TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PURWANCHAL CAMPUS

A

FINAL PROJECT REPORT

ON

FOUR SWITCH SYNCHRONOUS BUCK – BOOST CONVERTER WITH CLOSED LOOP FEEDBACK

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DEPARTMENT OF ELECTRICAL ENGINEERING

The undersigned certify that they have read and recommended to the Institute of Engineering for acceptance, a final year project work entitled **"FOUR SWITCH SYNCHRONOUS BUCK-BOOST CONVERTER WITH CLOSED LOOP FEEDBACK"** submitted by MR. ABISHEK RAJ KOIRALA (076/BEL/002), MR. BISHAL KHANAL (076/BEL/010), MR. HARI PRASAD ADHIKARI (076/BEL/018) and MR. NISHAN BHATTARAI (076/BEL/030) in partial fulfillment of the requirements for the degree of Bachelor in Electrical Engineering.

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DECLARATION

We declare that the work hereby submitted for Bachelors in Electrical Engineering at Institute of Engineering, Purwanchal Campus entitled **“FOUR SWITCH SYNCHRONOUS BUCK-BOOST CONVERTER WITH CLOSED LOOP FEEDBACK”** is our own work and has not been previously submitted by me at any university for any academic reward.

We authorize Institute of Engineering, Purwanchal Campus to lend this report to other institution or individuals for the purpose of scholarly research.

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Sincerely,

Abishek Raj Koirala

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ABSTRACT

This project encompasses control theory, mathematical models and practical methods for developing high efficiency synchronous DC-DC buck-boost converter with closed loop feedback for variable loads. The converter aims to address the limitations of traditional buck-boost converter by employing synchronous rectification and closed -loop control techniques to improve efficiency and dynamic response. Efficiency is increased by reducing the voltage drop across the power diode by replacing it with MOSFET in synchronous converter, less voltage drop translates into less power dissipation and higher power efficiency. Closed loop feedback control further enhances the converter's performances by continuously monitoring the output voltage and adjusting the duty cycle.

A comprehensive literature review is conducted to gain insights into existing synchronous buck-boost converter designs, closed – loop control algorithms, and relevant power electronic technologies. Based on this research a detailed converter topology will be developed, considering factors such as component selection, switching frequency and control strategy. A prototype of the synchronous buck-boost converter will be built and tested under various load conditions to evaluate its performance characteristics. Mathematical simulations are used to verify the control loop models before hardware verification. The closed–loop control system will be implemented using appropriate sensors, feedback amplifiers and microcontrollers. Extensive experimental measurements will be conducted to assess parameters such as output voltage regulation, efficiency, transient response and stability. Through a combination of theoretical analysis, simulation studies, and practical experimentation, this project aims to deliver a high – performance converter solution that meets the demanding requirements of modern power electronic applications.

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LIST OF ABBREVIATIONS

AC	: Alternating Current
DC	: Direct Current
MOSFET	: Metal Oxide Semiconductor Field Effect Transistor
VMC	: Voltage Mode Control
MATLAB	: Matrix Laboratory
PWM	: Pulse Width Modulation
FSBB	: Four Switch Buck Boost
IDE	: Integrated Development Environment
GPU	: Graphics Processing Unit
CPU	: Central Processing Unit
DSP	: Digital Signal Processing

CHAPTER ONE: INTRODUCTION

1.1. Introduction

In Power Electronics, converters play a pivotal role in efficiently transforming electrical energy from one form to another. Many applications require a dc-dc converter that is able to regulate its output voltage from a wide range of input voltages. These applications often require the output voltage to be higher than, lower than, or approximately equal to the input voltage. By utilizing a buck-boost topology, the input voltage can be either stepped-up or stepped-down to the desired voltage. Nevertheless, the fundamental structure of a buck-boost converter introduces several undesired traits. These issues encompass subpar efficiency, a reversal in output voltage polarity concerning the input voltage, unfavorable input and output current characteristics. Various remedies are accessible to address these limitations. Rather than relying on the conventional single-switch buck-boost design, a four-switch Buck-Boost configuration has emerged as a solution. This topology adeptly shifts between synchronous buck and boost modes, contingent upon the input voltage, thereby enhancing efficiency and other performance aspects [1].

DC-DC converters are the simplex power electronic circuits which transfer one level of electrical voltage into another level by switching action. These converters have obtained a greater considerable extent of concern in numerous fields like power supplies for individual computers, clerical device, telecommunication purpose, DC machine drives, aerodynamics, hybrid electric and fuel cell vehicles, renewable energy system etc. Voltage-mode regulate and current-mode regulate are two commonly used regulate schemes to regulate the output voltage and current of dc-dc converters [2]. Much of today's technology is dependent on direct current while alternating current is used for long distance transportation of energy. Modern electronic systems require high-quality, small, lightweight, reliable, and efficient power supplies.

The basic principle of a buck-boost converter involves a switching transistor, an inductor, a diode rectifier, and an output capacitor. By controlling the duty cycle of switching transistor, the buck-boost converter can step-down/step-up the input voltage to a lower or higher regulated output voltage as per requirement.

1.2. General Background

Before the development of power semiconductors and allied technologies, one way to convert the voltage of a DC power supply to a higher voltage, for low-power applications, was to convert it to AC by using a vibrator oscillator, followed by a step-up transformer and rectifier. These methods were relatively inefficient and highly expensive. However, with the introduction of power semiconductors and integrated circuits, new economically viable techniques became available to meet all the power requirements that most battery powered devices need. More specifically, the technology that is being used is called power electronics. Power electronics encompasses the four main types of electrical power conversion: AC to DC, AC to AC, DC to DC, and DC to AC. The application of power electronics is therefore not only limited to one problem, but rather there is wide array of issues that this type of technology can solve. For example, the simplest type of power circuit is the rectifier which can convert single/three-phase AC voltage to a fixed or variable DC voltage through uncontrolled or controlled rectifiers respectively. In addition, there are also inverters, transformer etc. The DC-DC converter, converts a fixed DC input to a variable DC voltage. It has applications ranging from very low levels of power like small batteries to extremely high-power applications like in power systems [3]. DC-DC converters can generally be divided into two main types based on their switching method: hard-switching or pulse-width-modulated (PWM) converters and resonant/soft switching converters. For the last three decades, the PWM DC-DC converters have been very popular. They have been able to provide high efficiency while having the ability to achieve high conversion ratios for both step-down and step-up applications. No matter the type of converter one chooses to use, one can be sure that a DC-DC converter will regulate the DC output voltage against load and line variations while reducing the AC voltage ripple on the DC output voltage below the required level. In essence, a switching DC-DC converter or a regulator is a circuit that uses power switch (such as a MOSFET), MOSFET driver, an inductor, a diode and a capacitor to transfer energy from the input to the output. These components can be arranged in a variety of ways to effectively construct three of the most used types of converters: a buck, boost or a buck-boost converter. In a typical buck-boost converter, the output voltage (V_{out}) depends on the input voltage (V_{in}), the inductance and capacitance values and the switching duty cycle (D) of the power switch.

As power electronics technology advanced, researchers and engineers explored various improvements and modifications to the basic buck-boost converter topology. One significant enhancement was the introduction of synchronous rectification. Instead of relying on a diode rectifier, synchronous rectification employs a controlled transistor in parallel with the switching transistor. This allows for more efficient power transfer by minimizing voltage drops associated with diode rectifiers. Synchronous buck-boost converters offer improved efficiency and reduced power losses, making them suitable for high-power and energy-efficient applications.

By incorporating synchronous rectification, the proposed converter minimizes energy losses associated with diode rectifiers, leading to improved efficiency and reduced heat dissipation. Furthermore, closed-loop feedback control continuously monitors the output voltage, adjusting the duty cycle of the switching transistor to maintain a stable and regulated output voltage. This closed-loop control mechanism enhances the converter's ability to handle varying load conditions, transient responses, and overall stability.

1.3. Statement of Problem

The traditional DC-DC buck-boost converter, while widely used for voltage step up/down applications, faces certain limitations that hinder its overall performance and efficiency. These limitations motivate the need for the development of a synchronous DC-DC buck-boost converter with closed-loop feedback control. The key problems associated with traditional buck-boost converters are:

1) Energy Losses: Due to the bidirectional nature of traditional buck-boost converters and employing diode rectifiers, it may incur higher losses. These losses reduce overall converter efficiency and increase heat dissipation, leading to decreased power conversion efficiency.
2) Limited Dynamic Response: The dynamic response of a buck-boost converter refers to its ability to quickly and accurately respond to changes in load conditions. Traditional buck-boost converters often exhibit slower transient response times, leading to fluctuations in the output voltage during load variations.
3) Voltage Regulation: Traditional buck-boost converters employ feedback control mechanisms for achieving voltage regulation. But the regulation is poorer due to the use of analog control techniques, control complexity and component limitations.

1.4. Objectives

The main objective of this project is focused on the improvement and enhancement of the traditional buck-boost converters used in various applications, which can be classified as:

1) Develop a four-switch synchronous converter with closed-loop feedback.
2) Reduce the switching losses and conduction losses by employing synchronous rectification.
3) Achieve higher efficiency, improved dynamic response and enhanced voltage regulation.
4) Construct the hardware prototype of the four-switch buck-boost converter.

1.5.Justification of the Research

The proposed research project on the development of a synchronous DC-DC buck-boost converter with closed-loop feedback control is justified by several key factors. Firstly, it aims to improve the efficiency of power conversion by addressing the energy losses associated with traditional buck-boost converters, contributing to energy conservation and sustainability. Secondly, the project focuses on enhancing voltage regulation, ensuring a stable and reliable output voltage even under varying load conditions. This is crucial for the optimal operation of sensitive electronic devices.

1.6.Limitation to the Research

It is essential to acknowledge the potential limitations and challenges that may arise during the research and development process. These limitations include:

1) Time Constraints: The research and development of a synchronous buck-boost converter with closed-loop feedback requires sufficient time for literature review, topology design, prototype development, control implementation, and performance optimization. The project timeline must be carefully managed to ensure that all necessary tasks can be completed within the available time frame.
2) Complexity of Control Algorithms: Implementing closed-loop feedback control algorithms can be complex, requiring advanced knowledge of control theory and programming. The design and implementation of an effective control algorithm may pose challenges in terms of computational complexity, stability, and accuracy.
3) Component Selection and Availability: The performance of the synchronous buck-boost converter is highly dependent on the selection and availability of suitable components, such as power switches, inductors, capacitors, and control circuitry. Limited availability of specific components or restrictions on component specifications may affect the overall performance and feasibility of the proposed converter design.

CHAPTER TWO: LITERATURE REVIEW

2.1.Introduction

A synchronous buck –boost converter is a type of DC-DC converter that efficiently converts a higher voltage to a lower voltage and lower voltage to a higher voltage using switching techniques. It is comprised of four power MOSFETs, an output inductor and an output capacitor as shown in figure.

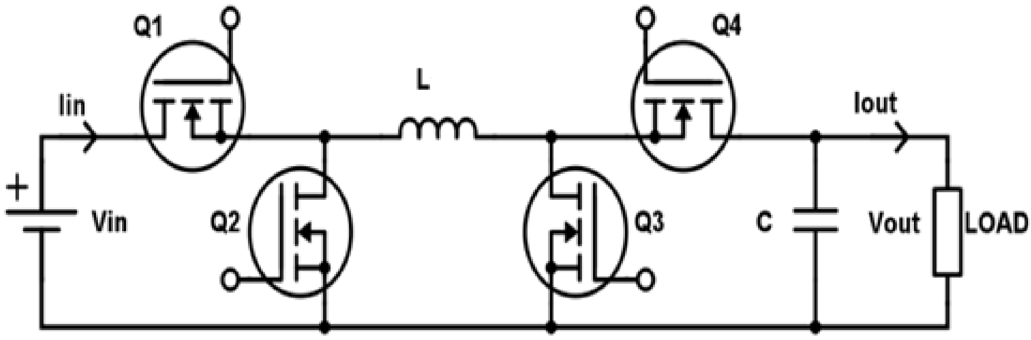

Figure 1: Four switch synchronous buck-boost converter

Nowadays, synchronous buck-boost converters have become very popular recently and are widely available for variety of applications such as to power display, GPU, CPU, cloud server data center, electric vehicles. The key advantage of four switch synchronous buck-boost converter is its ability to supply low voltage high current, ultra-fast transient, reduced losses and non-inverting output voltage.

2.2.Basic Operation and Components

The following components are involved in the working of a synchronous buck-boost converter:

1) Input Source: The voltage that has to be stepped up/down is supplied by the input source. It might be the output of a DC-AC converter, DC-DC converter or a DC power source.
2) Power MOSFETs: The synchronous buck-boost converter generally consists of four power switches which control the current flowing from input source to output load.
3) Capacitor: As shown in the above figure, a capacitor is connected parallel to the output load which helps to reduce the voltage ripple and stabilize the output voltage.
4) Inductor: It is connected in series with the input and output of the converter.

5) Schottky diode: It allows current to flow when the MOSFET is not conducting. This happens because the Schottky diode offers lower resistance compared to MOSFET in this situation. However, when the MOSFET is active and conducting current, then current flows through the MOSFET.
6) MOSFET driver: This circuit controls the switching of the MOSFETs based upon the PWM signal generated by the control circuit.
7) Control Circuit: The converter's control circuitry continuously checks the output voltage and modifies the duty cycle of the power switches as per requirement. The output voltage is regulated and kept at the desired level via a feedback loop.

The converter can be operated in three different modes:

1) Buck mode (Step down operation): The converter will operate as synchronous buck if switch Q4 is ON and Q3 is OFF, while switches Q1 and Q2 are switching.
2) Boost mode (Step up operation): The converter will operate as synchronous buck if switch Q1 is ON and Q2 is OFF, while switches Q3 and Q4 are switching.
3) Buck-Boost mode: The converter will operate in buck-boost mode when Q1 and Q3 are turned on simultaneously and Q2 and Q4 remains turned off and vice versa [4][5].

In conditions when the input voltage (V_{in}) is close to the output voltage (V_{out}), it is preferred for switch Q1 and Q4 to turn ON and bypass the input with output side, preferred as bypass condition with small inductor current ripple and low loss [5].

During the transition between buck and boost modes, the converter switches between the two configurations to smoothly adjust the output voltage. The switches are controlled dynamically to transition from buck to boost mode or vice versa. Pulse-width modulation (PWM) is typically used to control the duty cycle of the switch's operation, ensuring smooth transitions and stable output voltage regulation.

2.3.Control Techniques

Numerous analog and digital control methods for dc-dc converters have been proposed and have been adopted. Control methods ensures the efficient and reliable operation of the converters. Two of the most frequently used DC-DC converters control methods are voltage-mode and current-mode converter control. Besides these, control methods like sliding mode control, Pulse Width Modulation (PWM), predictive control, fuzzy logic control, digital control etc. are also employed according to their advantages [6][7][8].

1) Voltage Mode Control: Voltage mode control regulates the output voltage by comparing it with a reference voltage and adjusting the duty cycle of the switching signals accordingly. It provides a simple and effective method for voltage regulation, particularly when precise output voltage control is required. It is effective in maintaining a constant output voltage under varying load current conditions.

2) Current mode control: Another prevalent method of controlling the converter's output current is current mode control. It keeps track of the inductor current and modifies the duty cycle of the switches in accordance with the most recent data. Current mode control is appropriate for applications with changeable load conditions or where current regulation is crucial because it can offer quick transient response and cycle-by-cycle current limiting.

3) Pulse Width Modulation (PWM): PWM is the most widely used control technique for output voltage regulation of a buck-boost converter. It involves modulating the duty cycle of the switching signals applied to the converter's power switches. By adjusting the duty cycle, the average voltage applied to the load can be controlled, thereby regulating the output voltage.

4) Predictive Control: Predictive control techniques utilize mathematical models of the converter and predictive algorithms to optimize the switching signals. By predicting the future behavior based on the current state and load conditions, predictive control can achieve fast transient response and improved efficiency.

5) Digital control: Digital signal processors (DSPs) or microcontrollers are used in digital control systems to construct control algorithms. These algorithms are flexible and adaptable since they can be programmed and altered. Advanced features like fault protection, adaptive control, and communication interfaces can be incorporated with digital control approaches to provide accurate control.

2.4.Limitations of Synchronous Buck-Boost Converter

1) In comparison to settings with a heavy load, synchronous buck-boost converters may perform less efficiently under light load conditions due to the switching and conduction losses of the power MOSFETs used in the converter [9].

2) Compared to non-synchronous buck-boost converters, synchronous buck-boost converters need the usage of extra parts such as power MOSFETs and gate drive circuits. This additional complexity may result in an increase in the converter's price, size, and may introduce failures.

3) Synchronous buck-boost converters have more intricate control circuitry than non-synchronous converters. The design and execution of the control system may be more difficult because of this complexity.

4) Synchronous rectification is employed in this converter which increases efficiency by reducing the losses but requires precise control of the MOSFETs. Simultaneuos turning ON of the same side mosfet results in short circuit with the ground and to avoid it dead time should be implemented while switching so that low side mosfet only turns on after turning OFF of the high side mosfet .

CHAPTER THREE: METHODOLOGY

3.1.Hardware Components Used

3.1.1. Arduino NANO

The Arduino Nano is a widely embraced Arduino development board, closely resembling the popular Arduino UNO. Both boards utilize the same processor, the Atmega328P, enabling them to share programs seamlessly. The Nano features various power-related pins, including Vin for external power input (6-12V), 5V for a regulated power supply, 3.3V with a maximum current draw of 50mA, and GND for ground connections. The Reset pin is present to reset the microcontroller when necessary.

For analog functionalities, the Nano offers eight Analog Pins (A0-A7) capable of measuring voltages in the 0-5V range. Additionally, it provides 14 Digital I/O Pins (D0-D13), which can function as both input and output pins, with a voltage range of 0V (low) to 5V (high). The Serial communication pins (Rx and Tx) facilitate TTL serial data transmission

The Nano supports Pulse Width Modulation (PWM) on pins 3, 5, 6, 9, 10 and 11 offering 8-bit PWM output. The Nano's clock speed is 16 MHz, with 32 KB Flash Memory (2 KB for the bootloader), 2 KB SRAM, and 1 KB EEPROM.

We have used analog pin A_0, A_1 and A_3 to read output voltage, set voltage and input voltage. PWM pins 3 and 9 are used to generate PWM signal of 50KHz and 500 Hz.

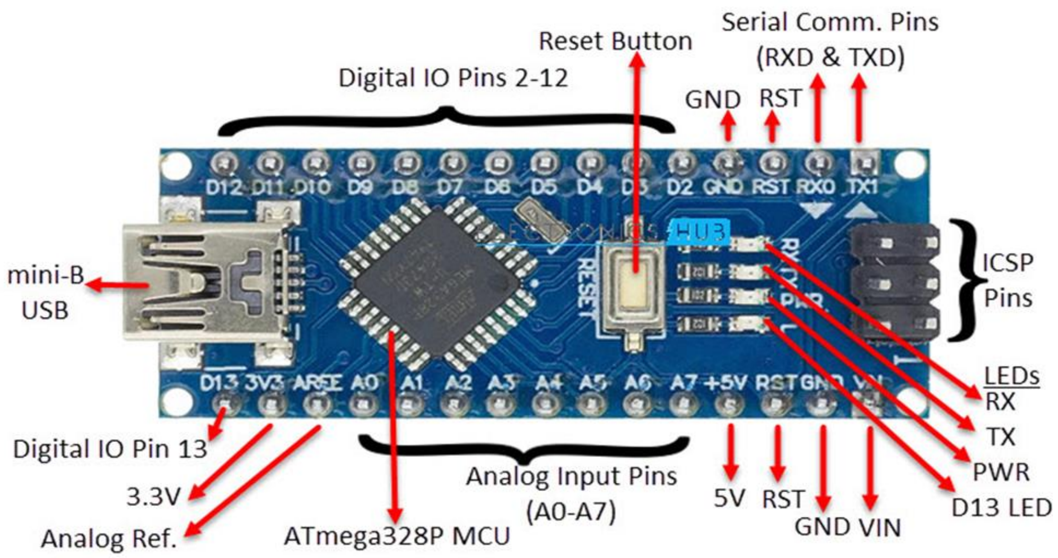

Figure 2: Arduino NANO

3.1.2. IRFZ44N N-Channel MOSFET

The IRFZ44N is an N-channel MOSFET renowned for its high drain current capacity of 49A and a low R_{DS} value of 17.5 mΩ. Its versatile application is attributed to features like a low threshold voltage of 4V, making it compatible with microcontrollers such as Arduino when driven with 5V. The pinout configuration comprises the Gate (controls biasing), Drain (where current enters), and Source (where current exits). With a continuous drain current of 49A at 25°C, pulsed drain current of 160A, and gate-source voltage of ±20V, it's suitable for applications requiring fast switching and high efficiency.

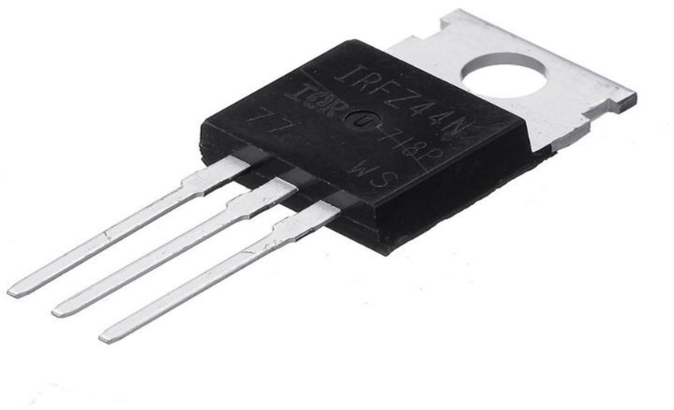

Figure 3: IRFZ44N N-Channel MOSFET

3.1.3. IR2104 MOSFET Driver

The IR2104 stands as a high-speed Half-Bridge gate driver chip, designed to efficiently convert low-power input into high-power current drives, making it ideal for driving high-power switching devices like MOSFETs and IGBTs. With the capability to drive both high-side and low-side MOSFETs, the IR2104 offers flexibility in diverse applications. Its pinout configuration includes crucial elements such as VCC for logic and internal gate drive supply voltage, IN for input, SD for shutdown (active low), COM for chip power and signal ground, LO for low-side gate driver output, VS for high side floating supply return, HO for high-side gate driver output, and VB for high-side gate driver floating supply.

Noteworthy specifications include a floating channel for bootstrap operation, full operational capability up to +600V, immunity to negative transient voltage, and $\frac{dV}{dt}$ immunity. The gate drive supply range spans from 10 to 20V, and the driver includes features like cross-conduction prevention logic, and internally set deadtime. To implement the IR2104 MOSFET, a typical application circuit involves a bootstrap diode and capacitor, crucial for driving the high side.

The value of the bootstrap capacitor plays a critical role in high side switching. For comprehensive technical details, the IR2104 datasheet provides in-depth information for design and integration considerations.

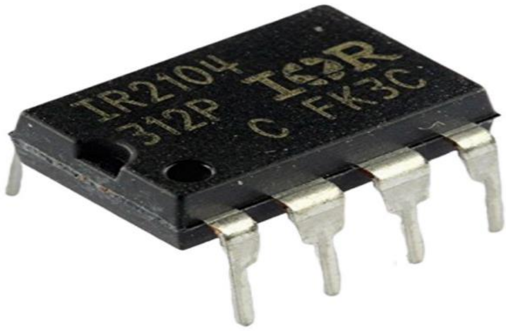

Figure 4: IR2104 MOSFET Driver

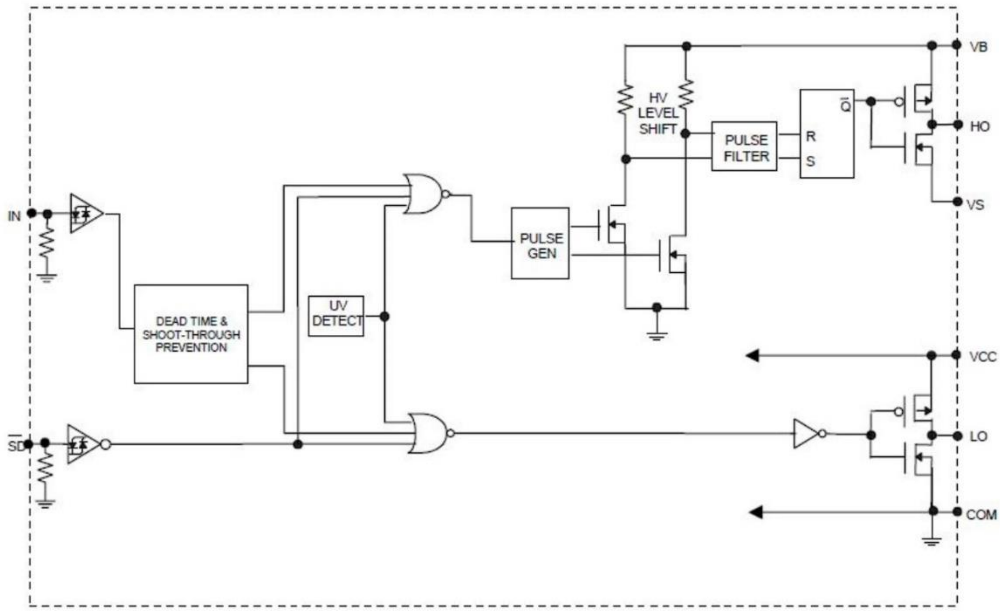

Figure 5: Internal Structure of IR2104

3.1.4. LM317 Voltage Regulator

The LM317 IC is a three terminal positive voltage regulator with an adjustable feature. It requires only two external resistors to set the output voltage. It has features like current limiting, thermal overload protection and safe operating area protection. It supplies more than 1.5A over an output voltage range of 1.25V to 37V.

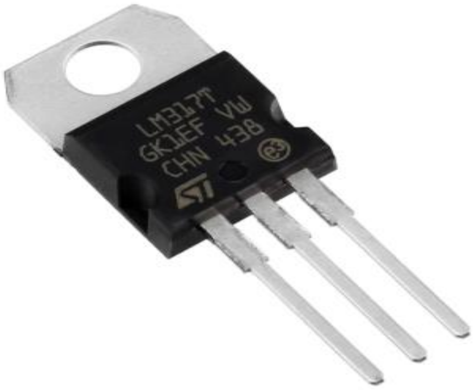

Figure 6: LM317 Voltage Regulator

3.1.5. Pull Down Resistor

A pull-down resistor serves a crucial role in digital electronic circuits by ensuring that inputs to logic systems settle at expected logic levels when external devices are disconnected or have a high impedance. Its primary function is to maintain the wire at a defined low logic level even when no active connections with other devices are present. The pull-down resistor achieves this by holding the logic signal close to zero volts (0V) when no other active device is connected, preventing an undefined state at the input.

When a switch is open, the pull-down resistor pulls the input voltage down to the ground, setting the logic signal to a low value. However, it's essential to choose a pull-down resistor with a larger resistance than the impedance of the logic circuit.

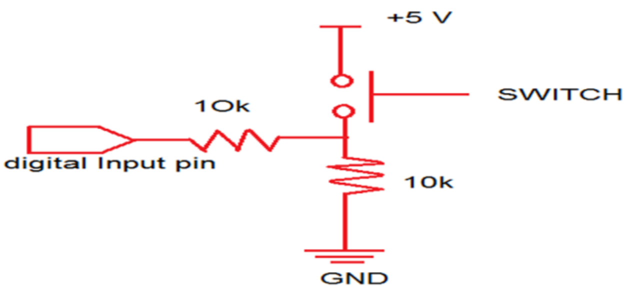

Figure 7: Pull Down Resistor

3.1.6. Perfboard

Perfboard, short for "perforated board," is a type of prototyping board used in electronics projects. It consists of a flat board with a grid of holes spaced at regular intervals. These holes are typically used to insert and solder electronic components, such as resistors, capacitors, integrated circuits, and connectors.

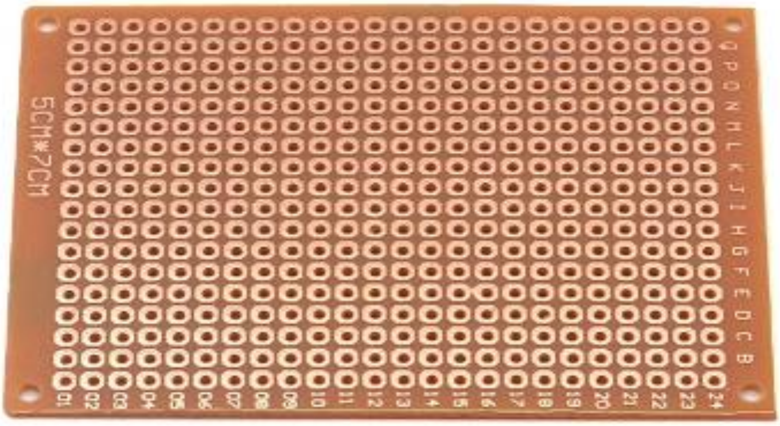

Figure 8: Perfboard

3.1.7. Potentiometer

A potentiometer is a manually adjustable variable resistor with 3 terminals. Two of the terminals are connected to the opposite ends of a resistive element, and the third terminal connects to a sliding contact, called a wiper, moving over the resistive element. The potentiometer essentially functions as a variable resistance divider. The resistive element can be seen as two resistors in series (the total potentiometer resistance), where the wiper position determines the resistance ratio of the first resistor to the second resistor. If a reference voltage is applied across the end terminals, the position of the wiper determines the output voltage of the potentiometer.

Figure 9: Potentiometer

3.1.8. Jumper Wire

Jumper wires are simply wires that have connector pins at each end, allowing them to be used to connect two points to each other without soldering. Jumper wires are typically used with breadboards and other prototyping tools in order to make it easy to change a circuit as needed.

Figure 10: Jumper wires

3.2.Software Used

3.2.1. MATLAB

MATLAB, which stands for "Matrix Laboratory," is a high-level programming language and interactive environment developed by MathWorks. It is widely used in academia, industry, and research for numerical computing, data analysis, algorithm development, and visualization. It is a programming and numeric computing platform used by millions of engineers and scientists to analyze data, develop algorithms, and create models.

3.2.2. Arduino IDE

The Arduino Integrated Development Environment (IDE) is an open-source software platform used to write and upload code to Arduino-compatible microcontroller boards. It provides a simple yet powerful interface for programming Arduino boards, making it accessible to both beginners and advanced users alike. The IDE includes a text editor for writing code, a compiler for converting code into machine-readable instructions, and a uploader for transferring the compiled code to the Arduino board.

3.2.3. Proteus 8 Professional

Proteus 8 Professional is a software application that allows you to design, test, and simulate electronic circuits and microcontrollers. Proteus software offers numerous benefits for PCB design and simulation. Its intuitive user interface, comprehensive component library, accurate simulation capabilities, and seamless integration between design and simulation make it an invaluable tool for engineers and designers.

3.3.Small Signal Model of Converter

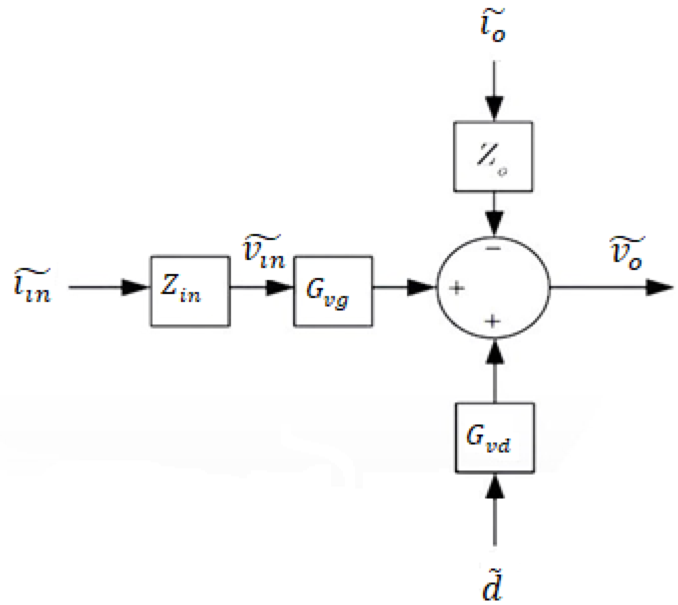

Figure 11: Block diagram of small signal model

3.3.1. For Buck Converter

Input impedance:

$$Z_{in} = \frac{V_{in}}{I_{in}}$$

$$Z_{in} = \frac{1}{D^2}\left[(r_e + sL) + \left\{\frac{\left(r_c + \frac{1}{sC}\right)}{R}\right\}\right]$$

$$r_e = r_{on} + r_l$$

$$\alpha = \frac{R + r_e}{R}$$

$$Z_{in} = \frac{\alpha R}{D^2} \times \frac{\Delta(s)}{\left(1 + \frac{s}{wp}\right)}$$

$$\Delta(s) = 1 + \frac{S}{Qwo} + \left(\frac{s}{wo}\right)^2$$

$$Q = \alpha \times \left[\frac{(r_{eq} + r_c)}{Z_c} + \frac{Z_c}{R}\right]^{-1}$$

$$w_o = \sqrt{\frac{r_{eq} + R}{R + r_c}} \times \frac{1}{\sqrt{LC}}$$

Output impedance, Z_o:

At low frequency, $Zo = re//R$

$$Z_o = \frac{r_e}{\alpha} \times \frac{\left(1 + \frac{s}{wesr}\right)\left(1 + \frac{s}{w_L}\right)}{\Delta(s)}$$

$$Z_o = \frac{r_e}{\alpha} \times \frac{\left(1 + \frac{s}{wesr}\right)\left(1 + \frac{s}{w_L}\right)}{\Delta(s)}$$

Where,

$$wesr = \frac{1}{r_c C}$$

$$and\ w_L = \frac{r_{eq}}{L}$$

Audio susceptibility:

$$G_{vg} = \frac{D\big(1 + r_C(s)\big)}{\alpha\left(1 + \frac{S}{Qwo} + \frac{S^2}{w_o^2}\right)}$$

Control to output transfer function:

$$G_{vd} = \frac{V_{in}\big(1 + r_C(s)\big)}{\frac{(R+r_e)}{R}\left(1 + \frac{S}{Qwo} + \frac{S^2}{w_o^2}\right)}$$

3.3.2. For Boost Converter

Input impedance of boost

$$Z_{in} = \frac{R\left(D'^{2} + \frac{SL}{R} + S^{2}LC\right)}{1 + SRC}$$

$$Z_{in}(0) = (1 - D)^{2}R$$

Output impedance

$$Z_{o} = \frac{SL}{D^{12} + \frac{SL}{R} + S^{2}LC}$$

Audio susceptibility

$$G_{vg} = \frac{D'}{D'^{2} + \frac{SL}{R} + S^{2}LC}$$

Control to output transfer function

$$G_{vd} = \frac{V_{in}\left(1 - \frac{SL}{R*D'^{2}}\right)}{D'^{2} + \frac{SL}{R} + S^{2}LC}$$

Loop gain under VMC

$$K_{loop}(s)=F_{m} * G_{vd}(s) * G_{C}(s)$$

$$V_{0}' = G_{vd}d' + G_{vg}V_{in}' - Z_{0}i_{0}'$$

We can conclude from above equation that:

- Positive change in input voltage results in positive change in V_{0}'.
- Positive change in duty cycle results in positive change in V_{0}'.
- Positive change in output current results in negative change in V_{0}'.

3.4.Frequency Response

We have plotted the Bode plots for the transfer functions derived for small signal model. Bode plots show the gain and phase margins of the system. Gain margin indicates the amount of gain that can be added to the system before it becomes unstable, while phase margin indicates the phase lag between input and output signals at the frequency where the gain is unity. Generally, a good design aims for positive gain and phase margins.

3.4.1. Buck Converter

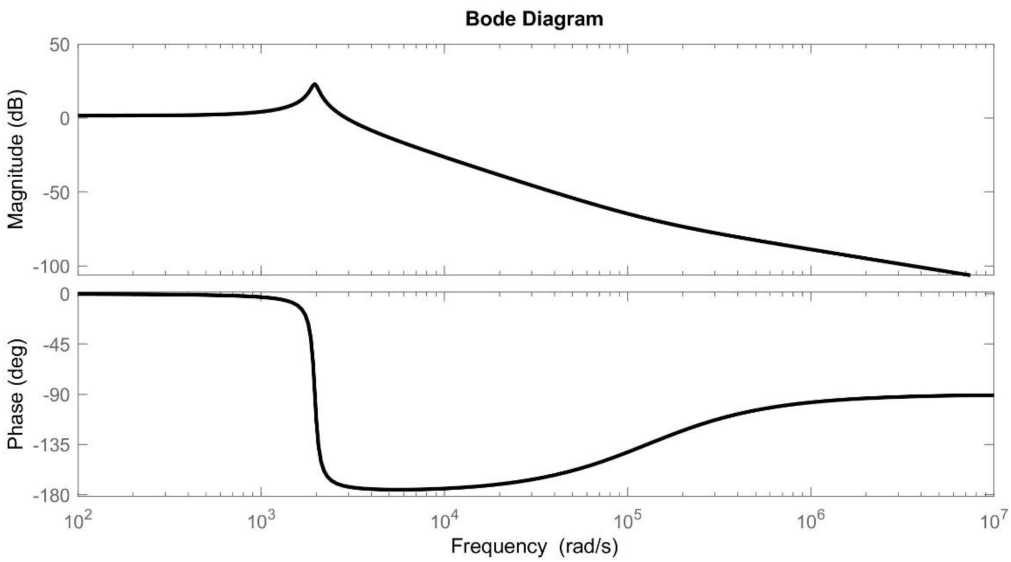

Figure 12: Bode plot for Buck mode

3.4.2. Boost Converter

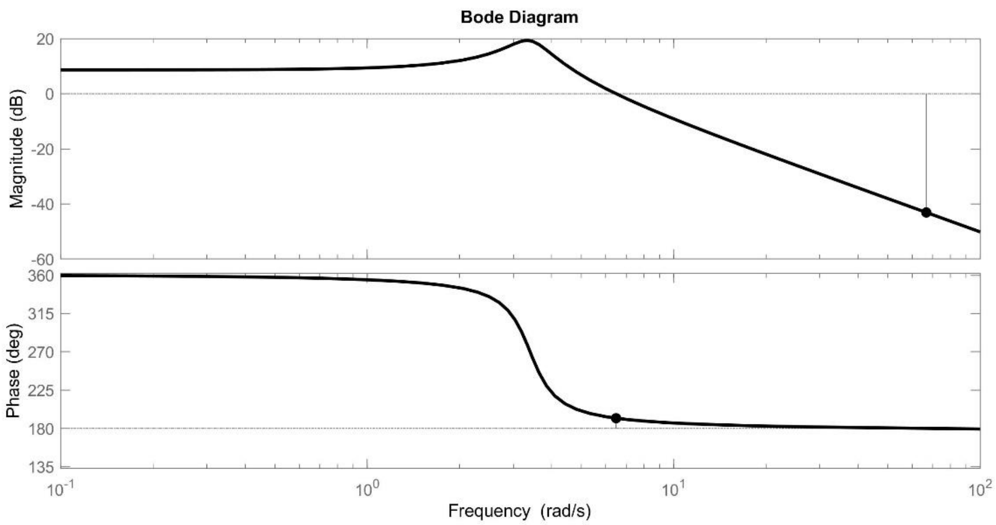

Figure 13: Bode plot for Boost mode

3.5.MATLAB Models

3.5.1. Buck Converter

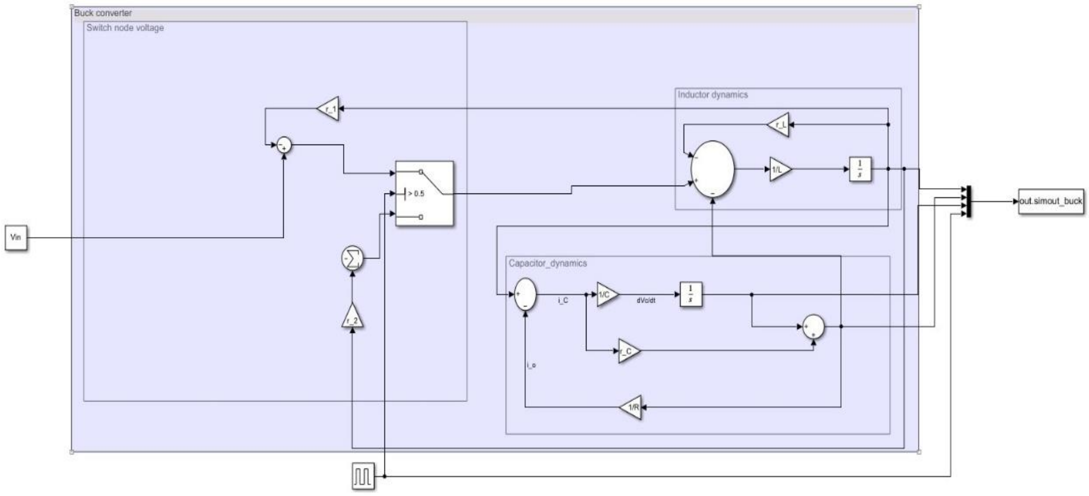

Figure 14: MATLAB model of Buck Converter

3.5.2. Boost Converter

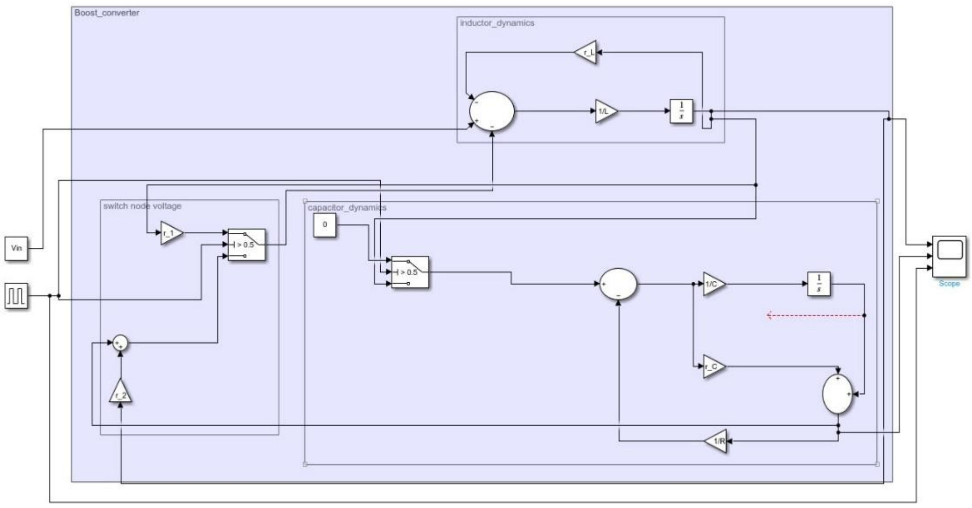

Figure 15: MATLAB model of Boost Converter

3.5.3. Buck Converter with Voltage Mode Control (VMC)

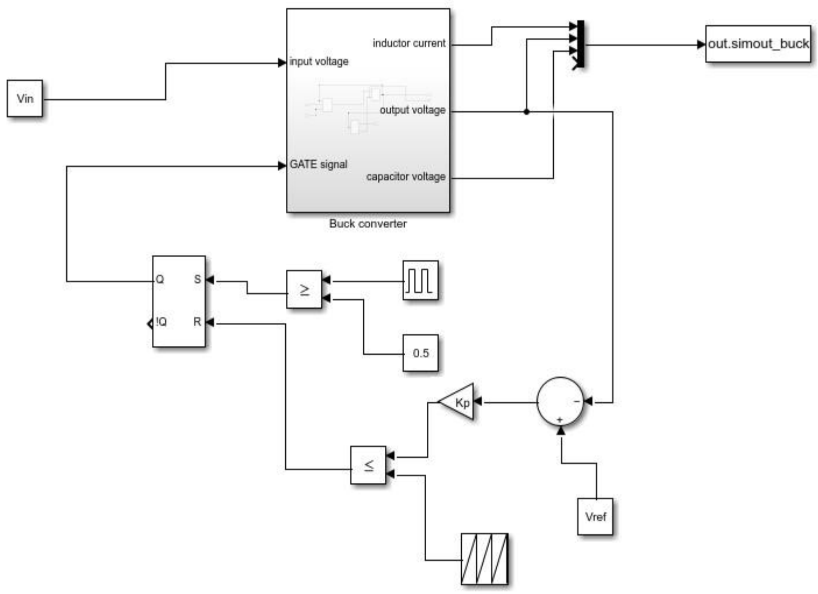

Figure 16: Converter with Voltage mode control

3.5.1. Response of Converter without Feedback to change in Input Voltage

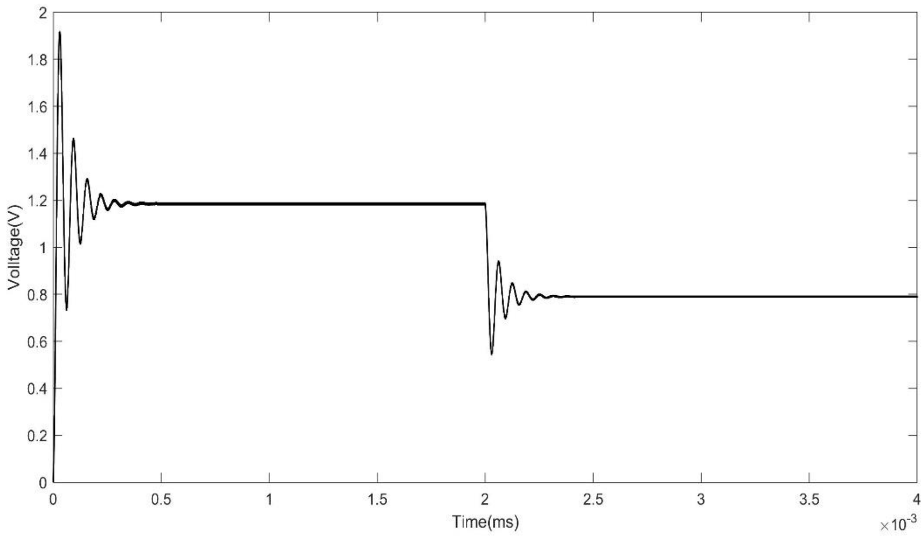

Figure 17: Response of converter for change in input voltage without feedback

Reference Voltage = 1.2V

Change in input voltage = 12V to 8V

3.5.2. Response of Converter with VMC to change in Input Voltage

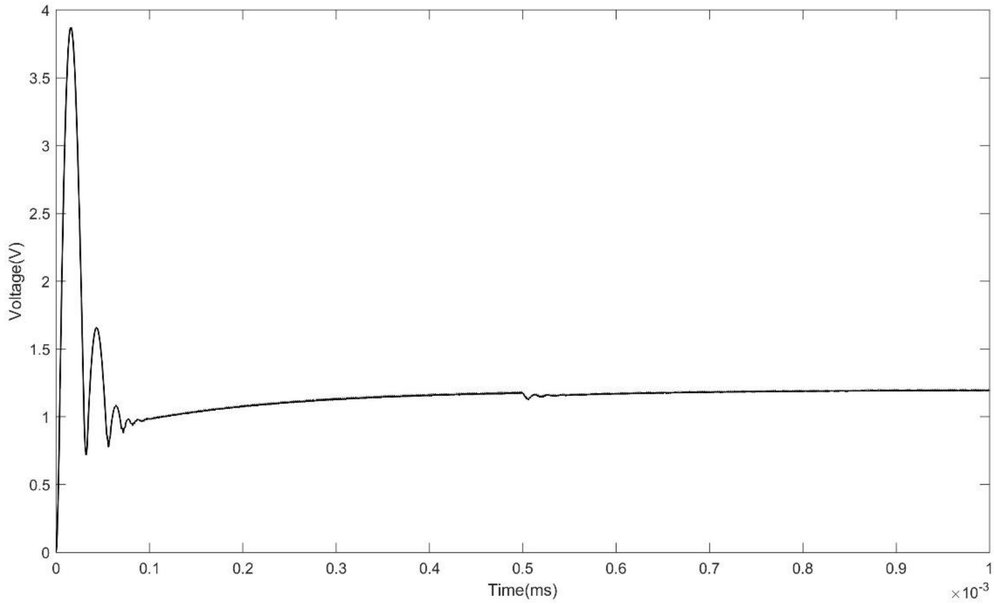

Figure 18: Converter with VMC response to change in input

When the input voltage changes from 12 to 6 volts, with reference voltage set at 1.2 V, we observe how the buck converter behaves with voltage mode control (VMC). The converter tries to maintain the output voltage at 1.2 V but there is initial volage spikes reaching up to 4V which is undesirable. This effect is during the start-up of the converter which can be avoided by using soft starter which is discussed below.

3.5.3. Converter with VMC and Soft Start

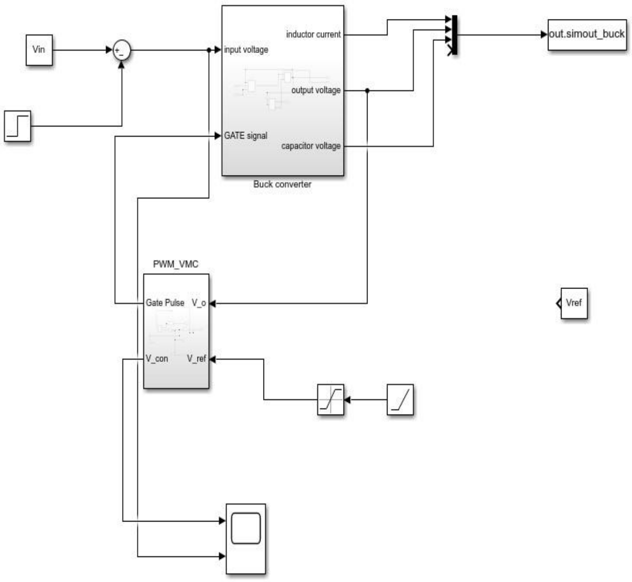

Figure 19: Converter with VMC and Soft Start

A soft-start feature starts with a low duty cycle and increases it gradually until it reaches the desired value. The rapid startup of power supply or sudden changes in input voltage causes inrush current and the overshoot of output voltage which damage the power supply. The soft-start control is used to suppress such negative effects [10].

Therefore, while VMC ensures precise voltage regulation, the absence of soft start may lead to transient problems and voltage overshooting at the startup, highlighting the importance of soft start.

3.5.4. Response of Converter with VMC and Soft Start to change in Input Voltage

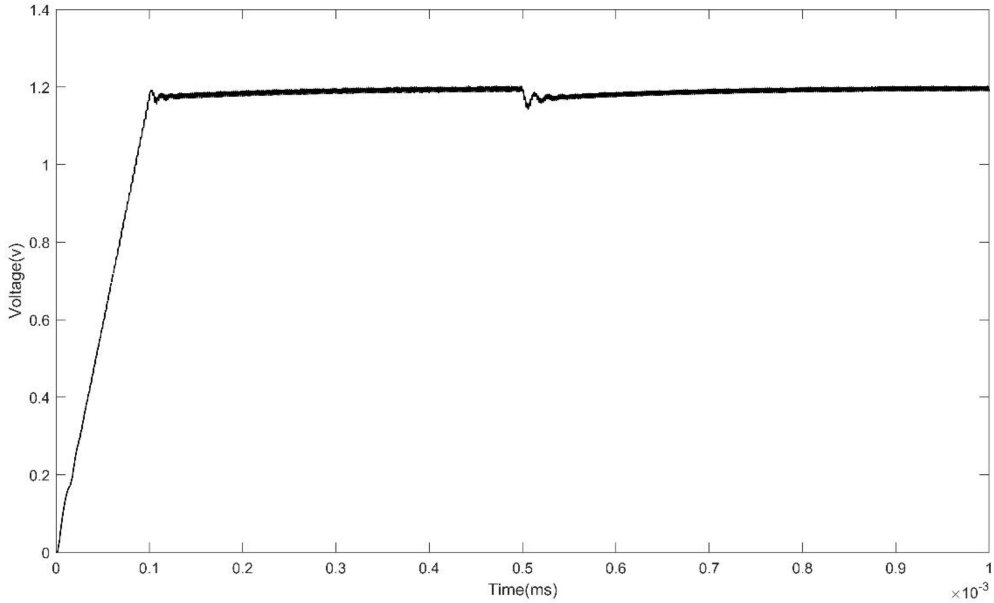

Figure 20: Converter response with VMC and soft start

3.5.5. Converter with VMC, Feedforward Control, and Soft Start

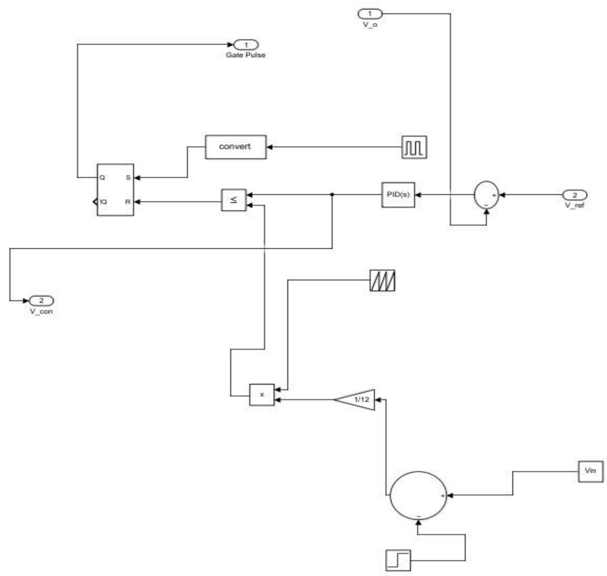

Figure 21: Converter with VMC, Feedforward Control and Soft Start

3.5.6. Response of Converter with VMC, Feedforward Control and Soft Start

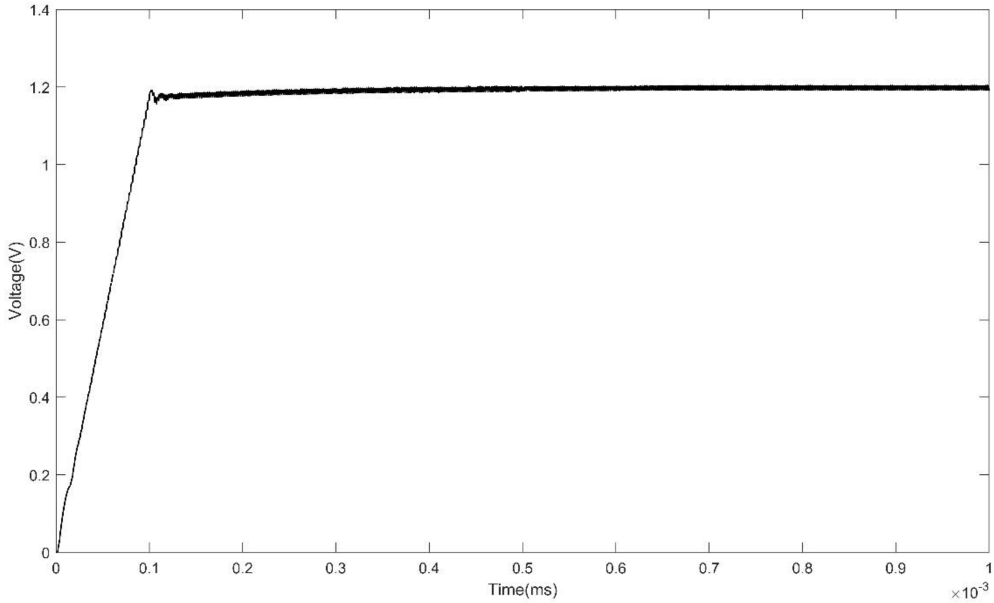

Figure 22: Converter response with VMC, Feedforward Control, and Soft Start

The above figure presents the response of a buck converter with VMC, feedforward control, and soft start functionality. The plot depicts the behavior of the converters output voltage over time, focusing on variations in reference voltage. With the inclusion of feedforward feedback and soft start features, the buck converter can dynamically adjust its parameters to maintain stable voltage regulation, even during startup or transient voltage changes. This analysis provides valuable insights into the performance of the buck converter under specific control conditions, aiding in its optimization.

3.6.Small Signal Model Validation

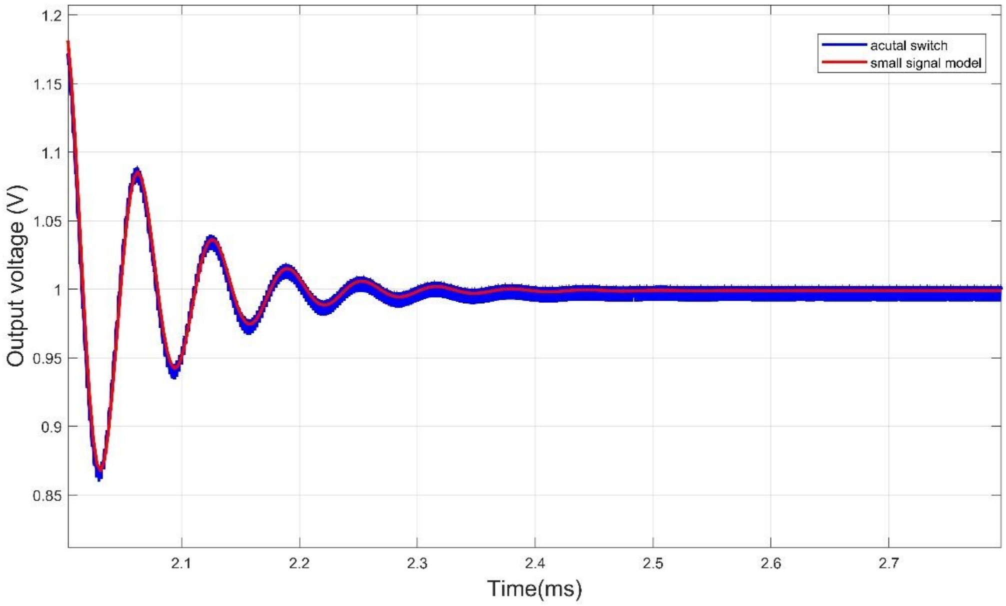

Figure 23: Output response of actual and small signal model

For Simulation Setup, Input Voltage: 6V, Reference Voltage: 1V

Both data sets $i.e.$ actual switch and small signal model exhibit similar output responses, indicating consistency between the actual switch simulation and the small signal model simulation. This consistency suggests that the small signal model is valid for the given operating conditions, where the input voltage is 6V and the reference voltage is 1V.

3.6.1. Small Signal Model under VMC

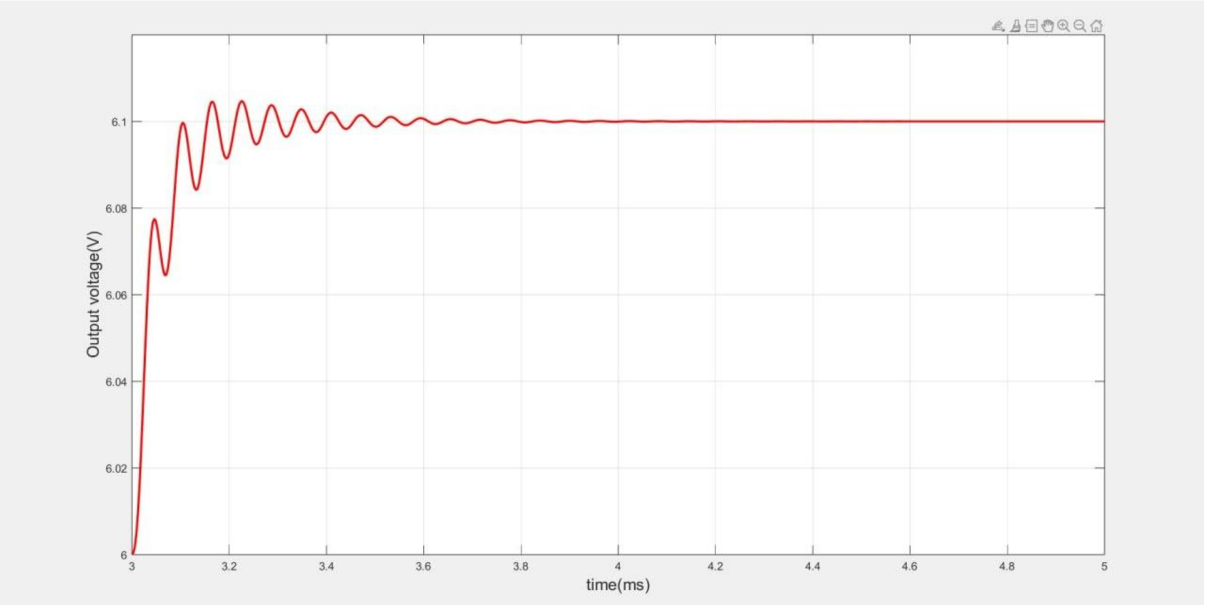

Figure 24: Output response of small signal model with VMC

Input voltage: 12V

Reference voltage: 6V

3.7. Bootstrap Circuit

The bootstrap circuit is used to generate a voltage higher than the input voltage to drive the high-side MOSFETs efficiently. In a four-switch synchronous buck-boost converter, there are typically two high-side MOSFETs (upper switches) that need to be driven. The bootstrap circuit typically consists of a bootstrap diode, a bootstrap capacitor, and a bootstrap resistor. When the lower switches turn off and the upper switches need to turn on, the bootstrap capacitor provides the necessary voltage to drive the high-side MOSFETs.

Gate resistors are used to control the switching speed of the MOSFETs and prevent ringing or oscillations. In a four-switch synchronous buck-boost converter, gate resistors are typically connected in series with the gate terminals of the MOSFETs.

3.7.1. Bootstrap Circuit Parameters Calculation

3.7.1.1. Bootstrap Capacitor

It provides a low impedance path to source the high peak currents to charge the high-side switch. This bootstrap capacitor should be sized to have enough energy to drive the gate of the high-side MOSFET without being depleted by more than 10%. This bootstrap capacitor is taken to be at least 100 times greater than the gate capacitance of the high-side FET. The reason for that is to allow for capacitance shift from DC bias and temperature, and also skipped cycles that occur during load transients. The gate capacitance can be determined using following equation:[11]

$$C_g = \frac{Q_g}{V_{Q_{1g}}}$$

Where, Q_g = gate charge = $62 * 10^{-9}C$ (MOSFET's datasheet)

$$V_{Q_{1g}} = V_{DD} - V_{BootDiode} = 12 - 0.7 = 11.3V$$

Where, $V_{BootDiode}$ = forward voltage drop across the boot diode

$$C_g = \frac{62 * 10^{-9}C}{11.3} = 5.48 * 10^{-9}F$$

Now, the minimum value for the bootstrap capacitor can be estimated using:

$$C_{Boot} \geq 100 * C_g \geq 100 * 5.48\, nF \geq 548nF$$

We take the value of the bootstrap capacitor to be $600nF$.

3.7.1.2.VDD Bypass Capacitor

The charge to replenish the bootstrap capacitor must come from some larger bypass capacitor, usually the VDD bypass capacitor. This bypass capacitor should be sized to be at least 10 times larger than the bootstrap capacitor so that it is not completely drained during the charging time of the bootstrap capacitor. This allows the bootstrap capacitor to be properly replenished during the charging sequence. This 10x ratio results in 10% maximum ripple on the VDD capacitor in worst case conditions.

$$C_{VDD} \geq 10 * C_{Boot} \geq 10 * 600nF \geq 6\mu F$$

3.7.1.3.Bootstrap Resistance

The role of the bootstrap resistor is to limit the peak currents at the bootstrap diode during start-up, it should therefore be carefully selected as it introduces a time constant with the bootstrap capacitor given by:

$$\tau = \frac{R_{Boot} * C_{Boot}}{Duty\ Cycle}$$

This time constant occuring during the high-side off time explains the dependency on duty cycle. This duty cycle being constant, the bootstrap resistor and bootstrap capacitor should be tuned appropriately to achieve the desired start-up time. Increasing the bootstrap resistor values will increase the time constant leading to slower start-up time.

3.8.Parameter Calculations of FSBB Converter:

Minimum and maximum input voltages, output voltage, output current, switching frequency, gate voltage of the switch, junction temperature, and ambient temperature are necessary design parameters. The relevant computations are performed after determining these values.

3.8.1. Duty Cycle

As the four-switch buck-boost converter can operate in both buck and boost modes, different duty cycles (D_{buck} and D_{boost}) are determined for each case according to (1) and (2). Here, V_{OUT} represents the output voltage, $V_{IN,max}$ represents the maximum input voltage, $V_{IN,min}$ represents the minimum input voltage, and η represents the estimated efficiency [12][13].

$$D_{buck} = \frac{V_{OUT}}{V_{IN,max} * \eta} = \frac{1.2}{12 * 0.93} = 10.75\%$$

$$D_{boost} = 1 - \frac{V_{IN,max} * \eta}{V_{OUT}} = 1 - \frac{12 * 0.85}{28} = 63.5\%$$

3.8.2. Inductance

3.8.2.1.Buck Mode

For buck mode the following equation is a good estimate for the right inductance:

$$L_{Buck} > \frac{V_{out} * (V_{in} - V_{out})}{K_{ind} * F_{SW} * V_{in} * I_{out}}$$

Where,

V_{in} = Input Voltage

V_{out} = Desired Output Voltage

K_{ind} = Estimated coefficient that represents the amount of inductor ripple current relative to the maximum output current. $(0.2 < K_{ind} < 0.4)$

F_{SW} = Switching frequency = $50{,}000Hz$

I_{out} = Desired Output Current = $4A$

$$L_{Buck} > \frac{1.2 * (12 - 1.2)}{0.2 * 50000 * 12 * 4}$$

$$\therefore L > 27\mu H$$

3.8.2.2.Boost Mode

For boost mode the following equation is a good estimate for the right inductance:

$$L_{Boost} > \frac{{V_{in}}^2 * (V_{out} - V_{in})}{K_{ind} * F_{SW} * I_{out} * {V_{out}}^2}$$

$$L_{Boost} > \frac{12^2 * (28 - 12)}{0.2 * 50000 * 4 * 28^2} > 73.5\mu H$$

The largest value of the inductance is given by the boost mode. Thus, we take the value of the inductance to be $100\ \mu H$.

3.8.3. Output Capacitance

3.8.3.1.Buck Mode

$$C_{Buck} = \frac{(K_{ind} * I_{out})^2 * L}{2 * V_{out} * \Delta V_{out}}$$

Where,

ΔV_{out} = desired output voltage change due to the overshoot $=$ 1% of the output voltage

$$C_{Buck} = \frac{(0.2 * 4)^2 * 100 * 10^{-6}}{2 * 1.2 * 0.012}$$

$$= 2.22mF$$

$$= 2220\mu F$$

3.8.3.2.Boost Mode

$$C_{Boost} = \frac{I_{out} * D_{boost}}{F_{SW} * \Delta V_{out}}$$

$$= \frac{4 * 0.635}{50000 * 0.28}$$

$$= 181.4\mu F$$

The largest value of the capacitance is given by the buck mode. Thus, we take the value of the capacitance to be $2000\ \mu F$.

3.9.Proteus and MATLAB Simulation

3.9.1. Flowchart

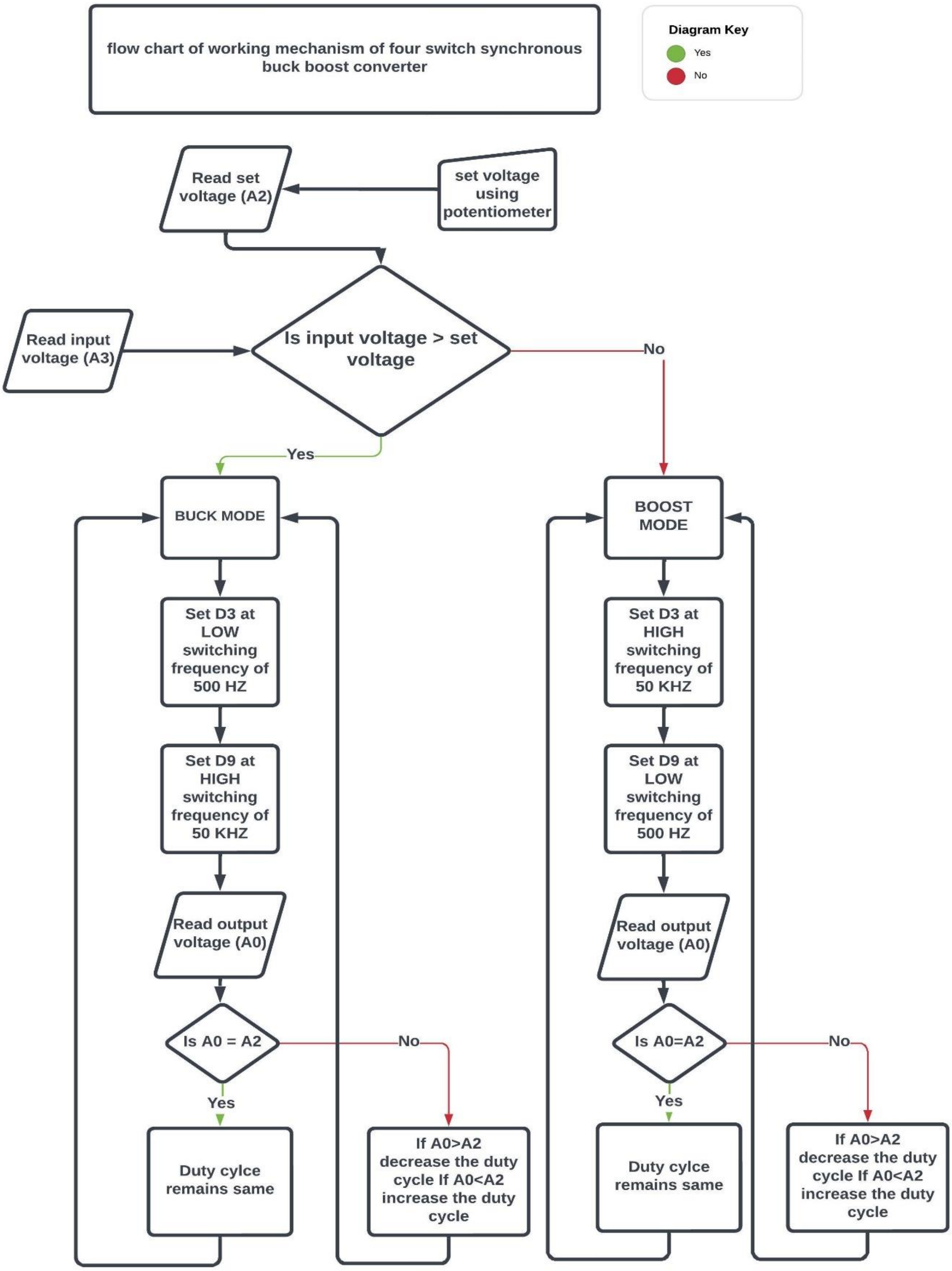

Figure 25: Flowchart

3.9.2. MATLAB Block Diagram of Four Switch Buck-Boost Converter

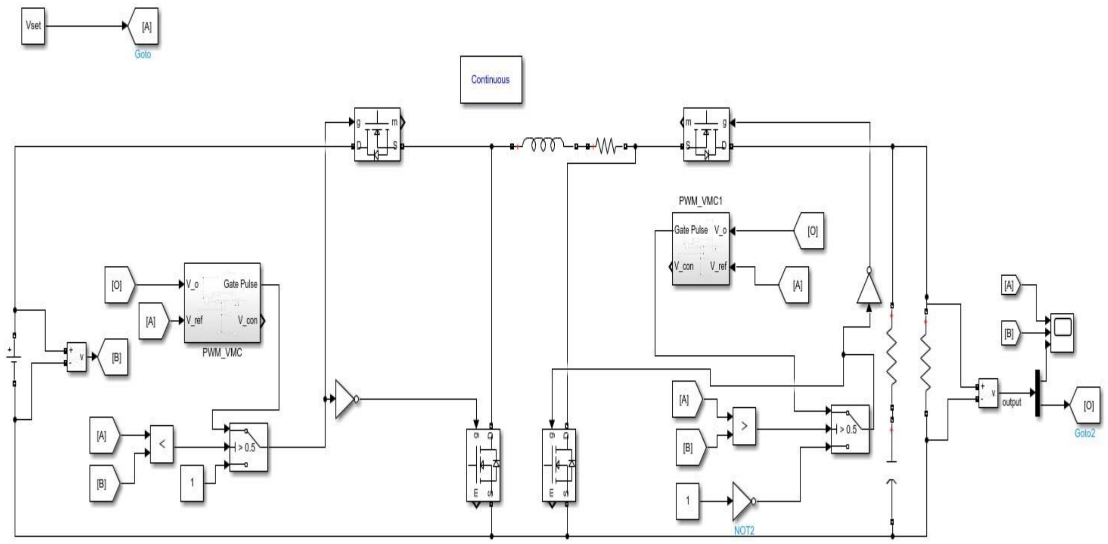

Figure 26: MATLAB Block Diagram of Four Switch Buck-Boost Converter

3.9.3. Driving a High Side MOSFET with 100% Duty Cycle

In a half-bridge configuration, the high input-voltage level prohibits the use of direct gate-drive circuits for a high side N-channel power MOSFET, thus requiring a bootstrap gate-driver technique. The bootstrap gate driver works like this: when the low-side MOSFET turns on, the switch node pulls to ground. A bootstrap capacitor is charged through a bootstrap resistor and bootstrap diode from the VDD power supply. When the low-side MOSFET turns off, the energy stored in the bootstrap capacitor becomes a floating bias for the high-side driving circuit, and is able to drive the high-side MOSFET.

This works fine if the high side never reaches a 100% duty cycle. However, in this multimode operation, when the converter works in the buck mode, Q4 needs to be fully on (100% duty cycle) and Q3 needs to be fully off. Then the bootstrap capacitor cannot be charged; therefore, there is no floating bias voltage for the high-side driving circuit and the high-side MOSFET cannot turn on. The same problem exists in the boost mode when Q1 needs to be on at a 100% duty cycle.

One solution to the buck-mode problem is to drive Q3 and Q4 with a very-low switching frequency (for example, 500 Hz) and drive Q3 with a very small duty cycle.

The turn-on time of Q3 will be just enough to charge the bootstrap capacitor to a certain voltage level, but Q3 will be otherwise off and Q4 will be on most of the time. The energy stored in the bootstrap capacitor will be able to keep Q4 on for a long period. Since Q3 only turns on (Q4 turns off) for a very short time (a few hundred nanoseconds), it won't cause any output voltage disturbance. Also, since Q3 and Q4 are running at such a low switching frequency, their switching losses are negligible. The same method is applied when the converter is in boost mode.

3.9.4. Cross Conduction Prevention

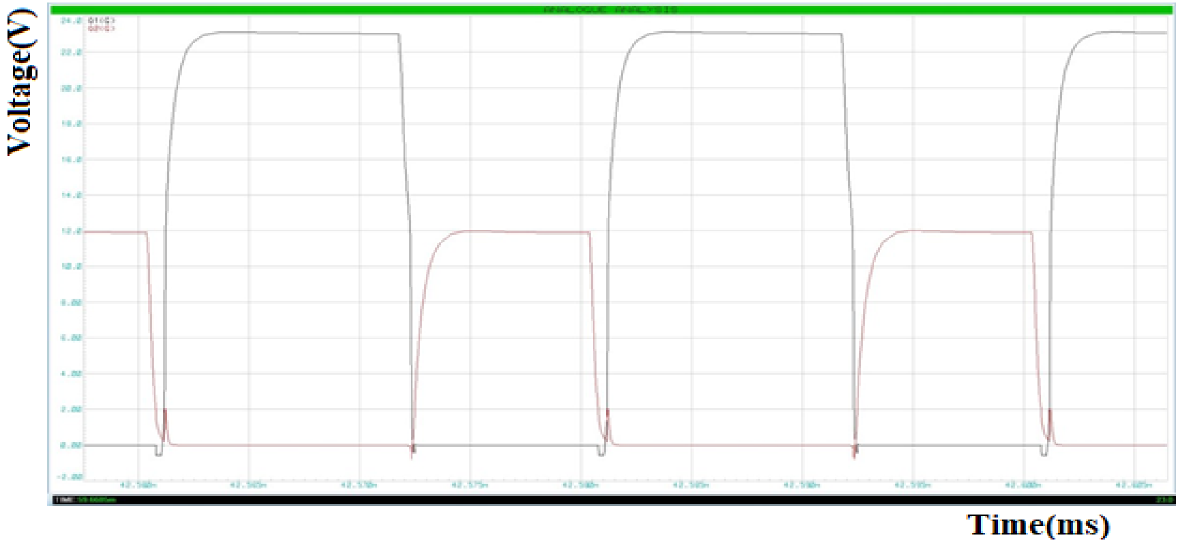

Figure 27: 50% Duty Cycle Operation

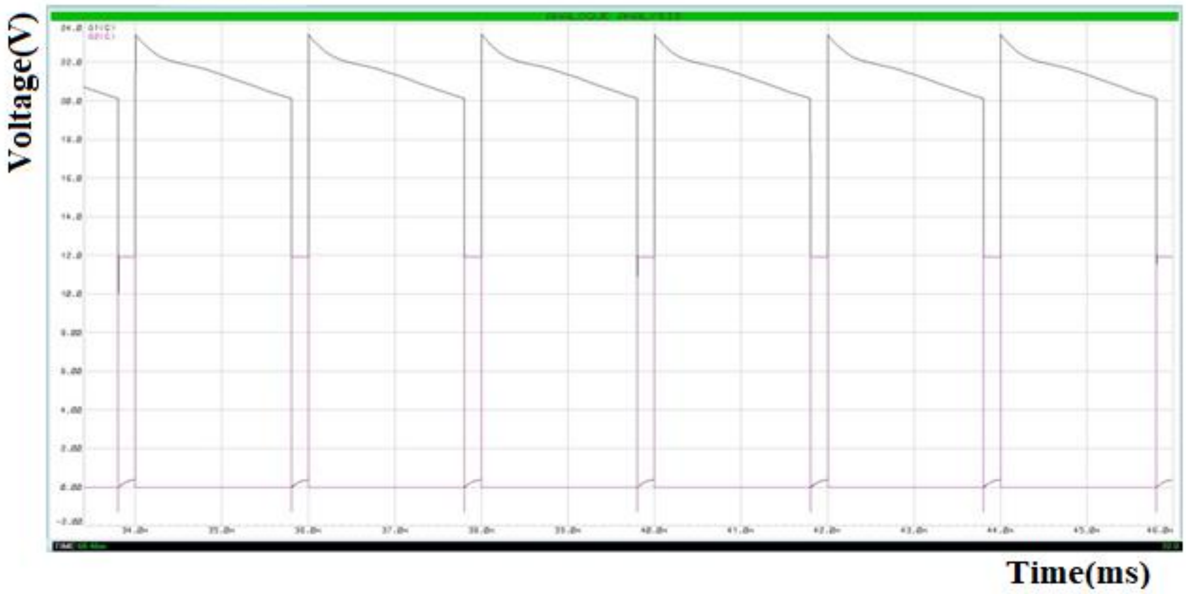

Figure 28: 90% Duty Cycle Operation

3.9.5. Proteus Simulation of Four-Switch Buck-Boost Converter

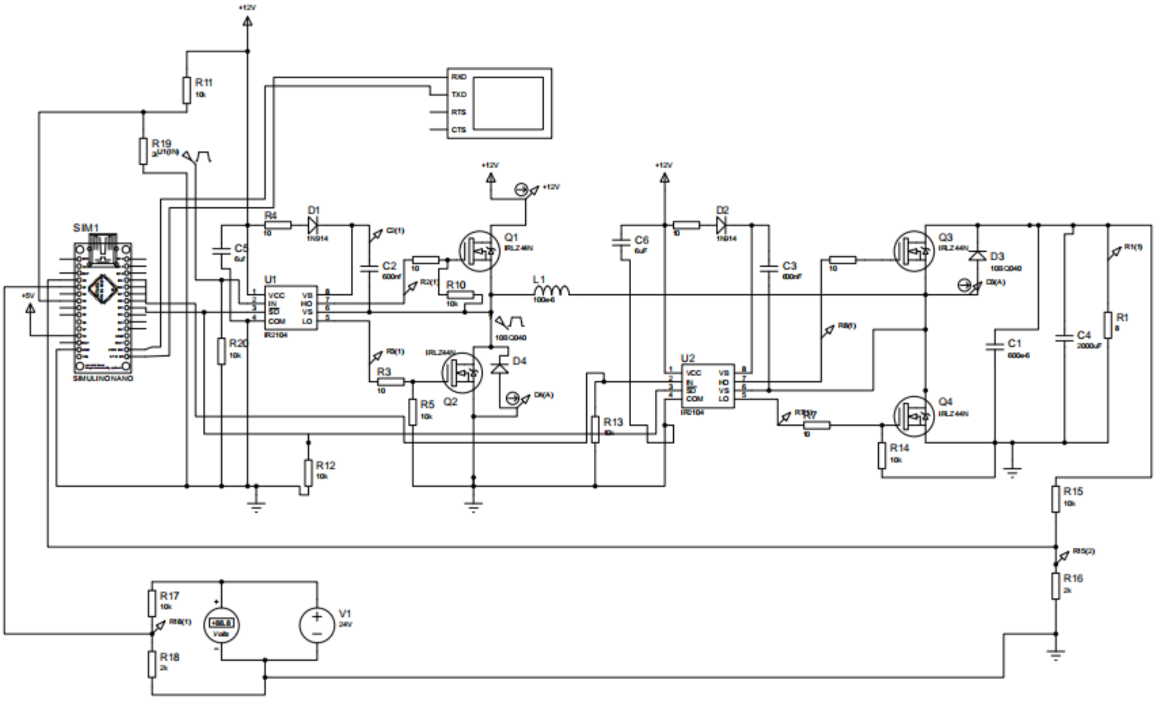

Figure 29: Proteus Simulation of FSBB Converter

3.9.5.1.Proteus Simulation for Buck Mode

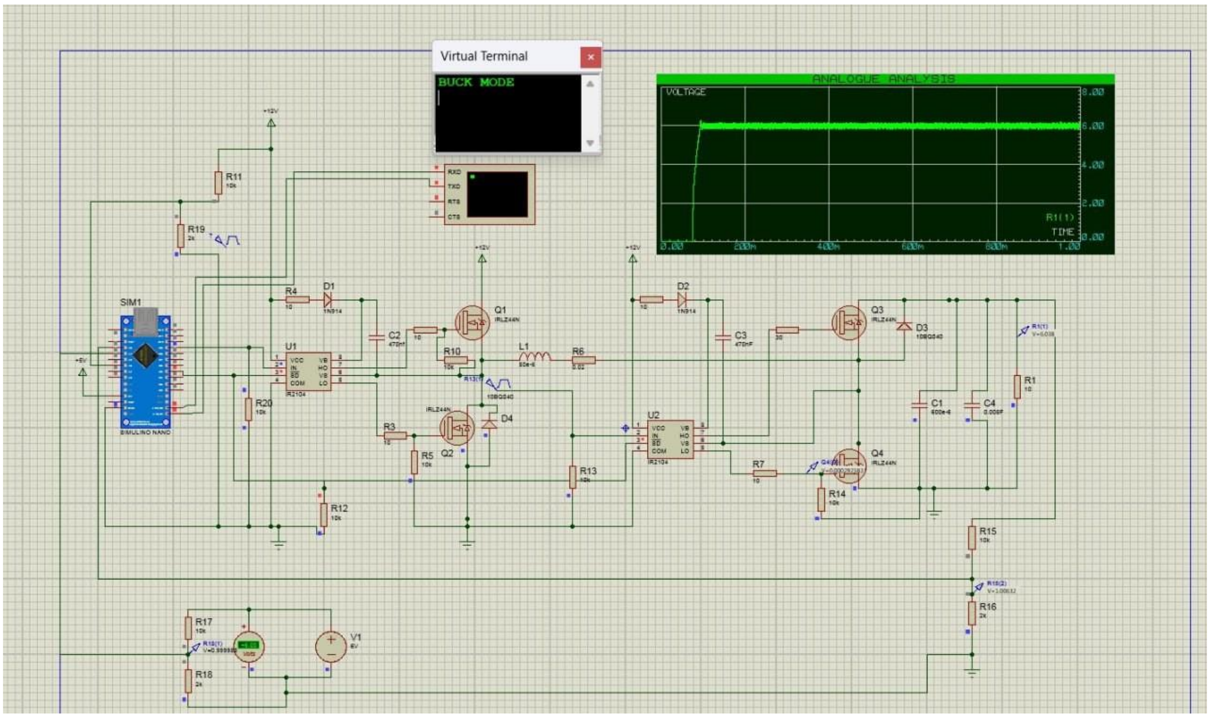

Figure 30: Converter in Buck Mode

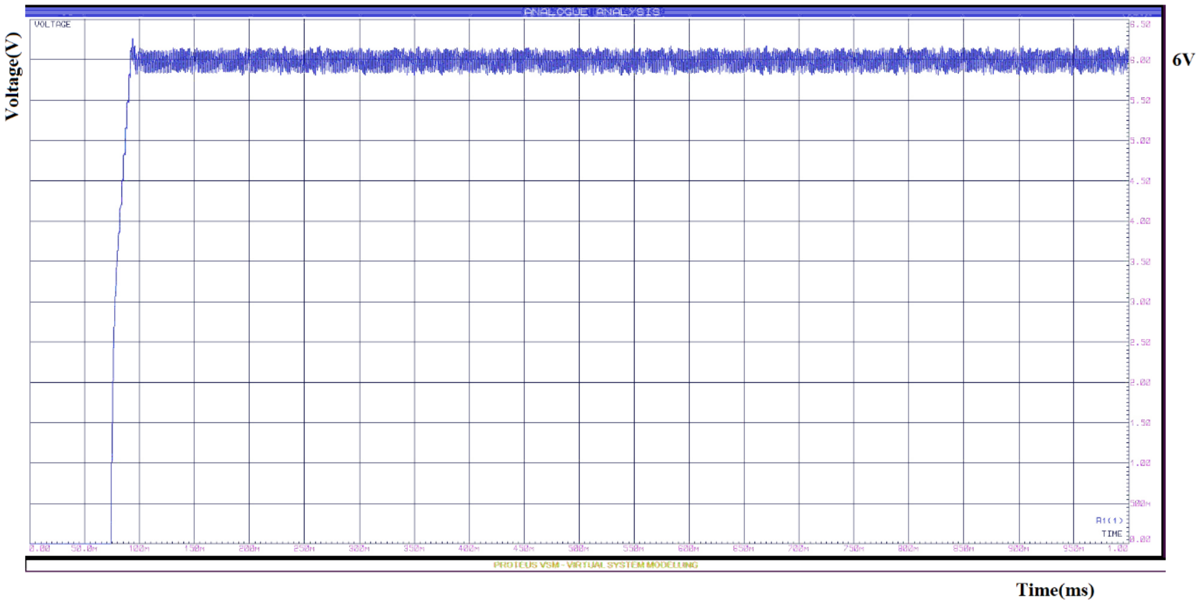

Figure 31: Waveform of Buck Mode

3.9.5.2.Proteus Simulation for Boost Mode

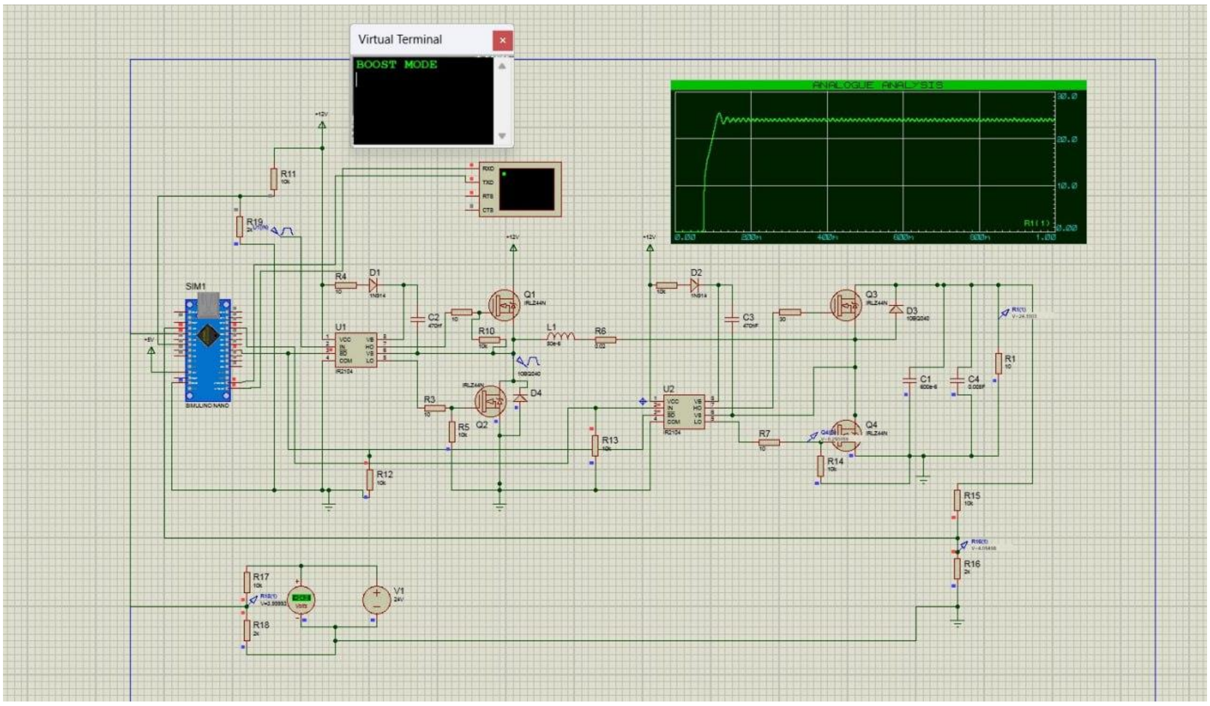

Figure 32: Converter in Boost Mode

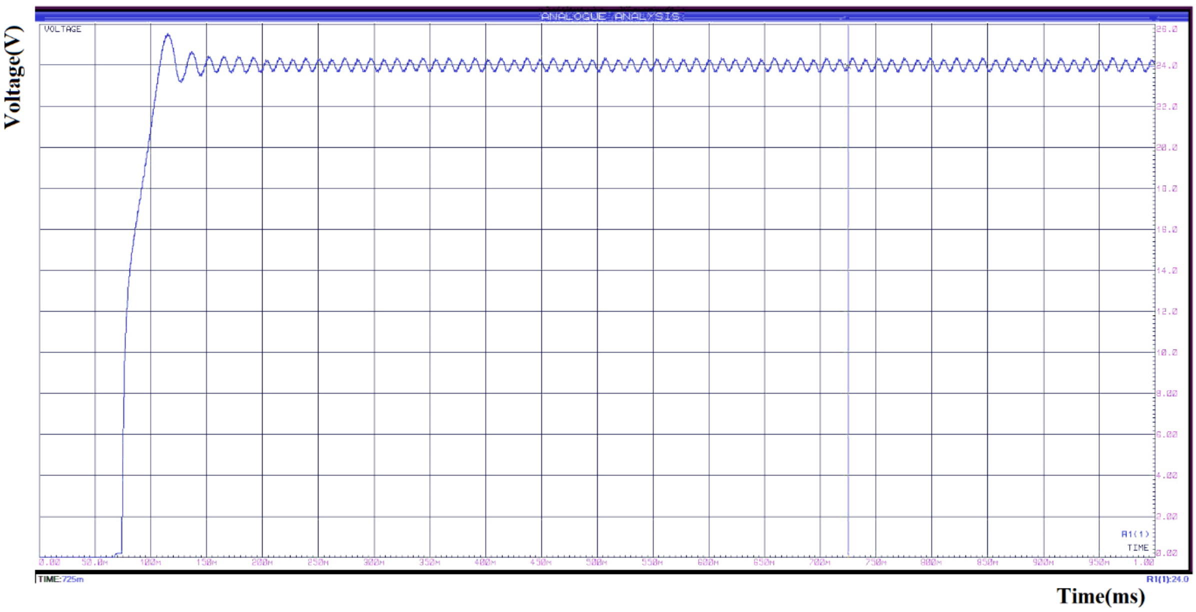

Figure 33: Waveform of Boost Mode

3.10. Efficiency of the Converter

$$Efficiency, \eta = \frac{V_{Out} * I_{Out}}{V_{In} * I_{In}}$$

3.10.1. Buck Mode

Table 1: Efficiency for Buck Mode Operation

Cases	Output Voltage (V_{Out})	Output Current (I_{Out})	Input Voltage (V_{In})	Input Current (I_{In})	Efficiency (η)
Case 1	5.90V	2.90A	12V	1.54A	92.5%
Case 2	5.82V	2.91A	12V	1.517A	93%
Case 3	8.78V	4.39A	12V	3.43A	93.5%
Case 4	1.005V	0.50A	12V	0.05A	83.75%

3.10.2. Boost Mode

Table 2: Efficiency for Boost Mode Operation

Cases	Output Voltage (V_{Out})	Output Current (I_{Out})	Input Voltage (V_{In})	Input Current (I_{In})	Efficiency (η)
Case 1	23.80V	3.12A	12V	6.95A	89.03%
Case 2	15.70V	1.57A	12V	2.40A	85.58%
Case 3	25.64V	2.58A	12V	6.30A	87.50%
Case 4	18.75V	1.86A	12V	3.35A	86.75%

Thus, we can conclude that during light load conditions, the efficiency of a four-switch buck-boost converter may decrease in comparison to its efficiency under heavy loaded conditions. It is because at light loads, the converter operates at lower power levels where fixed losses such as conduction and switching losses become a larger percentage of the total power transferred.

3.11. Hardware Implementation

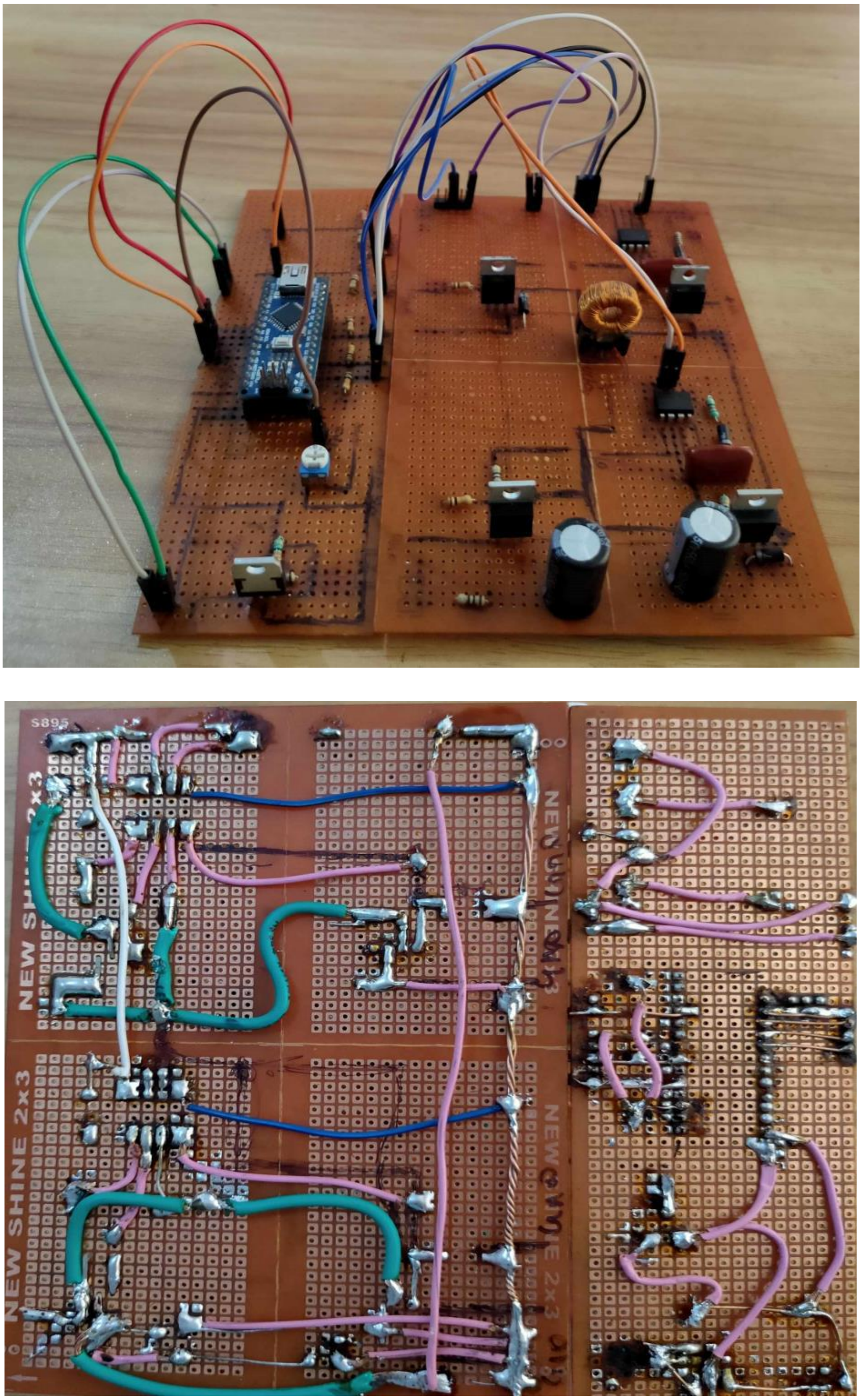

Figure 34: Hardware Prototype

CHAPTER FIVE: DISCUSSION AND CONCLUSION

In the domain of power electronics, the "Four Switch Synchronous Buck Boost Converter with Closed Loop Feedback" project is a prominent undertaking. The goal of this project is to develop, implement into practice, and assess a complex converter topology incorporating closed-loop feedback for precise control while combining the benefits of synchronous buck and boost converters.

In order to effectively step up or step down the input voltage as needed, this architecture uses four switches to control the output voltage or current. The four-switch configuration, in contrast to conventional converters, reduces switching losses and improves overall efficiency, which makes it especially appropriate for applications with frequent input voltage fluctuations. The converter has a closed-loop feedback system that is essential to its operation. The output voltage is continuously monitored by this system, and it is compared to a reference value. Control algorithms ensure fast correction of any divergence from the required output, ensuring accurate and stable regulation across a range of load scenarios. The closed loop feedback system helps to closely regulating the output parameters thereby enhancing reliability and performance.

Several design difficulties and challenges have been resolved during the course of the project. Every facet of the converter's design, from choosing the right parts to maximizing switching frequency and control schemes, is carefully investigated. High-frequency noise, component stress, and transient response are examples of challenges that have been identified and addressed via simulation-based optimizations and careful choice of design. The behavior of the converter is modeled and its performance under various operating situations is predicted through the extensive use of simulation tools. In addition, an experimental setup is designed to test the converter's performance in real-world scenarios.

The various simulations and experiment provide valuable insights into the converter's behavior and limitations. In the longer term, the project has the potential to open up new possibilities for future research and applications. The developed converter has the potential to find use in diverse applications where efficient power conversion is essential. Future research could include optimizing the converter design and control algorithms, as well as exploring new applications to take full advantage of the converter’s capabilities.

In conclusion, the "Four Switch Synchronous Buck Boost Converter with Closed Loop Feedback" project not only pushes the boundaries of power electronics but also provides students with essential skills in system design, simulation, and experimental validation. By addressing intricate engineering challenges and exploring innovative converter technology, this project effectively prepares students for successful careers in the dynamic and fulfilling field of electrical engineering.

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