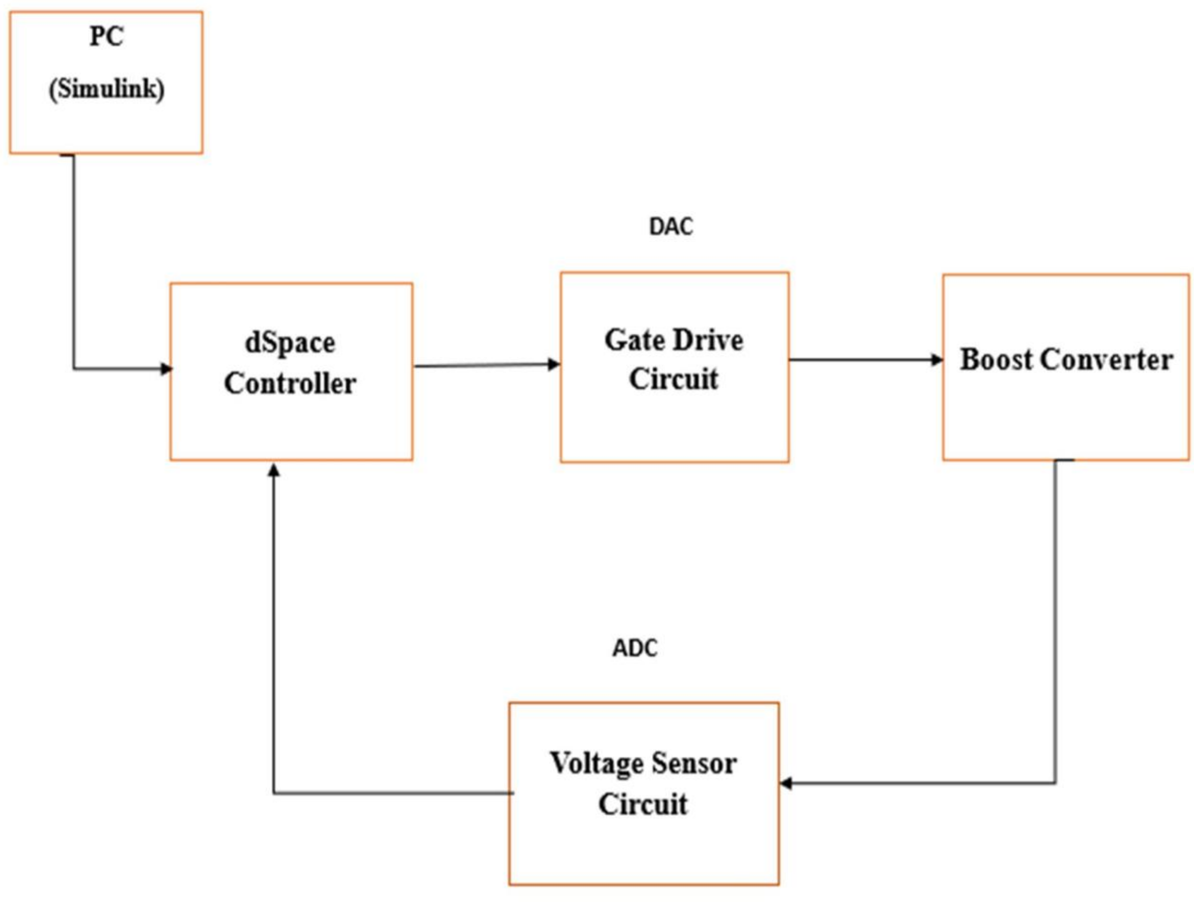

Fig.3.1. Comparison and Analysis of Control Techniques Implemented on Boost Converter for Renewable and EV Application

3.2 Working of Components

3.2.1 PC (MATLAB/Simulink):

i. MATLAB is used to design and simulate the boost converter, with built-in support for real-time implementation via the dSpace MicroLabBox platform, utilizing software tools such as ControlDesk and MATLAB/Simulink.
ii. The integrated PI controller simulation in MATLAB within the dSpace environment enables real-time control of the boost converter. This facilitates the development of control algorithms that continuously monitor and adjust the PWM duty cycle to maintain the desired output voltage.
iii. The control algorithms for the boost converter are designed and simulated in MATLAB/Simulink on the PC. These algorithms generate control signals based on the desired output voltage and system dynamics**.**

3.2.2 dSpace MicroLabBox:

i. The dSpace platform is a real-time control system that enables users to design, test, and implement control algorithms for various power electronics applications.
ii. It consists of a hardware platform (MicroLabBox) and software tools such as ControlDesk and MATLAB/Simulink. The system receives a low-level analog voltage signal (up to 5 V) from the voltage sensor and outputs a 5 V digital signal to the gate driver circuit.
iii. In this dSpace MicroLabBox (RT-1202) using continuously monitors key parameters including the output voltage, inductor current, and PWM duty cycle to facilitate precise real-time control.
iv. The control code developed in Simulink is deployed to the dSpace platform controller hardware, which executes the control algorithm in real time. The controller processes feedback data and calculates the appropriate control commands.

3.2.3 Gate Driving Circuit:

i. The gate driver circuit is embedded within the DC-DC boost converter.
ii. It uses a digital-to-analog converter (DAC) to process control signals and provides the necessary gate voltage to efficiently drive the MOSFET, enabling effective voltage boosting.

iii. The digital control signals from the dSpace controller are converted into analog signals using a Digital-to-Analog Converter (DAC). These analog signals drive the gate driver circuit, which provides the required voltage and current to switch the MOSFET efficiently in the boost converter.

3.2.4 Boost Converter:

i. A boost converter is a type of DC-DC converter that steps up the input voltage to a higher output voltage. It achieves this by using a combination of an inductor, capacitor, diode, and a switch (typically a MOSFET).

ii. In this work, the dSpace MicroLabBox will be used to implement and control the boost converter while comparing various control techniques. The control algorithms are designed in MATLAB/Simulink and executed in real-time on the dSpace hardware. The boost converter's switching operation is managed by a PWM (Pulse Width Modulation) signal generated by the dSpace system based on the implemented control algorithm.

iii. This block represents the power stage where the actual voltage boosting takes place. The MOSFET switching controlled by the gate driving circuit adjusts the energy stored and released by the inductor, stepping up the input voltage to the desired higher output voltage.

3.2.5 Voltage Sensor:

i. It is used for feedback, isolation and real-time voltage regulation.
ii. It is integrated into the PC37 boost converter model and interfaces with the dSpace MicroLabBox.
iii. The voltage sensor measures the boost converter output voltage and sends the analog signal to the dSpace MicroLabBox controller for monitoring, feedback and real-time regulation.
iv. The output voltage of the boost converter is continuously monitored by a voltage sensor. This sensor converts the analog output voltage into a signal suitable for measurement and feedback.

3.2.6 Analog-to-Digital Converter (ADC):

i. The voltage sensor output is fed back to the dSpace controller through an ADC, converting the analog voltage signal into digital form. This feedback allows the controller to compare the actual output voltage with the reference and adjust the control signals accordingly.

3.3 Implementation dSpace MicroLabBox (RT-1202) Platform:

3.3.1 Hardware Setup

i. Connect the MicroLabBox to the boost converter hardware.
ii. Configure the MicroLabBox I/O channels for the boost converters with load.

3.3.2 Software Setup

i. Install ControlDesk and MATLAB/Simulink on computer.
ii. Create a new project in ControlDesk and configure the MicroLabBox hardware.
iii. Design and implement the control algorithm using MATLAB/Simulink.

3.3.3 Control Algorithm Design

i. Design a control algorithm for the boost converter using MATLAB/Simulink.
ii. Choose a control technique (e.g., PI or fuzzy logic).
iii. Implement the control algorithm using Simulink blocks.

3.3.4 Implementation dSpace MicroLabBox for Real-Time Control

i. To make dSpace MicroLabBox platform control the Boost Converter. There need to configure the PWM signals and real-time execution.

3.3.4.1. Open dSpace Configuration Desk

- Launch dSpace Configuration Desk (a tool for setting up hardware connections).
- Create a new project and add MicroLabBox as the target hardware.

3.3.4.2. Assign PWM Output Channels for MOSFET Gate Driver

- The Boost Converter uses a MOSFET, which is switched ON/OFF by a PWM signal (Pulse Width Modulation).
- In Configuration Desk:
  a. Select PWM Output Channel, DIO1 on MicroLabBox.
  b. Set the switching frequency ,10 kHz.
  c. Connect this PWM output to the MOSFET gate driver.

3.3.4.3. Configure ADC Inputs for Voltage and Current Sensing

- The Boost Converter needs feedback from sensors to control the output voltage.
- In Configuration Desk:
  a. Select ADC Input Channels (e.g., AI ch1 for output voltage).
  b. Adjust scaling factors based on the sensor's voltage range.
  c. Ensure the ADC inputs are correctly connected to the voltage and current sensors.

3.3.4.4. Generate Real-Time Code using dSpace RTI

- dSpace RT (1202) converts your Simulink model into real-time code.
- In MATLAB/Simulink, click → Simulink → Build Model.
- This creates executable Simulation for MicroLabBox

3.3.4.5. Compile and Load Code into MicroLabBox

- Open ControlDesk and load the generated ".sdf" file (Simulink Data File).
- Click Download to Hardware to upload the program to MicroLabBox.
- The system is now ready for real-time testing

3.3.4.6. Real-Time Testing and Monitoring with dSpace ControlDesk

Step 3.3.4.6.1. Connect dSpace MicroLabBox to the Boost Converter Circuit

- Ensure that:
  a. PWM output is driving the MOSFET gate.
  b. Voltage and current sensors are correctly connected.
  c. MicroLabBox is powered on and connected to the PC via USB or Ethernet.

Step 3.3.4.6.2. Open dSpace ControlDesk and Create a Real-Time GUI

- Open ControlDesk and load the experiment file.

- Create a dashboard with indicators and controls to monitor and adjust parameters.
- Add live displays for Output voltage, Duty cycle, Control signals (e.g., error signal, reference voltage**)**
- Use sliders or input fields in ControlDesk to tune:
    a. Kp (Proportional Gain)
    b. Ki (Integral Gain)
- Observe how different values affect voltage stability and transient response

Step 3.3.4.6.3. Compare Performance of Different Controllers

- Run tests for:
    a. PI Controller
    b. Fuzzy Logic Controller
- Compare response time, steady-state error, and voltage ripple.
    a. Response time (how fast the voltage stabilizes).
    b. Steady-state error (how close the output voltage is to the target).
    c. Voltage ripple (how smooth the output voltage is).
    d. Monitor output voltage, inductor current and duty cycle.

Chapter 4

Control Techniques Implementation on Boost converter

4.1 Proportional Integral Controller (PI)

4.1.1 Overview of PI Control Technique:

The PI control technique is a widely used control strategy in power electronics, including boost converters. The main goal of PI control is to regulate the output voltage of the boost converter by adjusting the duty cycle of the switching signal.

The controller adjusts the MOSFET duty cycle depending on the error between reference and desired voltage, with Kp ensuring fast response and Ki eliminating steady-state error. Parameters are tuned using the 2^{nd} ordered Ziegler-Nichol's method and real-time implementation is done on dSpace MicroLabBox with MATLAB for performance evaluation. This combination enables the system to achieve accurate and stable output voltage even in the presence of disturbances and non-linearities.

- **Proportional (P) Action**: Reacts to the instantaneous error and provides a correction based on a proportional gain Kp.
- **Integral (I) Action**: Accumulates past errors to eliminate steady-state error and improve accuracy using an integral gain Ki.

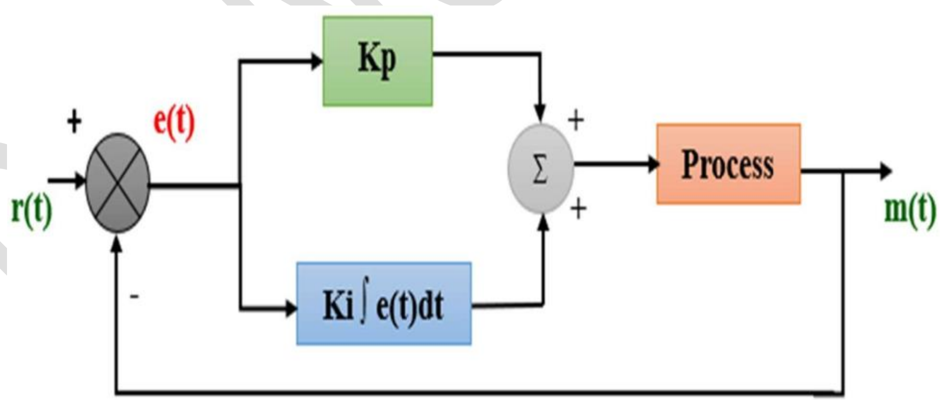

Fig.4.1.PI Controller

4.1.2 Mathematical Representation of PI Control:

The PI control algorithm can be mathematically represented as:

- **Vcontrol / D(t) = Kp * e(t) + Ki * ∫e(t)dt**

Where,
- D(t) is the control signal (duty cycle)
- Kp is the proportional gain
- Ki is the integral gain
- e(t) is the error between the desired output voltage and the actual output voltage

4.1.3 Implementation of PI Control on Boost Converter:

4.1.3.1 System Modeling

A boost converter consists of an **inductor (L), switch (MOSFET), diode (D), capacitor (C), and load (R)**. The key equations governing the system dynamics are:

i. **Inductor voltage equation**:

   a. $Ldi/dt = Vin - VL$

ii. **Output voltage equation**:

   a. $Vout/dt = iL - iR$

iii. **Duty cycle relationship**:

   a. $Vout = Vin/\ 1-D$

Where, D is the duty cycle controlled by the PI controller.

4.1.3.2 Error Calculation

a. The PI controller calculates the error signal as:

$$\mathbf{e(t) = Vref - Vout}$$

where,

Vref is the desired output voltage & Vout is the actual output.

4.2 Fuzzy Logic Controller (FLC)

Fuzzy Logic Control (FLC) is an intelligent control technique that does not require a mathematical model of the system. Instead, it uses linguistic rules and fuzzy sets to regulate the boost converter's output voltage.

Fuzzy Logic Controller (FLC) is a free model-intelligent control technique that regulates nonlinear systems using fuzzy sets and linguistic rules making it simpler and more adaptable. In this work, a Mamdani-type FLC is implemented to regulate the output voltage of a DC-DC boost converter. The controller processes two inputs error (e) and change in error (de) derived from the difference between the reference and actual output voltages.

The fuzzy logic offers an inference structure that allows suitable human mental capacities. Fuzzy structures appropriate near to the logic. The fuzzy method is a fast and smooth reply than other systems and less controller difficulty. The inference system is the IF THEN rule for plotting fuzzy set in input to output created on the fuzzy opinion. In fuzzy, data presentation, IF-THEN rules are methods for taking data are includes the fuzziness.

The key feature of logic is using fuzzy rules of fractional matching ability, the inference is completed after fuzzy rules even rule conditions are partially fulfilled. These inputs are translated into linguistic variables through fuzzification and processed using a set of IF-THEN rules within the inference engine. The final output, representing the control duty cycle, is obtained through defuzzification and then used to generate PWM signals that control the switching behavior of the MOSFET. The FLC is designed in MATLAB/Simulink and implemented in real-time using the dSpace MicroLabBox platform enabling dynamic performance evaluation and precise control under varying load conditions.

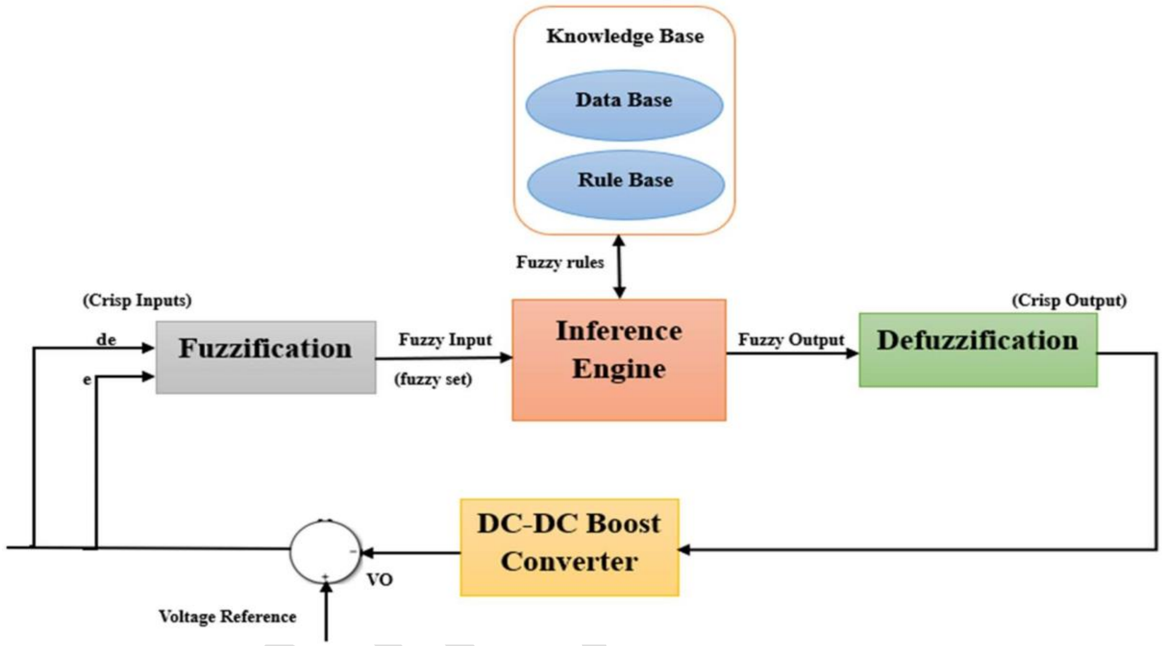

Fig.4.2. Fuzzy Logic Controller

Fuzzy control contains three parameters that are fuzzification, fuzzy inference system and defuzzification.
Overall, the system fuzzy-sets distributed to the represents fuzzy variables called membership function. The value changes of membership function between 0 and 1.

In Fig.4.2. FLC use three parameters. Fuzzification, Inference System, defuzzification. Here, error(e)and change in error(de). This input gives to the fuzzy logic controller.

- **Fuzzification:** Fuzzification is a process that converts input data (crisp input values) into the appropriate fuzzy linguistic value for a fuzzy logic system. Membership functions expressed are trapezoidal-shaped, triangle-shaped.
- **Fuzzy Inference System:** Decision-making in fuzzy logic uses fuzzy inputs, a rule base and a knowledge base to generate an output passed to the defuzzification process. Fuzzy inference scheme which expressed to combine membership function with controlling rules to drive fuzzy output.
- **Defuzzification:** Defuzzification converts fuzzy output into a single crisp value to control elements of the MOSFET in a boost converter. Get the compact output by using several defuzzification methods.

4.2.1 Fuzzy Logic Membership Function

Fuzzy Logic Membership operates three main stages: fuzzification, fuzzy inference and defuzzification. The fuzzification process means where membership function applied and the degree of the membership function is determined.

In this work, a Mamdani-type fuzzy inference system is designed to regulate the output voltage of a DC-DC boost converter. The controller uses two inputs error (e) and change in error (de) to generate one output, the duty cycle.

The input and output variables are described using five linguistic terms:

1. Negative Big (NB)
2. Negative Small (NS)
3. Zero (Z)
4. Positive Big (PB)
5. Positive Small (PS).

These five Membership Function use for input-1, input-2 and output Block.

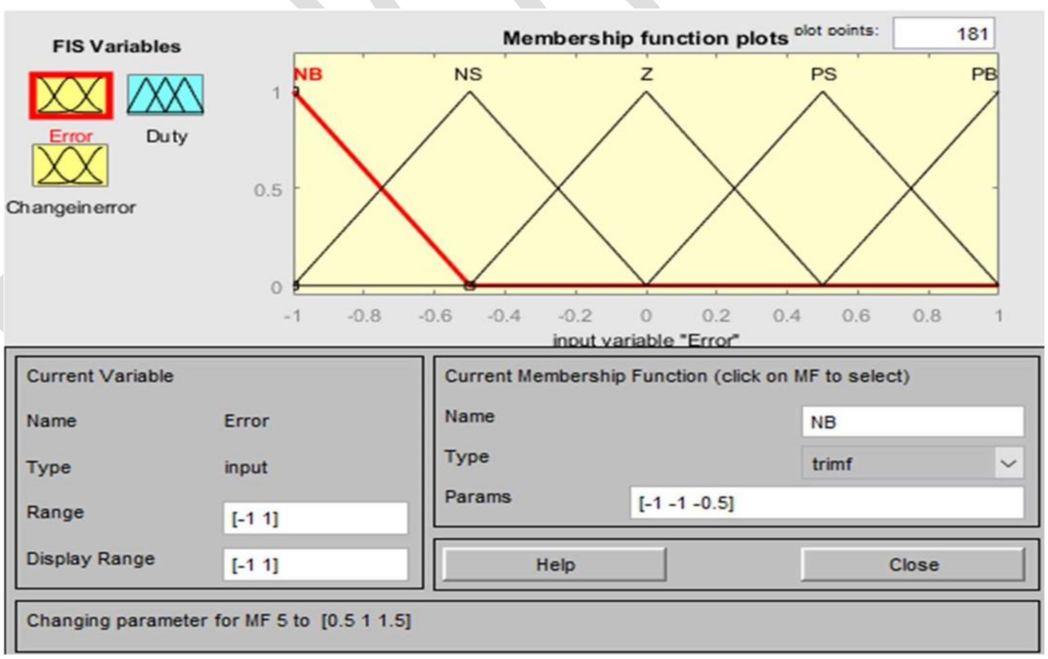

Fig.4.3. Input-1 Error with Five Membership Function

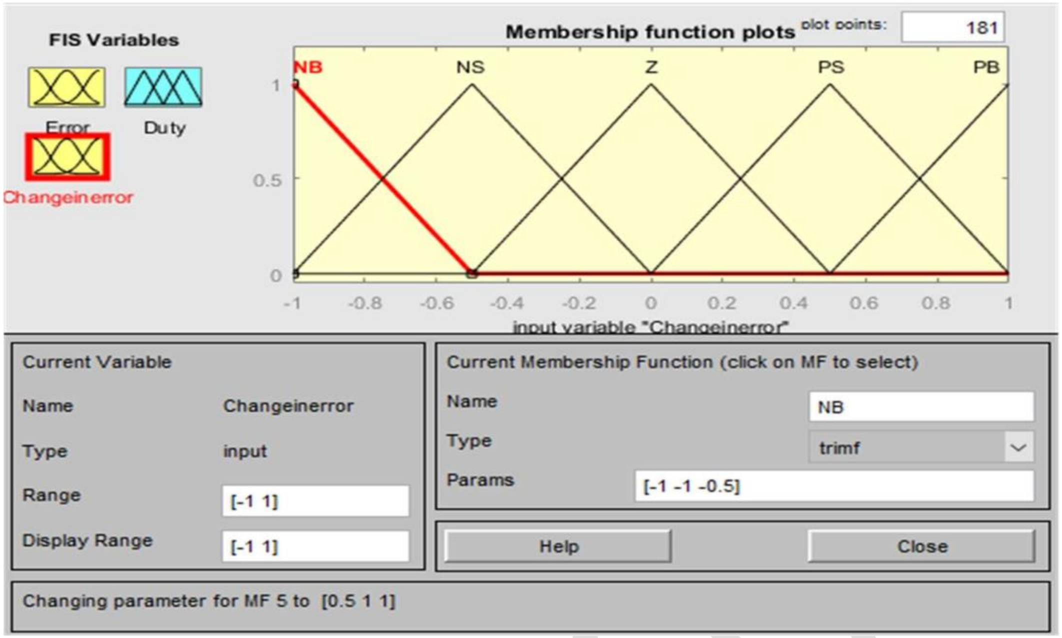

Fig.4.4. Input-2 Change in error with Five Membership Function

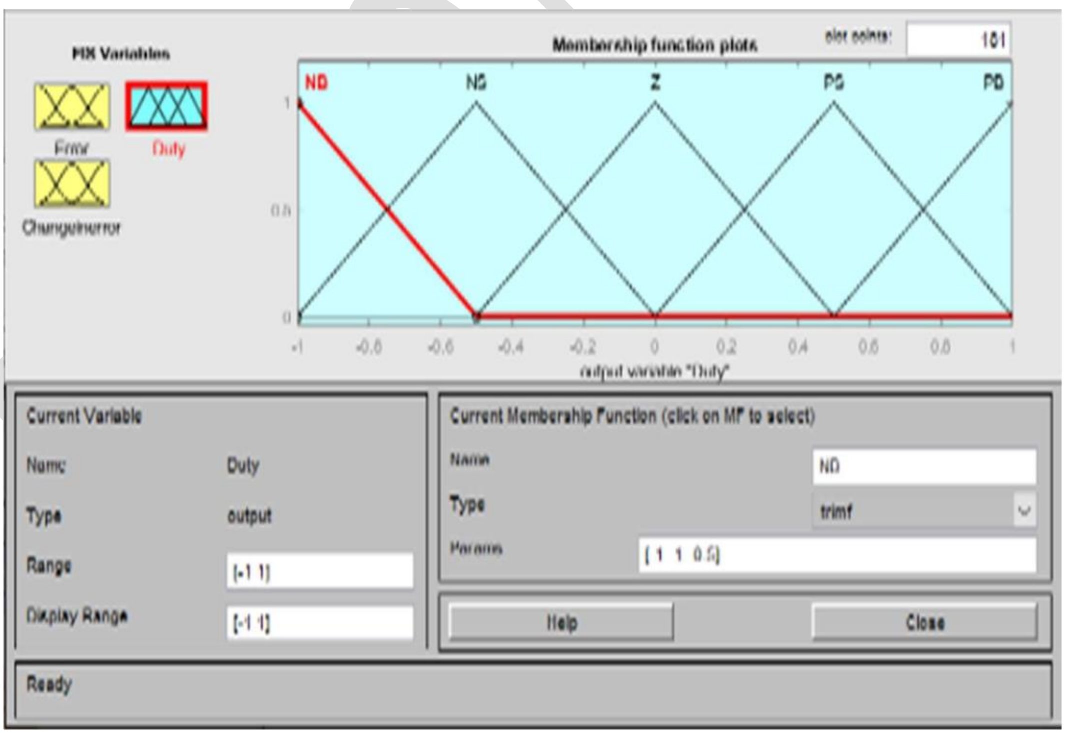

Fig.4.5 Output with Five Membership Function

4.2.2 Single Output Fuzzy Logic Table rules

In a DC/DC boost converter, the output voltage is increased using fuzzy logic controller. The fuzzy logic controller is based on a fuzzy set of IF-THEN rules, which are known as fuzzy rules. A fuzzy controller boosts DC/DC output using error (e) and change in error(de) as inputs. De-fuzzification using the centroid method converts fuzzy output values into a precise, single crisp value for system control. This value adjusts the converter to maintain steady voltage.

TABLE I. Fuzzy Logic Rule

de \ e	NB	NS	Z	PS	PB
NB	PB	PB	PB	PS	PS
NS	PB	PS	PS	PS	Z
Z	PS	PS	Z	NS	NS
PS	Z	NS	NS	NS	NB
PB	NS	NB	NB	NB	NB

i. **Interpretation of the Rule Table:**

a. The **horizontal axis (columns)** represents the **error (e)**.

b. The **vertical axis (rows)** represents the **change in error (de)**.

c. The **values inside the table** represent the **output (duty cycle adjustment).**

ii. **These terms describe:**

a. **Error (e):** How far the actual voltage is from the desired voltage. (Difference between the reference output voltage and the actual output voltage.)

b. **Change in Error (de):** How quickly the error is changing. (Rate of change of the error.)

The output of the FLC is typically the **Duty Cycle (D)** adjustment, which controls the switching of the converter.

iii. **Example Rules from the Table:**

a. **If error is NB (Negative Big) and change in error is NB (Negative Big), then output is PB (Positive Big).**

- This means when the voltage is very low and decreasing rapidly. we need a **large increase in the duty cycle** to boost the voltage.

b. **If error is Z (Zero) and change in error is Z (Zero), then output is Z (Zero).**

- This means when the voltage is stable at the desired value, no change in duty cycle is required.

c. **If error is PB (Positive Big) and change in error is PB (Positive Big), then output is NB (Negative Big).**

- This means when the voltage is too high and increasing rapidly the duty cycle should be **reduced significantly** to bring the voltage back to normal.

iv. **Working of the Fuzzy Logic Controller in Boost Converter:**

a. **Input Processing (Fuzzification)**

The error (e) and change in error (de) are converted into fuzzy variables using membership functions.

b. **Rule Evaluation (Inference)**

The controller uses the **rule table** to determine the required change in duty cycle.

c. **Output Processing (Defuzzification)**

The fuzzy output is converted back into a crisp value to adjust the PWM duty cycle.

4.2.3 Boost Converter using Solar Panel as a Input and DC load (output) to EV Application

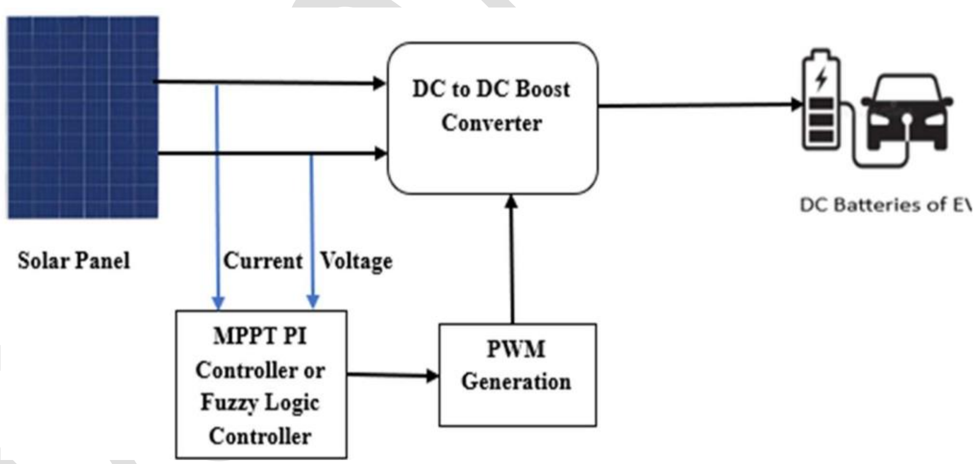

Fig.4.6 Block Diagram of Boost Converter using Input from Solar Panel and DC load output to EV Application

As an example, in this fig.4.6 system uses a solar panel (1Soltech 1STH-215-P) renewable energy source to power an EV battery through a DC-DC boost converter, which steps up the panel voltage.

A MPPT controller with PI or Fuzzy Logic continuously monitors the panel's voltage and current to maximize power output. The controller sends signals to a PWM generator, which controls the boost converter's switching. The boost converter then provides the right voltage to charge the EV battery efficiently.

Chapter 5
Calculations

TABLE II. The parameters and their values for boost convertor

Number	Parameters	Values
1.	Input	12 V
2.	Output	24 V
3.	Reference Voltage	24 V
4.	Switching Frequency	10,000 Hz
5.	Inductance	6 mH
6.	Capacitor	500 µF
7.	Resistance	10 Ω

TABLE III. (1Soltech 1STH-215-P) Total parameters of photovoltaic cell

Parameters	Discriptions	Values
Vocr (v)	PV source's Open Circuit Voltage	37.14
Iscr (A)	PV Source's Short Circuit Current	8
Vmppr (v)	PV Source's Voltage's At MPP	3.72
Imppr (w)	Max Current that Our PV source can provide	7.2
niscT	The Temperature coefficient of short circuit current	0.05535
nvocT	The temperature coefficient of open circuit voltage	-0.35339
P (w)	Maximum Power	230.4
Ncell	Cell Per Module	60

- **Duty Cycle = (Ton-Toff)/Total Time**
- **Voltage output = Voltage Input/1-D = 12/1-0.5 = 24V**

- **Selection Of Inductor and Capacitor**
- **Voltage input = 12 V**
- **Voltage output = 24 V**
- **Power = 50 Watt**
- **Resistance = 10 Ω**
- **Frequency = 10,000 Hz**

1) Capacitor:-

$$C = \frac{I_{\text{out}} \times D}{f_s \times \Delta V_c}$$

(Consider ΔVc = 1v)
ΔVc = 0.01×24=0.24 V

C= Output I * Duty Ratio/Switching Frequency*ΔVc

$$C = \frac{2.08 \times 0.5}{10000 \times 0.24}$$

$$C = \frac{1.04}{2400}$$

$$C = 0.000433 \text{ F}$$

$$C = 4.33 \times 10^{-4} \text{ F} = 433\ \mu\text{F}$$

- **Choose C=500 µF for design margin**

Where,

a. C = Output capacitor (F)
b. Iout = Output load current (A)
c. D = Duty cycle
d. fs = Switching frequency (Hz)
e. ΔVc = Allowable peak-to-peak output voltage ripple (V)

2) Inductor: -

$$L = \frac{V_s \times k}{f \times \Delta I_L}$$

(Consider ΔL= 10%)

$$L = \frac{12 \times 0.5}{10000 \times 0.1}$$

$$L = \frac{6}{1000} = 0.006\ \text{H} = 6\ \text{mH}$$

Where,

a. ΔIL=10% of the input current (0.10.10.1 in decimal form)
b. K = Duty Ratio
c. f = switching frequency

3) Ziegler–Nichols Method:-

$$K_p = 0.45 K_u$$

$$K_i = \frac{1.2 K_p}{P_u}$$

Kp = 0.45 *Ku = 0.45*1 = 0.45, I put Kp=1
Ki = 1.2*0.45*1/0.0014 = 386 after, I increased ki value till constant output waveform

Where,

a. Kp= Proportional Gain
b. Ki=Integral Gain
c. Ku= Ultimate Gain
d. Pu= Ultimate Period

Chapter 6
Simulation Studies and Results

6.1 Simulation studies and Results in steady state condition

6.1.1 MATLAB Simulation Close Loop Boost Converter Using PI Controller

i. Closed loop boost converter is simulated with PI controller tuned via Ziegler–Nichol's method.

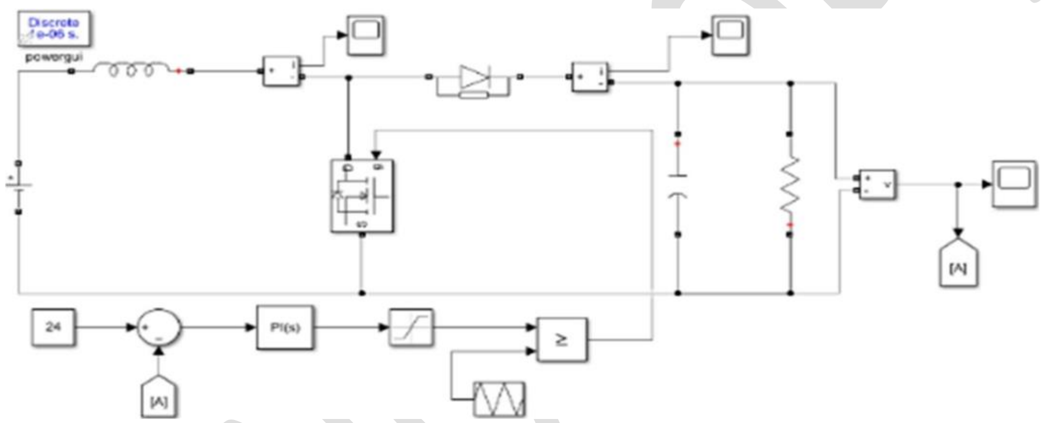

Fig.6.1. Boost converter using PI controller simulation

<u>Steady state output Waveform result:</u>

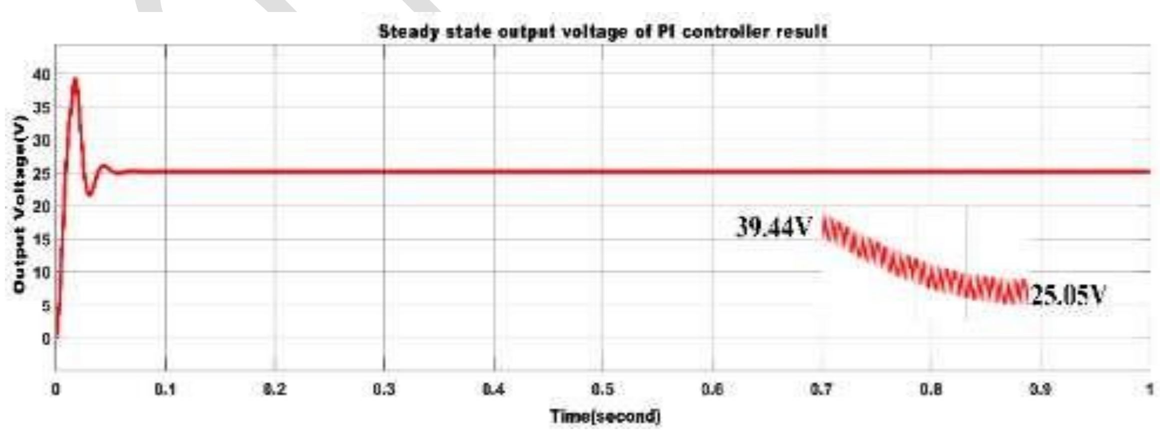

Fig.6.2.steady state output waveform of boost converter performance using PI at input voltage 12V

In this fig.6.2 waveform of output voltage boost converter simulation performance using PI results transient response is got 39.44V and after 59.29ms time output voltage waveform will be steady state condition on 25.05V. In this indcutor current is CCM. it's value 5.27amp.

6.1.2 MATLAB Simulation Boost Converter Using Fuzzy Logic Controller

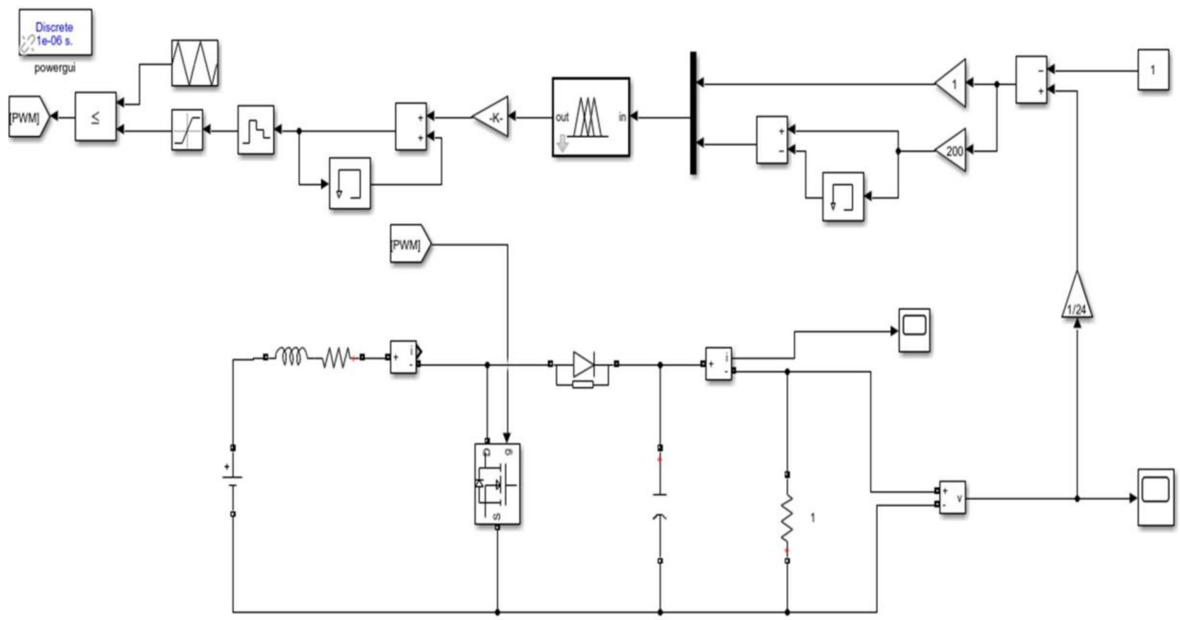

Fig.6.3. Boost converter using Fuzzy Logic Controller simulation

Steady state output voltage waveform result:

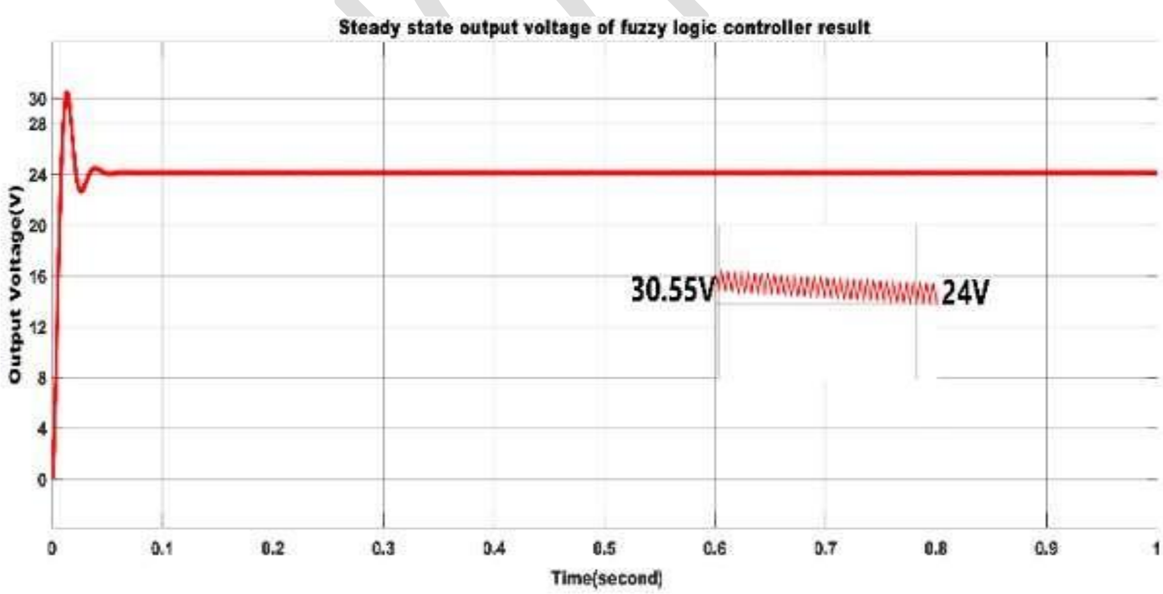

Fig.6.4.Steady state output voltage waveform of boost converter simulation using fuzzy logic controller at input voltage 12V.

In Fig.6.4 In this output waveform got the transient state value 30.55V and after 42.220ms time will have got the steady state condition output voltage 24V. In this indcutor current got CCM. It’s value 5.43amp.

6.1.3 MATLAB Simulation of a Closed-Loop Boost Converter Using a Solar Panel Input with controlling MPPT and a PI Controller

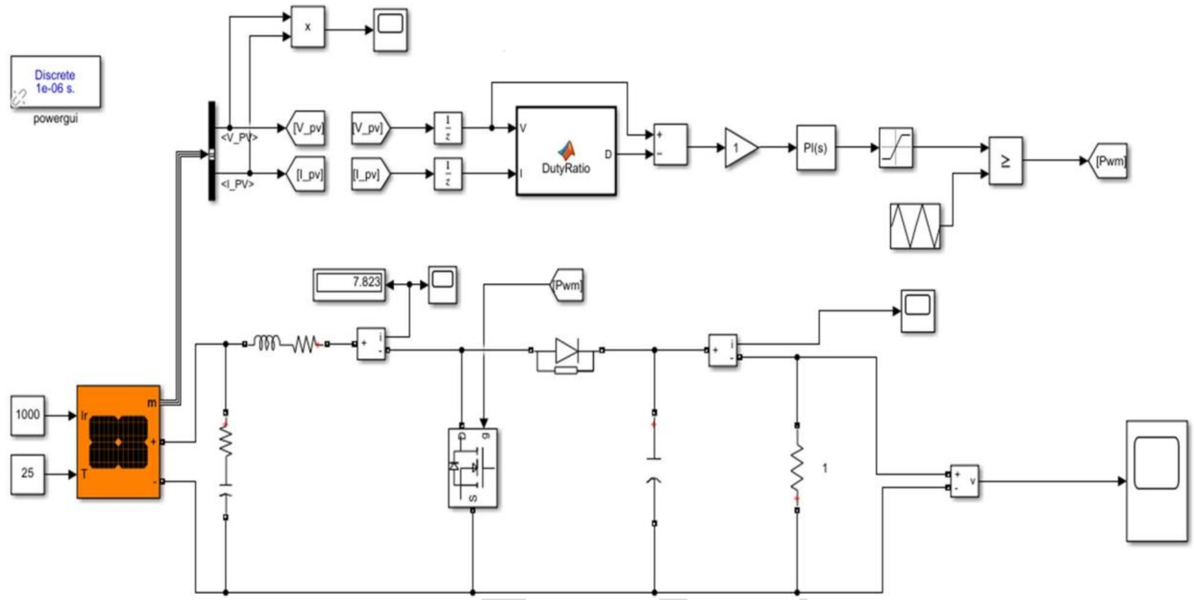

Fig.6.5 Closed-Loop Boost Converter Using a Solar Panel Input with controlling MPPT and a PI Controller

Steady state output Waveform results:

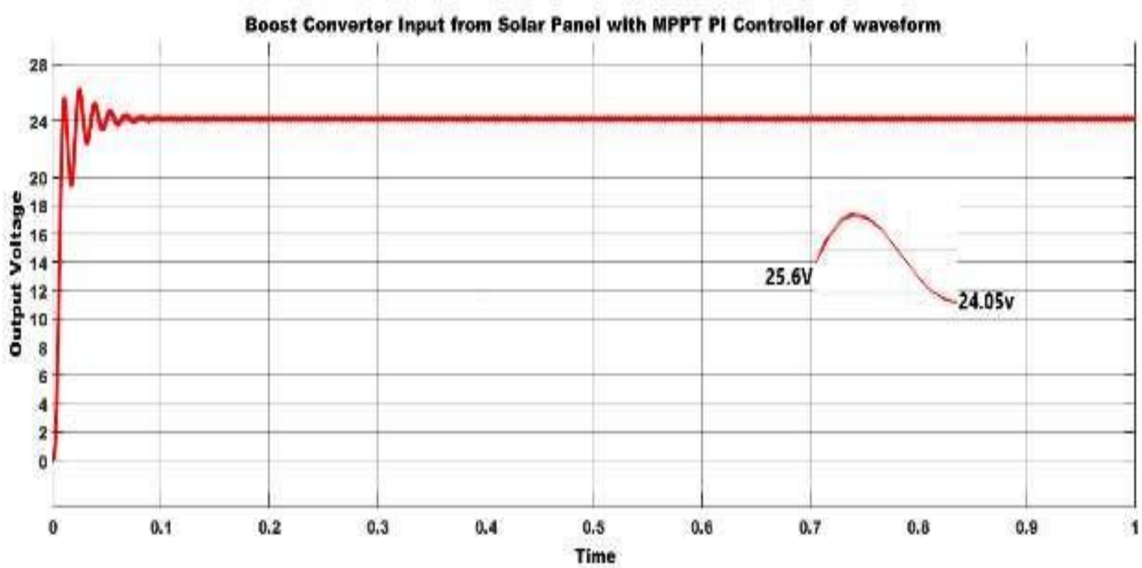

Fig.6.6 Boost Converter using solar panel input with MPPT and a PI controller of waveform

In this Fig.6.6 waveform of output voltage boost converter simulation performance using PI results transient response is got 25.6V and after 73.136ms time output voltage waveform will be steady state condition on 24.02V. In this indcutor current is CCM. it’s value 7.89amp.

6.1.4 MATLAB Simulation Boost Converter Using input Solar Panel with Fuzzy Logic Controller

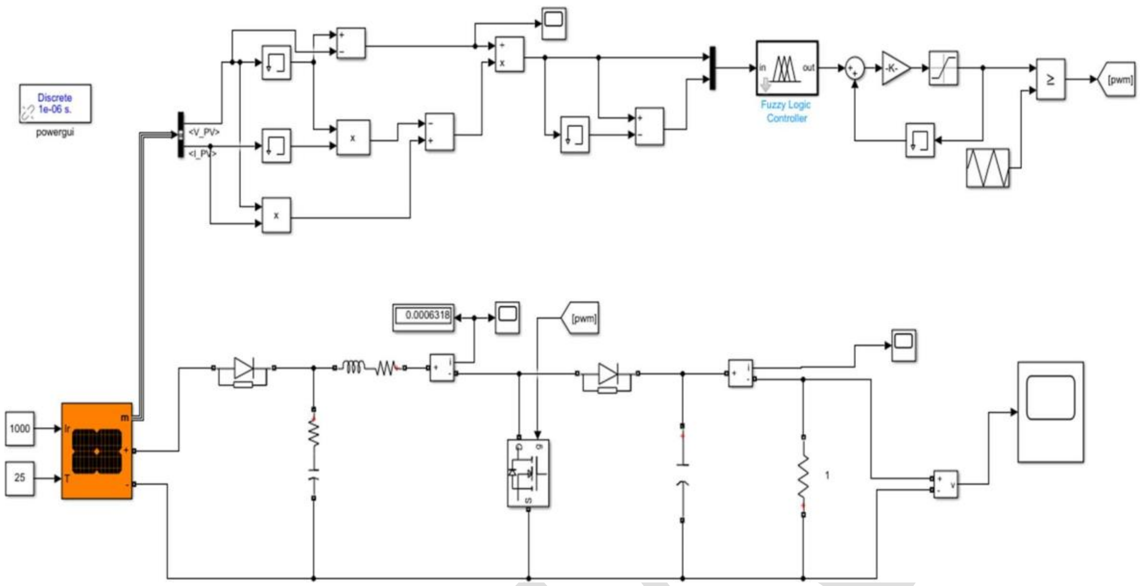

Fig.6.7 Boost converter using input solar panel with using Fuzzy Logic Controller simulation

Steady state output Waveform results:

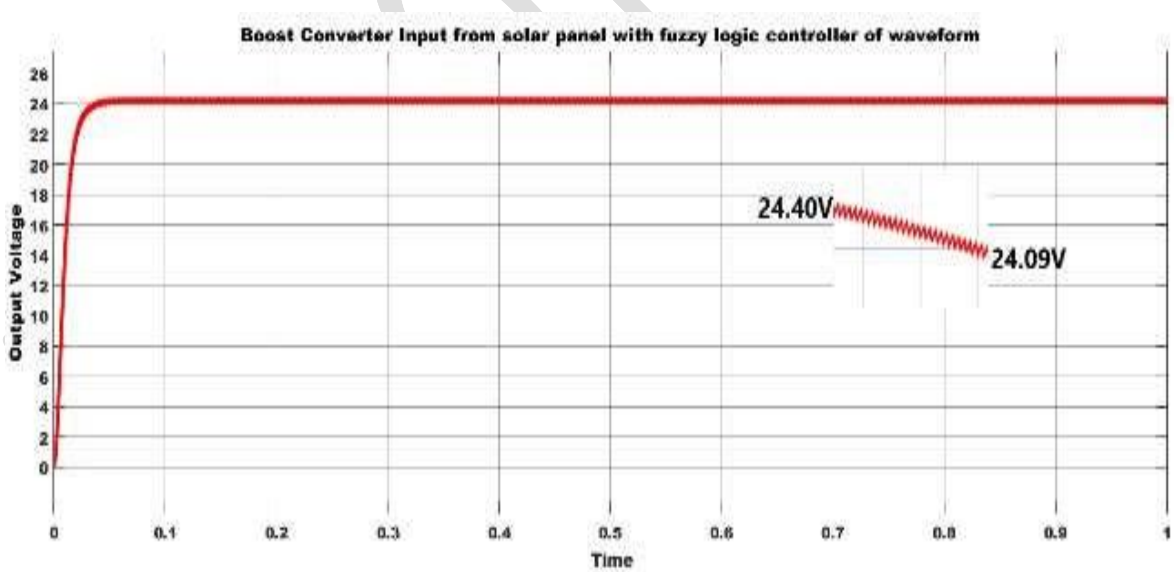

Fig.6.8. Boost converter from input solar panel using Fuzzy Logic Controller simulation of waveform results

In Fig.6.8.In this output waveform got the transient state value 24.40V and after 36.80ms time will have got the steady state condtion output voltage 24.09V. In this indcutor current got CCM. It's value 14amp.

6.2 Simulation Studies and Results in Dynamic Condition

6.2.1 Close loop boost converter using PI controller

6.2.1.1 Boost converter performance using PI controller at load variation by 50% of simulation

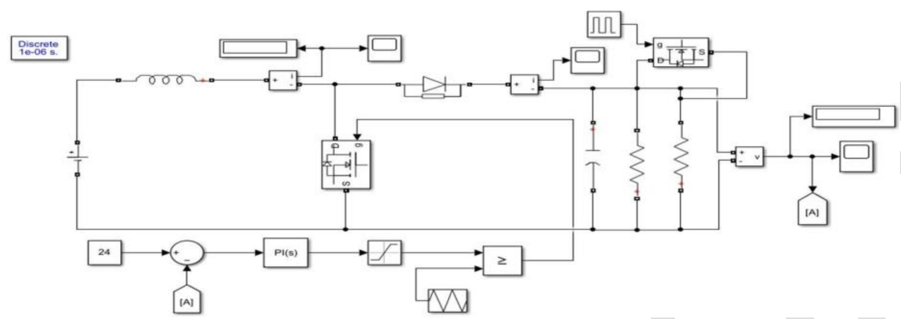

Fig.6.9. Boost converter performance using PI controller at load variation by 50% of simulation

<u>Waveform Result:</u>

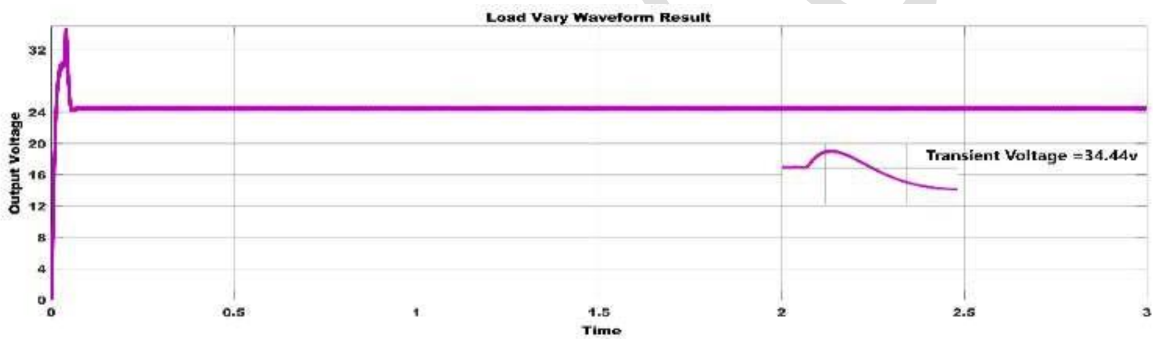

Fig.6.10. Boost converter performance using PI controller at load variation by 50%.

Fig.6.10. illustrates the boost converter's performance under load variation using a PI controller.When load is vary with a 10Ω,output voltage reaches a peak transient of 34.44 V before settling at 24.28 V. The inductor current operates in Continuous Conduction Mode (CCM). With a 25% duty cycle (pulse width), the output voltage drops to 23.55 V, while a 50% duty cycle results in an output voltage of 24.28 V.

6.2.1.2 8V Input voltage vary for boost converter performance using PI controller of simulation

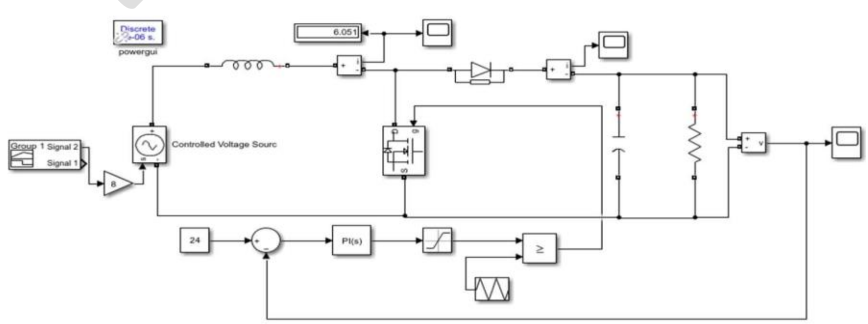

Fig.6.11. 8V Input voltage vary for boost converter performance using PI controller of simulation

Waveform Result:

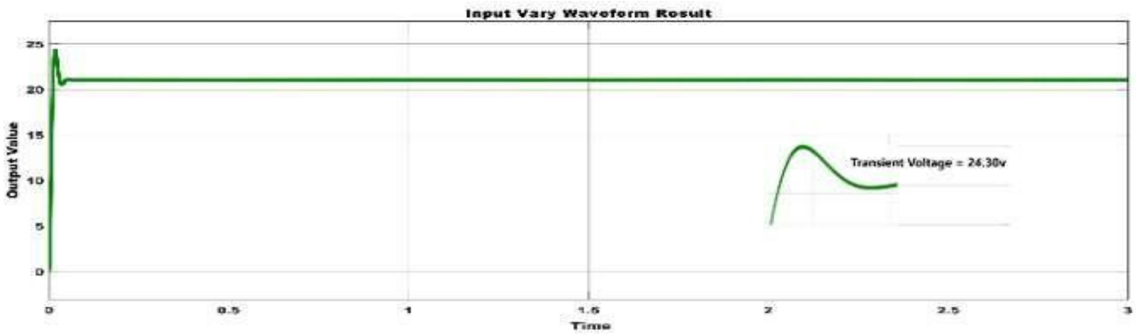

Fig.6.12. 8V Input voltage vary for boost converter performance using PI controller.

Fig.6.12 presents the performance of a boost converter regulated by a PI controller with an input voltage of 8 V. The transient response reaches a peak output of 24.30 V; however, the voltage settles to 20.94 V after approximately 43.925 ms, indicating limited regulation accuracy under steady state conditions. The inductor current remains in Continuous Conduction Mode (CCM) with a value of 6.069 A.

6.2.1.3 10V Input voltage vary for boost converter performance using PI controller of simulation

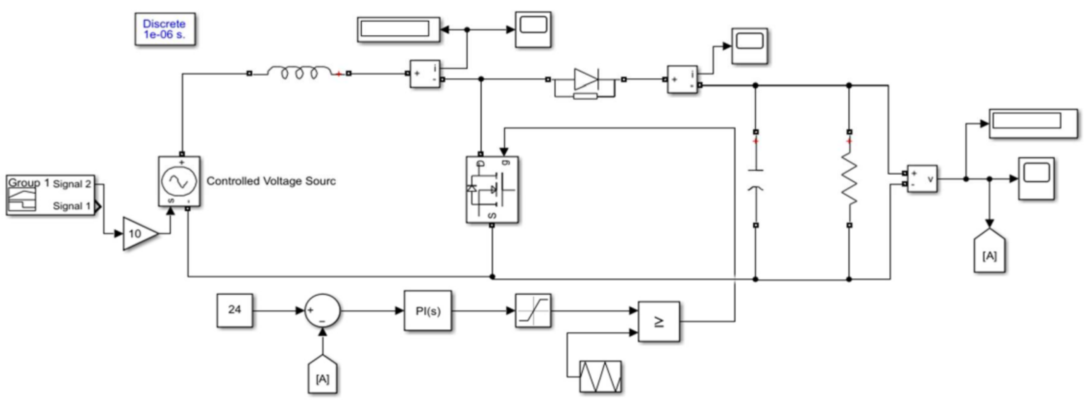

Fig.6.13. 10V Input voltage vary for boost converter performance using PI controller of simulation

Waveform Result:

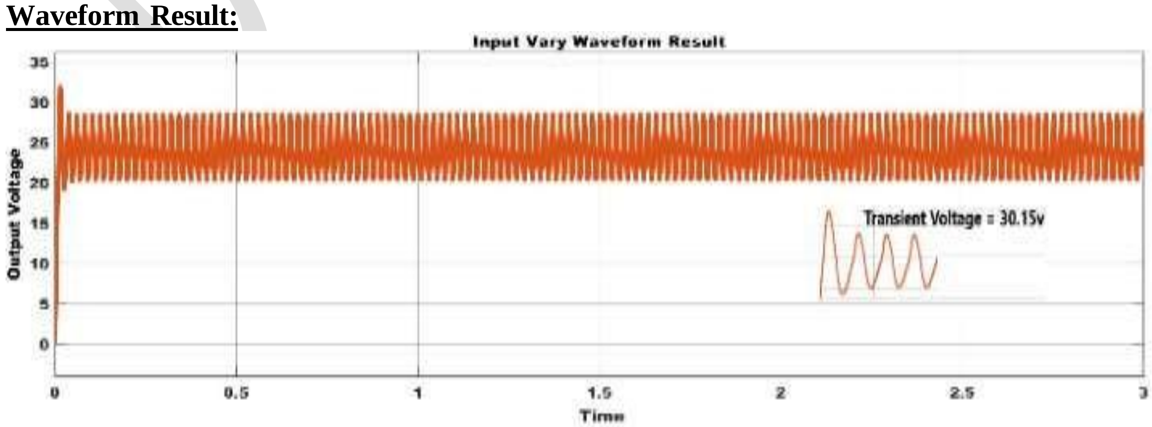

Fig.6.14. 10V Input voltage vary for boost converter performance using PI controller

Fig.6.14 shows the boost converter performance using a PI controller when the input voltage is 10 V. During the transient period, the output voltage rises to 30.15 V and then settles to 22.04 V after 26.358 ms, which is lower than the desired 24 V. The inductor current stays in Continuous Conduction Mode (CCM) with a value of 4.704 A. In this dynamic condition, the output voltage ripple is high at 8.3%.

From Fig.6.10, 6.12, 6.14 input value 8V,10V,12V it indication PI controller regulate the boost converter output voltage irrespective input voltage to 8v or 10v to 24v.

6.2.1 Boost converter using Fuzzy Logic controller

6.2.2.1 Boost converter performance using FLC controller at load variation by 50% of simulation

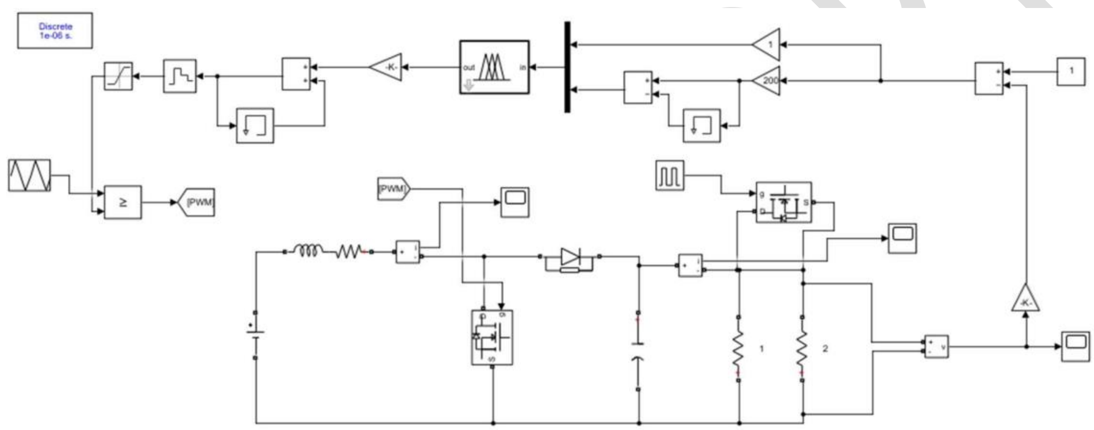

Fig.6.15. Boost converter performance using FLC controller at load variartion by 50% of simulation

<u>Waveform Result:</u>

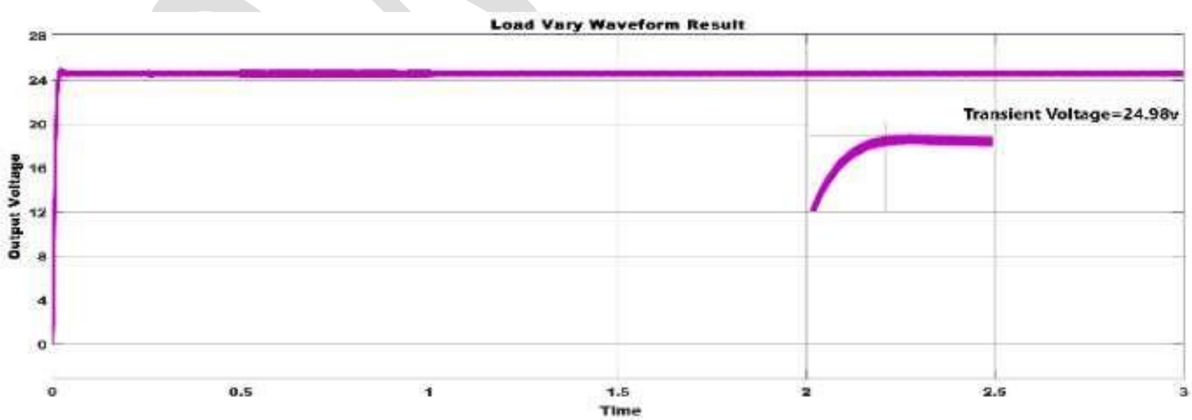

Fig.6.16. Boost converter performance using FLC controller at load variartion by 50%.

Fig.6.16. shows the boost converter performance using a Fuzzy Logic Controller (FLC) under dynamic load variation with a 10 Ω resistor. The transient voltage reaches 24.98 V, which is close to the desired value. The inductor current operates in Continuous Conduction Mode (CCM) with a value 12.33 A. The output stabilizes at 24.33V during the load variation. When a 25% duty cycle is applied for 1 second, the output remains stable at 24.33V. Similarly, with a 50% duty cycle, the output voltage also remains stable at 24.33V.

6.2.2.2 8V Input vary for boost converter performance using FLC of simulation.

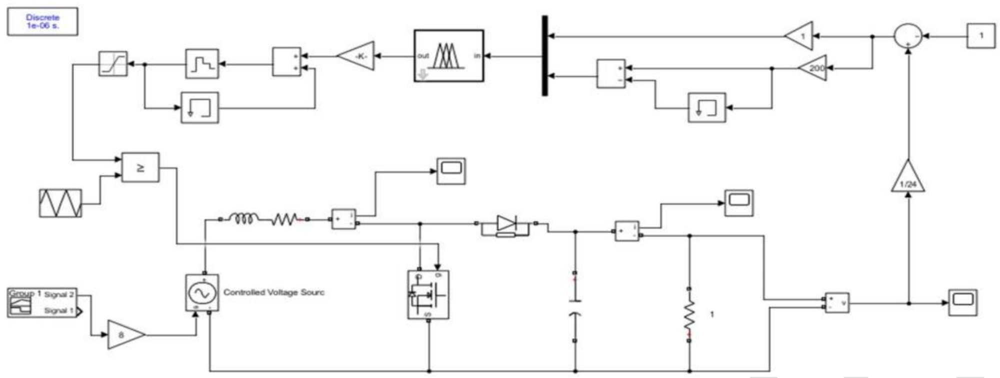

Fig.6.17. 8V Input vary for boost converter performance using FLC of simulation.

<u>Waveform Result:</u>

Fig.6.18. 8V Input vary for boost converter performance using FLC.

Fig.6.18 Illustrates the simulation results of a boost converter regulated by a Fuzzy Logic Controller (FLC) under input voltage 8 V the output exhibits a transient peak of 26.04 V and stabilizes to the desired output voltage of 24.66 V within 35.286 ms. The inductor current operates in Continuous Conduction Mode (CCM), reaching a stable value of 9.973 A.

6.2.2.3 10 V Input voltage vary for boost converter performace using FLC of simulation

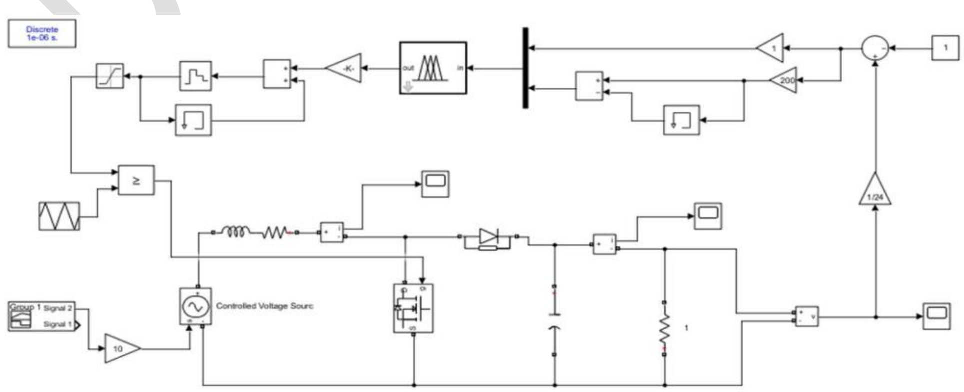

Fig.6.19. 10 V Input voltage vary for boost converter performace using FLC of simulation

Waveform Result:

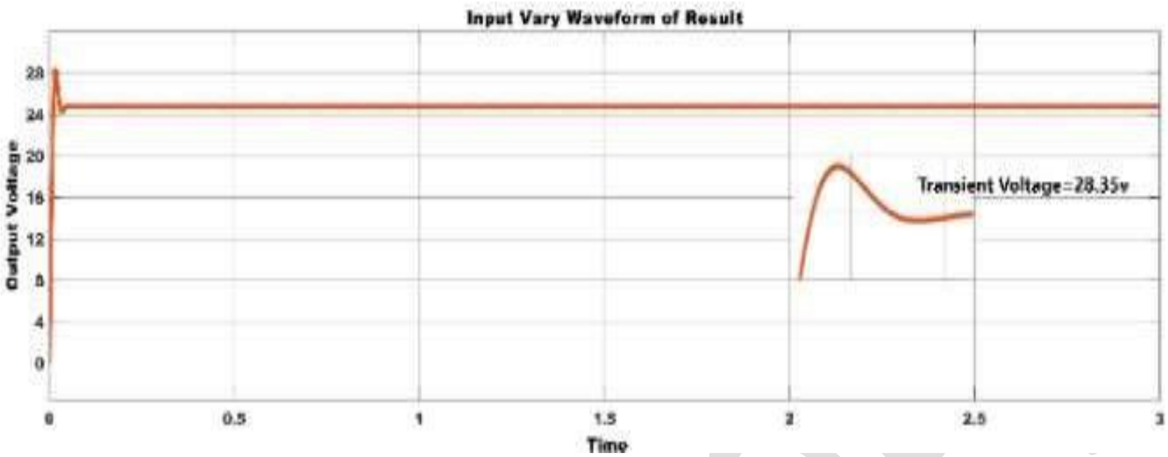

Fig.6.20. 10V Input voltage vary for boost converter performace using FLC

Fig.6.20. demonstrates the dynamic performance of a boost converter controlled by a Fuzzy Logic Controller (FLC) with a constant input of 10 V. The output initially overshoots to 28.35 V before settling to the target voltage of 24.64 V within 39.330 ms. The inductor current remains in Continuous Conduction Mode (CCM) and reaches a peak value of 7.14 A, indicating efficient voltage regulation under transient conditions.

From Fig.6.16, 6.18, 6.20 input value 8v,10v,12v it indication fuzzy controller regulate the boost converter output voltage irrespective input voltage to 8v or 10v to 24v.

6.2.3 Close loop boost converter from input solar panel with controlling MPPT and PI Controller of load variation

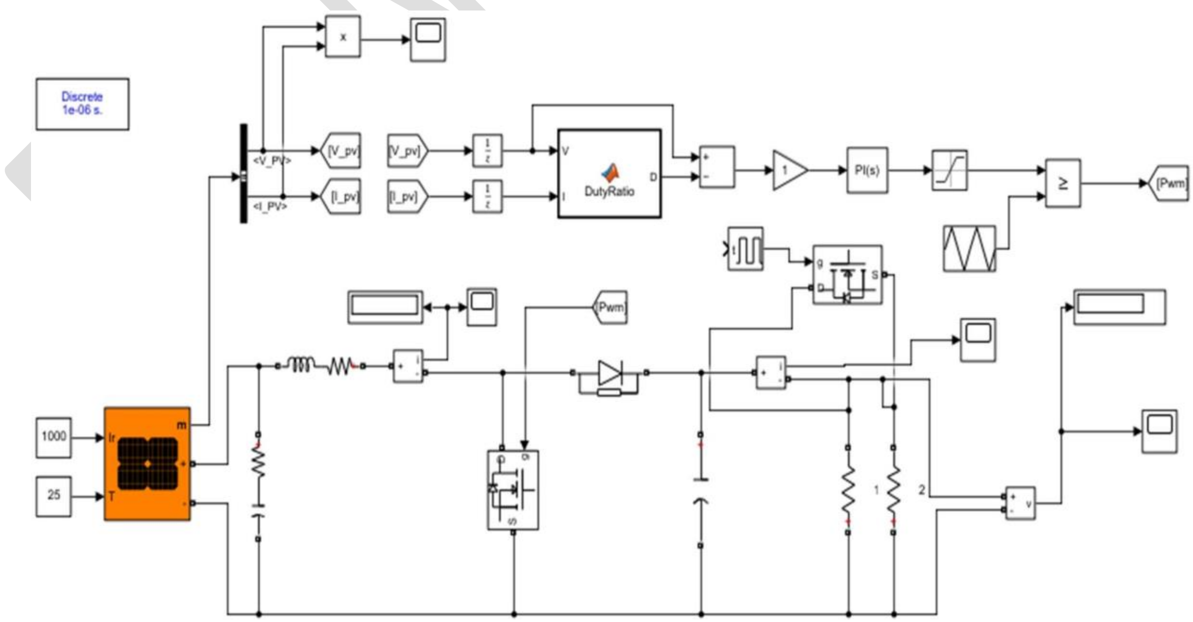

Fig.6.21 Close loop boost converter from input solar panel with controlling MPPT and PI Controller of load variation simulation

Waveform Result:

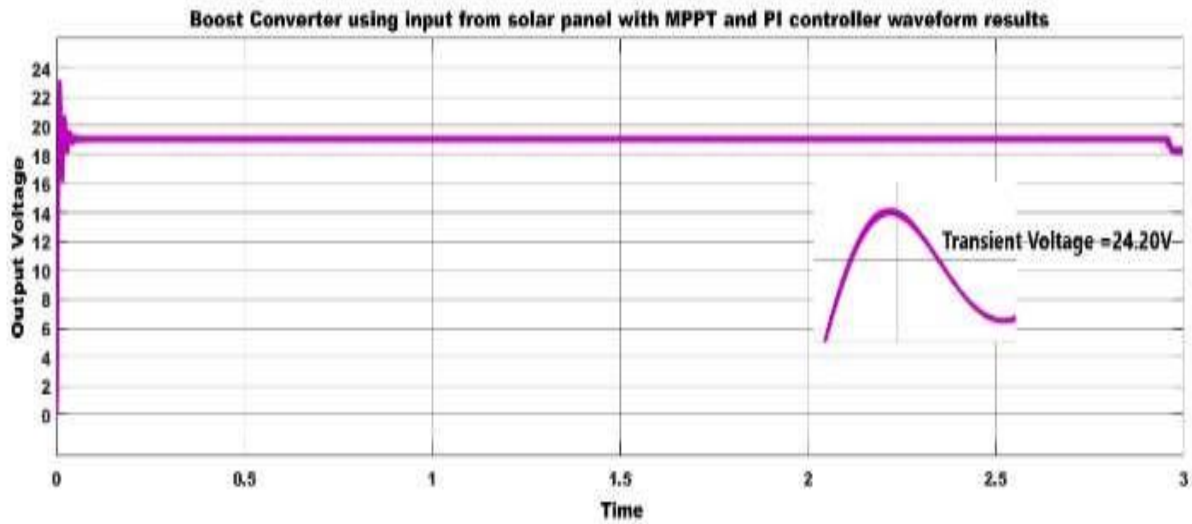

Fig.6.22 Close loop boost converter from input solar panel using MPPT with PI controller of Load variation waveform

Fig.6.22..illustrates the boost converter's performance under load variation using a PI controller.When load is vary with a 10Ω output voltage reaches a peak transient of 24.20 V settling at 18.91 V. The inductor current operates in Continuous Conduction Mode (CCM) with valus is 7.8A. With a 25% duty cycle (pulse width), the output voltage drops to 18.15 V, while a 50% duty cycle results in an output voltage of 18.91V.

6.2.4 Boost converter input from solar panel with Fuzzy Logic Controller of Load Variation Waveform

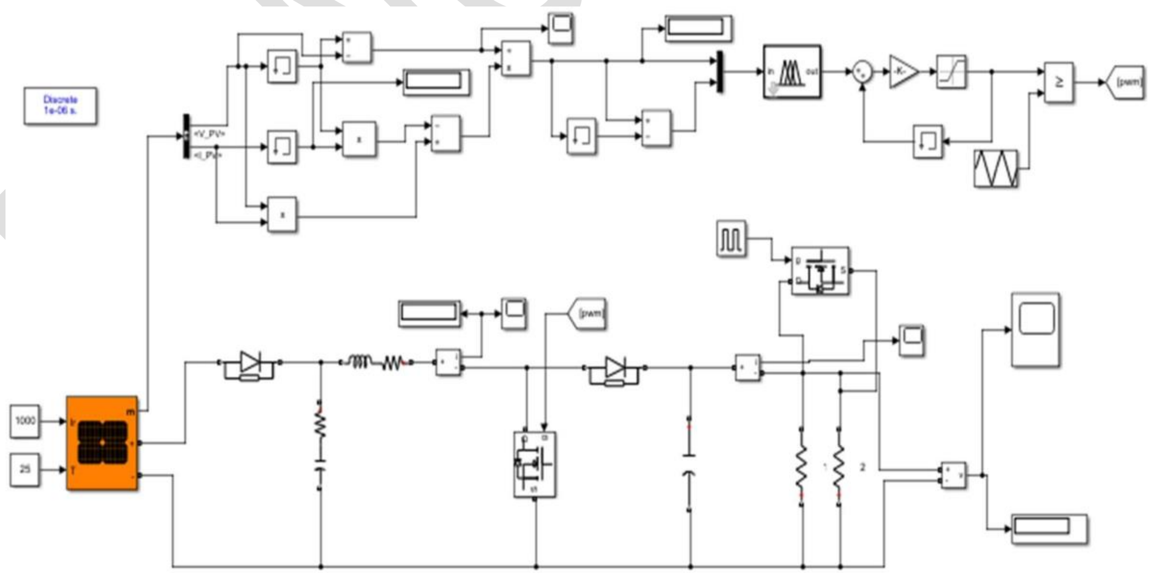

Fig.6.23 Boost converter input from solar panel with Fuzzy Logic Controller of Load Variation Waveform simulation

Waveform Result:

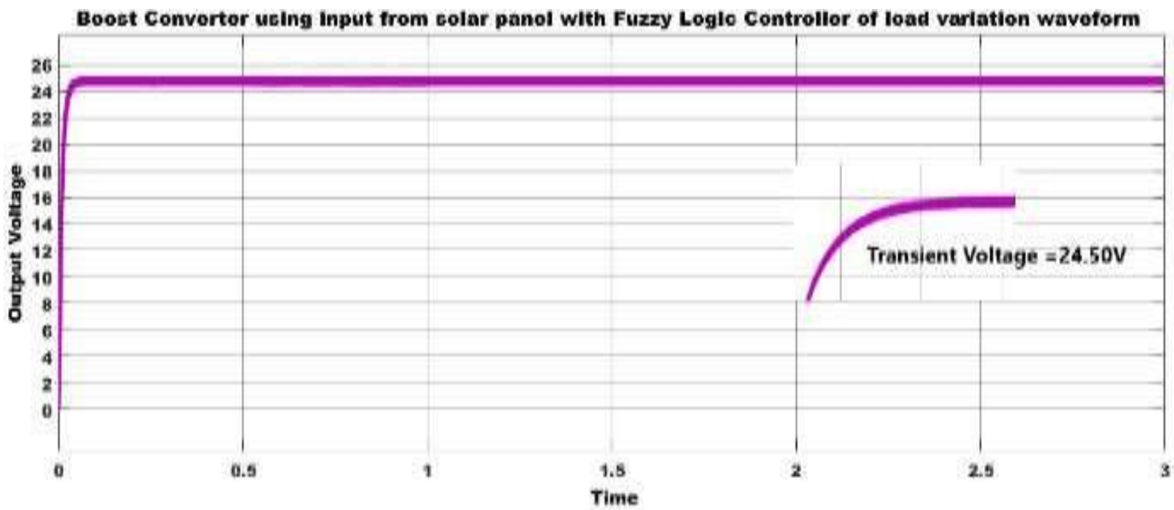

Fig.6.24 Boost converter input from solar panel with Fuzzy Logic Controller of Load Variation waveform

Fig.6.24 shows the boost converter performance using a Fuzzy Logic Controller (FLC) under dynamic load variation with a 10 Ω resistor. The transient voltage reaches 24.50 V, which is close to the desired value. The inductor current operates in Continuous Conduction Mode (CCM) with a value 14.6 A. The output stabilizes at 24.05 V during the load variation. When a 25% duty cycle is applied for 1 second, the output remains stable at 24.05 V. Similarly, with a 50% duty cycle, the output voltage also remains stable at 24.05V.

From Fig.6.22 and 6.24 the Fuzzy Logic Controller demonstrates superior performance compared to the PI controller, maintaining a stable output of 24.05 V with minimal deviation under varying loads and duty cycles, while the PI controller experiences significant voltage drops and slower settling, indicating lower adaptability and regulation accuracy in renewable application.

Chapter 7
Boost Converter MATLAB Simulation implemented on a dSpace MicroLabBox (RT1202) Hardware for real-time control

7.1 Open loop Boost Converter MATLAB Simulation implemented on a dSpace MicroLabBox (RT1202) Hardware for real-time control

In this simulation use the dSpace MicroLabBox (RT1202) for digitally real-time control and analysis the boost converter of PWM generator duty ratio waveforms.

Open loop boost converter hardware results:

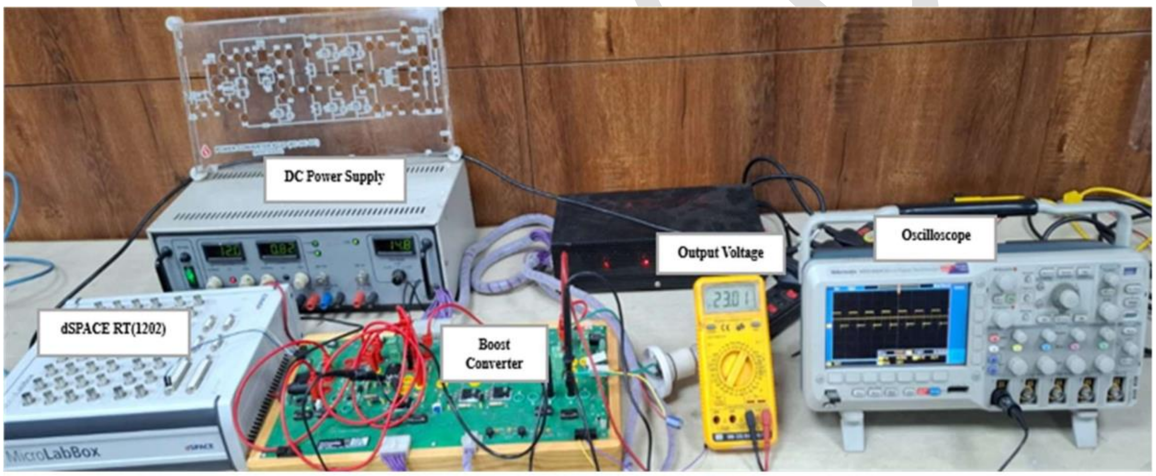

Fig.7.1 Open loop boost converter hardware results

Fig.7.1 This is results of hardware boost converter using dSpace real-time control. Multimeter shows the output voltage value 23.01v.

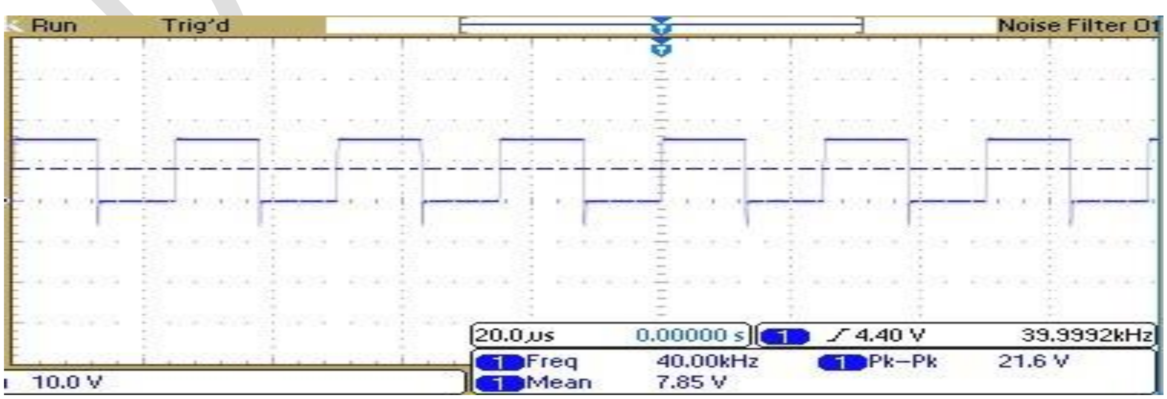

Fig.7.2. PWM signal with constant duty ratio by dSpace

7.2 Boost Converter using PI Controller MATLAB Simulation implemented on a dSpace MicroLabBox (RT1202) Hardware for real-time control

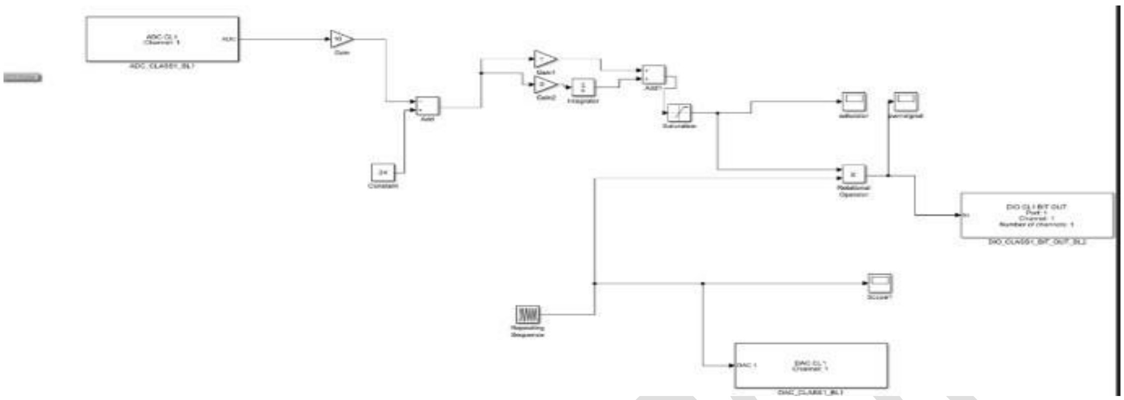

Fig.7.3.PI controller implemented on dSpace MicroLabBox

Boost converter performance using PI controller implemented on a dSpace MicroLabBox for real-time controlling hardware results:

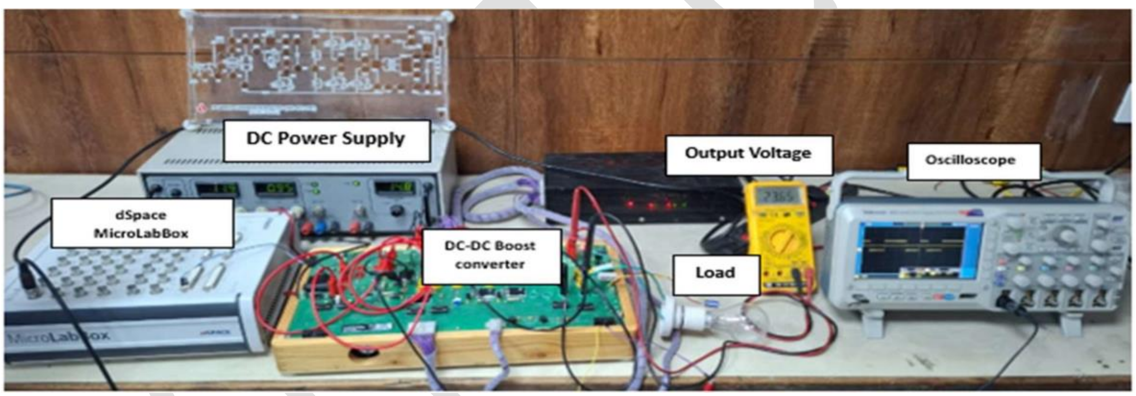

Fig.7.4 ***Boost converter using PI controller implemented on a dSpace MicroLabBox for real-time controlling hardware results***

In this Fig.7.4 The results of hardware close loop boost converter using PI controller implemented on dSpace MicroLabBox (RT-1202). In this multimeter shown the output voltage of dSpace real-time control. It is output 23.90v with duty ratio vary.

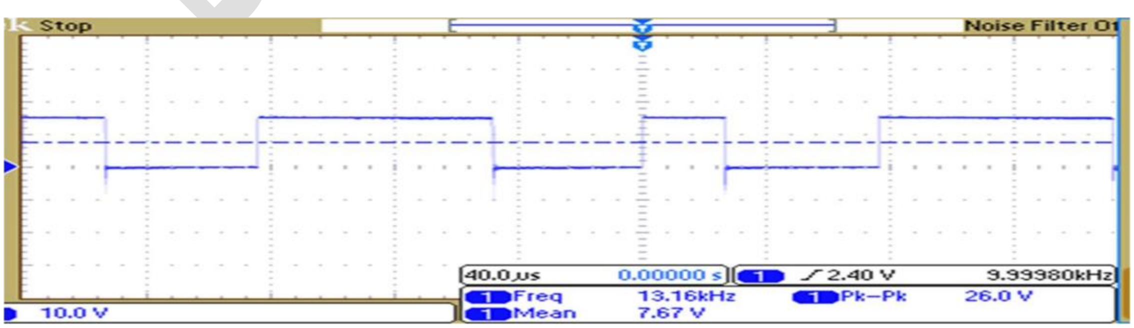

Fig.7.5 PWM signal with variable duty ratio at closed loop control using PI by dSpace

Chapter 8

Comparative Results and Analysis of PI controller and fuzzy logic controller for boost converter

TABLE IV. Results in Steady State Condition

SR No.	Parameters	Mamdani Fuzzy Logic Controller	PI Controller
1.	**Transient voltage State Value**	30.55 v	39.44 v
2.	**Settling Time (ts)**	49.810 ms	63.333 ms
3.	**Steady state output voltage**	24 v	25.05 v
4.	**Ripple Value**	0.25 mv	0.35 mv
5.	**Rise Time(tr)**	6.641 msec	8.095 msec
6.	**Error (e)**	0 %	0.0425 %

TABLE V. Results in Dynamic Condition

Load Variation (R= 10ohm)								
Controller	Vin	Vref	Vout	Transient State Voltage	Rise Time	Ripple Value	Settling Time	Error
PI	**12** v	**24** v	**24.28** v	**43.70** v	**13.333** ms	**0.57** mv	**70.000** ms	**0.01%**
FLC	**12** v	**24** v	**24.33** v	**24.98** v	**12.556** ms	**0.53** mv	**20.023** ms	**0.01%**
Input Variation (Vin= 8V)								
Controller	Vin	Vref	Vout	Transient State Voltage	Rise Time	Ripple Value	Settling Time	Error
PI	**8** v	**24** v	**20.94** v	**24.30** v	**8.048** ms	**0.27 mv**	**43.925 ms**	**-0.12 %**
FLC	**8** v	**24** v	**24.66** v	**26.04v**	**13.375** ms	**35.286 ms**	**35.286 ms**	**0.02 %**
Input Variation (Vin = 10v)								
Controller	Vin	Vref	Vout	Transient State Voltage	Rise Time	Ripple Value	Settling Time	Error
PI	**10** v	**24** v	**22.04** v	**30.15** v	**6.120** ms	**8.46 mv**	**26.358** ms	**-0.08 %**
FLC	**10** v	**24** v	**24.64** v	**28.35** v	**7.749 ms**	**0.31 mv**	**39.330** ms	**0.02 %**

TABLE IV. Results In Dynamic Condition Input of Solar Panel to The Boost Converter

Load Variation (R= 10ohm)			
SR No.	**Parameters**	**Mamdani Fuzzy Logic Controller**	**PI Controller**
1.	**Transient voltage State Value**	24.50 V	24.20 V
2.	**Settling Time (ts)**	47.13 ms	52.85 ms
3.	**Steady state output voltage**	24.05 V	18.91 V
4.	**Ripple Value**	0.63 mv	0.49 mv
5.	**Rise Time(tr)**	14.28 msec	3.824 msec
6.	**Error (e)**	0.02%	0.21%

Chapter 9
Conclusion and Future Scope

9.1 Conclusion

In this study a dSpace MicroLabBox RT-1202 implemented for pwm signal generation in open loop as well as close loop operation of boost converter. Boost converter is tested extensively in simulation and through hardware. It is suitable candidate for operations with renewables in input variation mode and a promising candidate in EV application in both dynamic conditions by applying fuzzy control. The comparison and the analysis is presented from the results of overshoot, settling time, ripple value, rise time and error, stability in steady state condition. Simulation and experimental results show that the fuzzy logic controller technique is precise. Fuzzy logic control in steady state condition and dynamic condition shows less overshoot, less error, less settling time and less transient response than PI control. Fuzzy logic control method is to be implemented to achieve stability in dynamic conditions to enhance integrity in renewable energy and EV applications.

9.2 Future Scope

1. **Integration of (AI based) advanced intelligent control algorithms:** Integration of (AI based) advanced intelligent control algorithms such as fuzzy logic controllers (FLC) deep reinforcement learning, can further enhance system performance and adaptability under varying operating conditions.
2. **Exploration of hardware-in-the-loop (HIL) testing:** Exploration of hardware-in-the-loop (HIL) testing with real-world disturbances for validation before deployment in industrial applications. Hardware Implementation.
3. **Development of fault detection:** Development of fault detection and diagnosis features to improve system reliability and reduce downtime.
4. **Optimization of the converter design:** Optimization of the converter design for miniaturization and cost reduction, facilitating applications in portable and low-power devices.

5. **Optimization of the converter design:** Optimization of the converter design for miniaturization and cost reduction, facilitating applications in portable and low-power devices.

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