STUDY ON TRANSFORMERLESS HIGH GAIN DC-DC CONVERTER

A thesis submitted in partial fulfilment of the requirements for the award of the degree of

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2024

DEDICATED
TO MY BELOVED FAMILY MEMBERS

CERTIFICATE

This is to certify that the thesis entitled **"STUDY ON TRANSFORMERLESS HIGH GAIN DC-DC CONVERTER"** has been carried out by **Mr. Supravat Saren (Class Roll No: 002210802024 and Registration No: 139719 of 2017 – 18)** under our guidance and supervision and accepted in partial fulfilment for the degree of Master of Engineering in Electrical Engineering from the Department of Electrical Engineering of Jadavpur University. To the best of our knowledge the content of this thesis or any parts thereof have not been previously submitted for the award of any degree or diploma.

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that this thesis "**Study on Transformerless High Gain DC-DC Converter**" contains literature survey and original research work by me, as a part of my Master of Engineering Degree in Electrical Engineering during the academic session 2022 – 2024. All information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by this rules and conduct. I also declare that, as required by this rules and conduct, I have fully cited and referred all material and results that are not original to this work.

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CERTIFICATE OF APPROVAL

*The foregoing thesis, entitled as "**Study on Transformerless High Gain DC-DC Converter**" is hereby approved by the committee of final examination for evaluation of the thesis as a creditable study of an engineering subject carried out and presented by Mr. Supravat Saren (Registration No: 139719 of 2017 – 18) in a manner satisfactory to warrant its acceptance as a prerequisite to the degree of Master of Engineering in Electrical Engineering. It is understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but approve the thesis only for the purpose for which it is submitted.*

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Full-Form
DC	Direct Current
AC	Alternating Current
PWM	Pulse-Width Modulation
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction Mode
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
IGBT	Insulated Gate Bipolar Transistor
HVDC	High Voltage Direct Current
SiC	Silicon Carbide
GaN	Gallium Nitride
PFC	Power Factor Correction
PV	Photo-Voltaic
VMC	Voltage Multiplier Cells
ZVS	Zero Voltage Switching
ESR	Equivalent Series Resistance
BJT	Bipolar Junction Transistor
CCBC	Conventional Cascade Bidirectional Buck/Boost Converter
ACLN	Active Coupled Inductor Network
ESR	Equivalent Series Resistance

ABSTRACT

Conventional DC–DC boost converters face significant limitations in achieving high step-up voltage gains due to the intrinsic effects of power switches, rectifier diodes, and the equivalent series resistance (ESR) of inductors and capacitors. This work presents a novel approach by proposing transformerless DC–DC converters designed to achieve high step-up voltage gains without extremely high duty ratios. In the proposed converters, two inductors with the same level of inductance are charged in parallel during the switch-on period and are discharged in series during the switch-off period.

A comprehensive study of essential parameters such as voltage gain, output power, efficiency, and voltage stress is conducted for comparative analysis of performance metrics. Finally, MATLAB simulation of proposed converter circuits have been performed to verify the performance. This research contributes to enhancing the efficiency of DC–DC converters in applications where high step-up voltage is crucial, ultimately promoting advancements in areas like renewable energy systems and electric power supplies.

Index Terms- DC–DC boost converter, high step-up voltage gain, transformerless.

CHAPTER – I

Introduction

1.1. Power Electronic Converter

The dynamic field of power electronics focuses on controlled, flexible, compact, clean, and efficient electrical energy conversion. Power devices and passive components like transformers, inductors, and capacitors are skillfully combined for conversion purposes. Converters utilize an assortment of electrical elements to perform conversion, with varying levels of complexity and sentences bursting forth accordingly.

Advancements in power semiconductors and solid-state devices with extremely high voltage and current ratings have greatly expanded potential applications of power electronic converters. These developments allow their application across an extraordinarily wide range of power levels, from remarkably low to impressively high power.

The primary classes of power electronic converters include:

1. AC to DC Converters (Rectifiers): These converters transform alternating current (AC) into direct current (DC).
2. DC to AC Converters (Inverters): These devices convert DC into AC.
3. AC to AC Converters: These converters change AC parameters such as voltage, frequency, or phase.
4. DC to DC Converters: These converters modify the DC voltage and current levels through the switching mode operation of semiconductor devices.

In power electronic converters, semiconductor devices function either in fully on or fully off state to control power flow to the load. The power semiconductor device manages high current with a small voltage drop across it when the switch is fully on. On the other hand, when the switch is off, the full voltage is across it and only a very small current is permitted. Due to their low power loss resulting from switching, power electronic converters are very efficient.

Power electronic converters have many benefits, such as increased efficiency from minimum power losses while switching and excellent reliability from the extended life of solid-state components. They require less maintenance as they have fewer moving parts and less mechanical wear. Power electronic converters can also react quickly to variations in load circumstances because of their quick dynamic responsiveness. Their smaller size and lower material use come from a lower weight and improved semiconductor technology. These converters are also efficient and economical.

Power electronic converters are essential components of many different applications

like industrial motor drives, electric cars, renewable energy systems (such solar and wind power), power supplies for electronic devices, and HVDC (High Voltage Direct Current) transmission systems. The development of wide bandgap materials like silicon carbide (SiC) and gallium nitride (GaN), among other developments in semiconductor technology has the potential for even higher efficiency, improved thermal management, and improved performance at high frequencies and voltages.
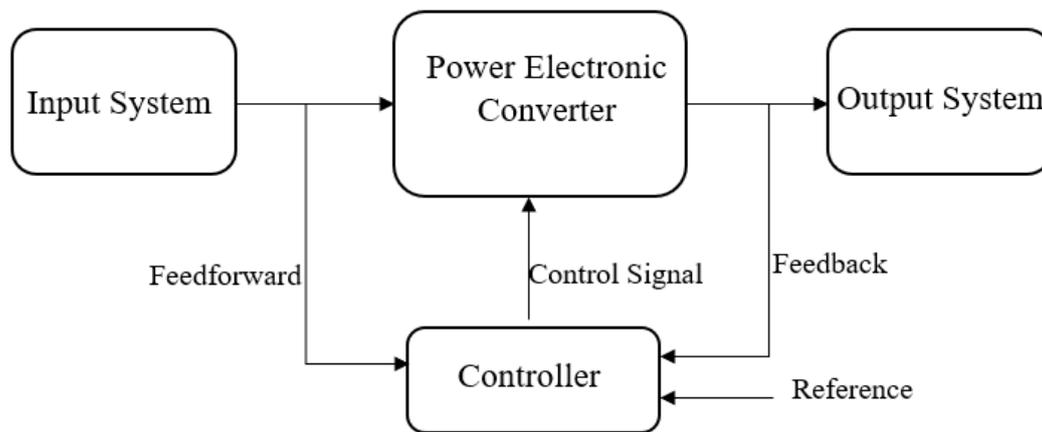
Figure 1.1: Block diagram of power electronic converter

Power electronic converters have a bright future because of ongoing innovation that aims to improve energy efficiency, lower carbon footprints and help in the world's shift to sustainable energy sources as technology progresses, these converters will play a crucial role in optimizing energy utilization and minimizing environmental impact and opening the way for a cleaner and more efficient energy landscape.

1.2. DC-DC Converters

DC-DC converters are electronic circuits that convert a source of direct current (DC) from one voltage level to another. Their main purpose is to adapt the input voltage from a power source to suit the voltage requirements of various components or devices.

There are several types of DC-DC converters, each serving different functions. A Buck Converter, also known as a step-down converter, reduces voltage while increasing current from its input to its output. Conversely, a Boost Converter increases voltage while decreasing current from its input to its output. The Buck-Boost Converter is versatile, capable of either

stepping up or stepping down voltage depending on the input and output requirements

The basic operation of a DC-DC converter involves a switching element that modulates the input current into a square wave, which can then be processed using inductors and capacitors to achieve either voltage stepping up or stepping down. The regulation of output voltage is maintained through closed feedback loops that adjust the operation of the converter based on changes in load current and input voltage.

Efficiency is crucial in the performance of DC-DC converters. Many converters can achieve efficiencies exceeding 90%. It is advisable to select a power source that can provide about 125% of the load power to accommodate inefficiencies. The efficiency is typically defined as the ratio of the output power to the input power expressed in percentage form.

DC-DC converters are widely used across various fields, including consumer electronics, automotive systems, and industrial applications. In smartphones, for example, they adjust the voltage output from lithium-ion batteries to the different voltage levels needed for various components like processors and displays. In solar photovoltaic systems, they optimize energy extraction by converting variable voltage outputs from solar panels to a stable voltage.
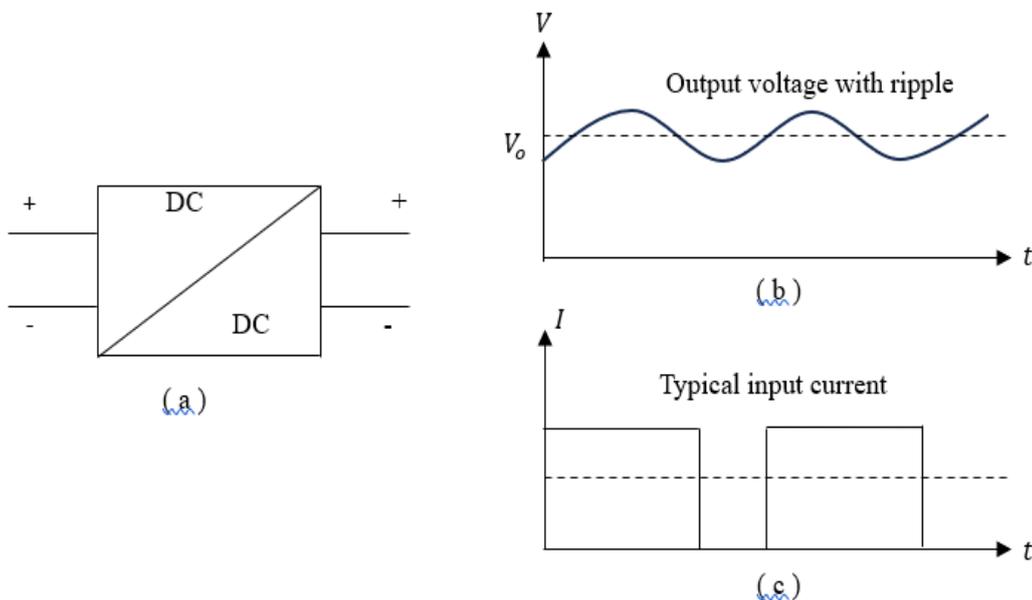
Figure 1.2: (a) *DC-DC converter,* (b) *DC-DC converter output voltage with ripple,* (c) *DC-DC typical input current*

One notable challenge with DC-DC converters is their potential to exhibit chaotic behavior under certain operating conditions, leading to unpredictable output voltages. Research is ongoing to better understand this phenomenon and develop control strategies that enhance the stability and reliability of these devices.

Common components in DC-DC converters include the switching element, typically a transistor that controls current flow within the circuit, the inductor, which stores energy in a magnetic field during the conversion process, and the capacitor, which smooths out the voltage output and filters out unwanted AC components. These components work together to achieve the desired voltage transformation, demonstrating the complexity and sophistication involved in DC-DC converter designs.

1.3. The Need for High Boost Ratio in DC-DC Converters

In various applications, DC-DC converters with high voltage gain are crucial, particularly when no isolation is required. To attain the necessary output voltage, series connections or voltage boosters are frequently used for renewable energy sources like fuel cells and solar cells, which frequently provide low output voltages. High step-up gain, high efficiency, and non-isolation are essential characteristics for these applications. As simple boost converters usually cannot efficiently meet the demands, different topologies are used to achieve this voltage gain.

High boost ratio DC-DC converters exhibit several key characteristics to meet the demands of modern electronic applications. These include high step-up gain, which significantly increases the input voltage, and high efficiency. All these characteristics maximizes energy conversion and minimizes loss. Non-isolation is preferred to simplify the design and reduce costs. These converters must be cost-effective and have a compact size and weight to facilitate easy integration into various systems.

Conventional boost converters face several challenges when attempting to achieve a high boost ratio. One major issue is the high duty cycle requirement, as the duty ratio (D) increases to achieve higher voltage gain and the efficiency of the converter decreases. This reduced efficiency is compounded by practical issues such as parasitic ringing which causes additional voltage stress on the components. High voltage stress on switches makes the use of components with high blocking voltage ratings, and the higher rating power loss increases. Moreover, MOSFETs with higher blocking voltages usually have larger on-resistances, which contributes to even more power loss.

Conventional boost converters suffer from the reverse recovery problem where the output

diode's reverse recovery issue becomes problematic at higher duty cycles. Due to this reason conduction loss increases and overall efficiency of the converter reduce. These challenges show the limitations of traditional boost converters for achieving the desired high voltage gain.

High boost ratio DC-DC converters are essential for applications requiring significant voltage gain from low input voltages, such as renewable energy systems. To address the limitations of conventional boost converters, innovative topologies and design improvements are necessary. These enhancements can ensure high efficiency, reduced voltage stress, and compact, cost-effective solutions for modern electronic applications. By overcoming these challenges, high boost ratio DC-DC converters can effectively meet the needs of various applications, particularly in the domain of renewable energy.

1.4. Voltage Stress on DC-DC Converter

Voltage stress is crucial for DC-DC converters since it directly affects the efficiency, performance, and dependability of the system. High voltage stress causes higher heat dissipation and consequent power losses, and as a result difficulties arrive in thermal management and lower overall efficiency. High voltage stress may accelerate semiconductor component deterioration and leading to early failure and higher maintenance costs. For converters to function well and retain long-term durability, voltage stress must be appropriately managed.

Reducing voltage stress in DC-DC converters is important as it allows the use of components with lower voltage ratings and it can be more cost-effective and reduce the overall system's cost. Reduced voltage stress also minimizes the possibility of thermal stress and dielectric failure. It also increases the life and reliability of the components. It also enables the application of sophisticated methods like soft switching, which can improve performance even further by reducing losses during switching events. All things considered, maintaining low voltage stress is the key to creating a DC-DC converter to make it more efficient, dependable, and reasonably priced.

1.5. Transformerless DC-DC Converter

Transformerless DC to DC converters are crucial in applications where high voltage gain is required without the need for isolation. These converters are particularly valuable in systems where efficiency, size, weight, and cost are critical considerations. Renewable energy systems, such as photovoltaic and fuel cells, often necessitate high voltage gain from a low input voltage, making transformerless designs highly advantageous.

The primary purpose of transformerless DC-to-DC converter design is to achieve a more compact, cost-effective, and efficient power supply solution compared to traditional transformer-based converters. Some key reasons for using transformerless converters include:

Compactness and Size Reduction: Removing the bulky transformer allows transformerless converters to have a much smaller physical footprint. This makes them more suitable for applications with space constraints, such as portable electronics and embedded systems.

Cost Effectiveness: Transformerless converters require fewer components, which reduces the overall manufacturing cost. This makes them a more affordable power supply solution compared to transformer-based designs.

Improved Efficiency: Eliminating the transformer losses allows transformerless converters to achieve higher power conversion efficiencies, especially in low power applications. This is particularly beneficial for battery-powered devices where efficient power usage is crucial.

Weight Reduction: The absence of a transformer significantly reduces the overall weight of the power supply. This is advantageous for portable devices where weight is an important factor.

In summary, transformerless DC-DC converter design offers a more compact, cost-effective, and efficient power supply solution compared to traditional transformer-based approaches, making it well-suited for a variety of low-power electronic applications.

1.6. Pulse Width Modulation (PWM)

In electrical systems, pulse-width modulation, or PWM, is a modulation technique that adjusts the pulse signal's width to control the average power delivered to a load. PWM is very useful for effectively regulating motor speed, light brightness, and audio amplifier output. They are commonly found in specialized PWM controller integrated circuits (ICs) and microcontrollers.

PWM Generation:

A comparator is used to create a signal that modulates pulse width. One component of the comparator's input is the modulating signal, while the other component is either a sawtooth wave or a non-sinusoidal wave. The comparator creates an output waveform of a PWM signal after comparing two signals.

One possible output of a monostable multivibrator is a PWM signal. When an external trigger is applied, a monostable multivibrator will only produce one output pulse and have one stable state. An operational amplifier comparator can be used to build a monostable multivibrator circuit.
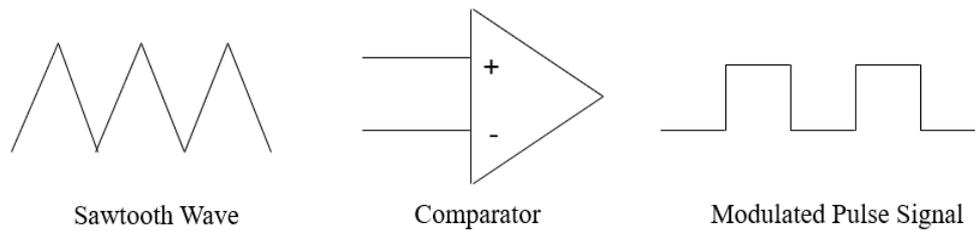
Figure 1.3: PWM Generation

One portion of the input to the comparator is structured by the modulating signal, and the other portion is wave formed non-sinusoidally. After analyzing two signals, the comparator generates a PWM signal as the output waveform. The output is in a "High" condition when the sawtooth or non-sinusoidal signal exceeds the modulating signal.

The output signal is in a "High" condition if the sawtooth signal exceeds the modulating signal. The comparator output, which establishes the pulse width produced at the output, is determined by the magnitude value.

Duty Cycle of PWM:

The fraction of a second that a signal or system is operational is called a duty cycle. A duty cycle is usually expressed as a percentage or ratio. The amount of time a signal takes to complete an ON-OFF cycle is called a period.

$$D = \frac{t_{on}}{T}$$

The proportion of time a digital signal is on throughout a period of time or interval is precisely described by the percentage duty cycle. The waveform's time is equal to its inverse frequency.
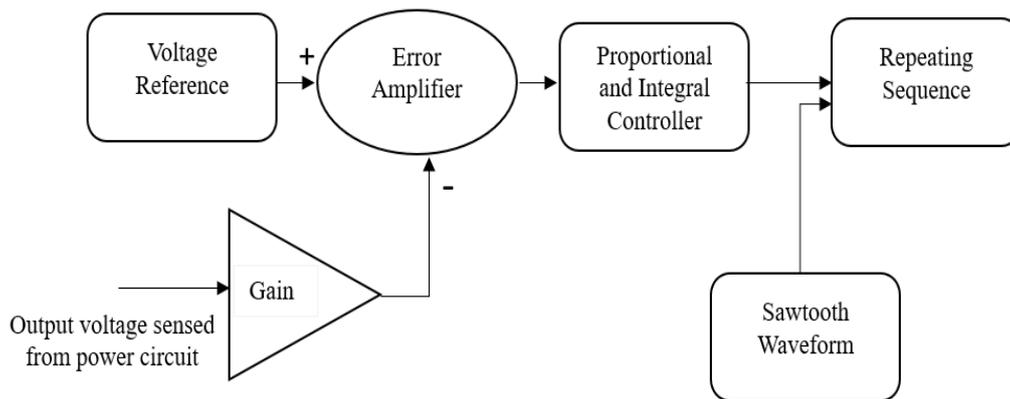
Figure 1.4: Block Diagram of PWM controller

1.7. CCM & DCM

Definitions of CCM and DCM: Continuous Conduction Mode (CCM) is characterized by the inductor current remaining above zero throughout the entire switching cycle, ensuring that it flows constantly. This mode ensures a stable, fixed frequency operation and smooth output voltage and current, which is critical for applications requiring consistent performance.

Discontinuous Conduction Mode (DCM), on the other hand, occurs when the inductor current drops to zero before the end of the switching cycle. In this mode, there are periods when current is not flowing through the inductor, leading to a less stable output and can cause underdamped oscillations.

Behavior of Inductor Current: In CCM, the inductor current never fully collapses; it ramps back up from a non-zero value, which minimizes current ripple and provides a more constant output voltage. This behavior aids in achieving better efficiency and reliability, especially under varying load conditions.

Conversely, in DCM, the inductor current completely collapses to zero, resulting in an off-state for connected components like the diode and MOSFET. This mode is typically observed under light load conditions where the current demand is insufficient to maintain continuous conduction.

Advantages and Disadvantages: The advantages of CCM include reduced ripple, improved voltage stability, and better performance under varying load scenarios. However, it requires a more complex control circuit to manage the continuous current flow effectively,

which can add design complexity.

DCM offers some benefits such as simplified control and generally easier stability compared to CCM. However, it presents challenges such as increased output ripple and reduced efficiency at higher loads due to the necessity for the inductor to handle high peak currents.

Applications of Each Mode: CCM is ideal for applications demanding stable power delivery and is generally preferred where load currents can vary significantly. It serves well in scenarios such as power supplies for sensitive electronics, where output consistency is critical.

On the other hand, DCM is suitable for applications where the load is relatively constant, as well as under conditions where power efficiency is a key concern. It is often utilized in flyback converters and other circuits that operate under low load conditions, where energy conservation is prioritized.

CHAPTER – II

Literature Review

2.1. Literature Survey

Literature Survey Related to DC-DC Converter with High Duty Ratio

Bryant *et al.* [1]

The creation of small-signal transfer functions for boost PWM DC–DC converters operating in continuous-conduction mode (CCM) is studied in this paper. Using a normalized linear circuit small-signal model, the study generates transfer functions from input voltage to output voltage (Mv), output current to output voltage (Zo), and duty cycle to output voltage (Tp). The study highlights the effect of MOSFET delay on high-frequency performance and loop stability by incorporating it using a first-order Padé approximation. The theoretical accuracy of these transfer functions is validated experimentally using Bode plots and step responses. These validations are required for constructing controllers for both voltage-mode and current-mode control of PWM converters. According to the findings, Zo is necessary to figure out closed-loop output impedance, Tp for analysing the voltage loop, and Mv to evaluate closed-loop audio susceptibility. The transfer functions and approaches discussed here are relevant for optimizing switch-mode power supply because they may be applied to various converter topologies.

Lu *et al.* [2]

A novel boost converter operating in continuous-conduction mode (CCM) designed to reduce reverse-recovery and switching losses is introduced in this paper. This is accomplished by reducing the turn-off rates (di/dt) of the boost output and additional rectifiers, hence lowering reverse-recovery loss, and by utilizing the leakage inductances of connected inductors. To further reduce switching loss, the boost power transistor is further adjusted to function in a low-voltage turn-on condition. Theoretical analysis is supported by experimental data, which also show improved performance of the converter at 200-W output power. By implementing a clamping rectifier, the design also safely eliminates transient spikes and parasitic ringing during switch turn-on. Power factor correction (PFC) applications can benefit greatly from the boost converter because its modifications and underlying concepts can also be applied to other non-isolated converter topologies including buck, buck–boost, and Cuk.

Shalini *et al.* [3]

This paper presents a novel single-switch DC–DC converter designed to achieve high voltage gain and low voltage stress, specifically for photovoltaic applications. The converter achieves a high step-up conversion ratio without the need for an exceptionally high duty ratio

or high turns ratio through the use of coupled-inductor and switched-capacitor approaches. The approach reduces conduction losses by decreasing voltage stress on the primary switch with a passive clamp circuit, while simultaneously achieving significant voltage gain through parallel charging and series discharging of capacitors. Further improving efficiency is the use of a linked inductor, which also solves the diode's reverse-recovery issue. The proposed converter's working principles, steady-state behaviour, voltage gain, and voltage stressors are all thoroughly examined in this paper. MATLAB Simulink simulations are used to evaluate the design, showing that the converter can attain a maximum output power of 300 W, a 24 V input, and an output of 400 V. The converter's capability to recycle the energy of the leaking inductor and improve power-conversion efficiency is confirmed by the results, which makes it suitable for energy storage systems, smart grids, and solar applications.

Mohamed *et al.* [4]

This paper introduces a novel single-switch non-isolated DC-DC converter that has been developed specifically for photovoltaic (PV) applications. It is designed to provide high voltage transfer gain with low semiconductor voltage stress. By merging a boost converter and a quadratic boost converter, this high-gain converter may achieve substantial voltage gain at moderate duty cycles while preserving low voltage stress across the switch and diodes. The utilization of lower voltage, low R_{DS-ON} MOSFETs is made possible by the reduced switch voltage stress, which lowers costs and reduces switch conduction and turn-on losses. Schottky rectifiers can also be used when there is less voltage stress on the diodes. This lowers reverse-recovery current and further reduces switching and conduction losses, which enhances thermal management. The converter's single non-floating power switches enable simple PWM control of the output voltage. The converter's power density is increased through the integration of both inductors on a single core. The operation principle is explained, the proposed topology is compared to previous high step-up converters, and simulation and experimental results are presented to support the design's efficacy.

2.1.2. Literature Review Related to DC-DC Converter without High Duty Ratio

Yang *et al.* [5]

This paper addresses the limitations of conventional DC–DC boost converters, which struggle to provide high step-up voltage gains due to inherent constraints such as power switch effects, rectifier diodes, and equivalent series resistance in inductors and capacitors. The authors propose innovative transformer-less DC–DC converters designed to achieve

high step-up voltage gains without requiring an excessively high duty ratio. These converters utilize a simple structure with two inductors of equal inductance, which are charged in parallel during the switch-on period and discharged in series during the switch-off period. This design not only simplifies the converter architecture by using a single power stage but also reduces the voltage stress on the active switch, allowing the use of switches with lower voltage ratings and lower ON-state resistance levels (R_{DS-ON}). The study includes a detailed steady-state analysis of voltage gains and boundary operating conditions. Experimental validation is provided through a 40-W prototype circuit, confirming the theoretical claims of achieving high step-up voltage gain. The comparative analysis illustrates the superior performance of the proposed converters over traditional boost converters

P. *et al.* [6]

This paper introduces a bidirectional DC-DC converter that provides high voltage gain and efficiency, designed for interfacing storage systems in various applications. This converter has symmetrical working modes, integrated soft-switching during switch turn-on, and the ability to step up (boost) or step down (buck) voltage in one direction. The system is small as it uses a single linked inductor for both modes and a clamped capacitor network to recover leakage energy. Even at high voltage gain, the converter reaches a peak efficiency of 94.5 percent, achieving a voltage gain of 10 in boost mode and 1/10 in buck mode. A 500W prototype was used for experimental validation, which showed reduced switching and conduction losses, lessened voltage stress on switches, and simplified closed-loop control. On the other hand, the absence of galvanic isolation is mentioned as a disadvantage. High-power applications where high system voltages and storage integration are necessary, like microgrids, standalone renewable energy systems, and drive systems, are best suited for the proposed converter.

Lakshmi *et al.* [7]

A non-isolated DC–DC converter that is intended to generate high voltage gain without the need of hybrid switched capacitor techniques or voltage multiplier cells (VMC) has been introduced here. Two non-isolated inductors are used in this converter; they are connected in parallel or series for the charging and discharging modes, respectively. The operation of three switches with two different duty ratios, which permits large voltage gain without extreme duty ratios, is the original feature of this design. A 100W, 20/200V prototype circuit was designed and tested; it showed low voltage stress on the diodes and switches and a high efficiency of 93.6% at full load. The experimental results, which demonstrated just a 2.5% change in output voltage under open loop conditions, closely matched theoretical

predictions. According to the article, adding a closed-loop control approach will stabilize the output even more, which makes the converter ideal for DC microgrid applications that need to integrate low-voltage renewable energy sources efficiently.

Zhang *et al.* [8]

A novel bidirectional DC-DC converter designed to achieve wide voltage gain and reduced voltage stress on power switches through the use of a coupled inductor has been mentioned here. The low current ripple design of the proposed converter reduces input/output current ripple and removes the need for larger filters. Having a similar ground structure stops more du/dt problems. The converter's highest efficiency of 94.2% was attained using a 400W/300V prototype. Fuel cell sources and DC buses in fuel cell vehicles can interact with the design, which minimizes switching losses and enables zero-voltage-switching (ZVS) for some power switches. However, the converter has drawbacks, like the inability to soft switch all switches, higher current stress on some switches, and excessive duty cycle operation when voltage gain is less than four. Future studies seek to resolve these flaws.

Liu *et al.* [9]

In order to improve sustainable energy systems, an innovative high step-up DC-DC converter using an active coupled-inductor network (ACLN) is presented in the study by Liu and Li (2015). This converter uses two switches and combines two connected inductors into a single magnetic core. These inductors' secondary sides discharge in series with the source of input to produce a high step-up voltage gain that is adjustable by a suitable duty ratio, while their primary sides are charged in parallel by the input source. By utilizing leakage energy, a passive lossless clamped circuit increases efficiency and reduces high voltage spikes that strain the primary switches. Leakage inductance additionally helps in resolving the output diode's reverse-recovery issue, which results in an overall enhanced power conversion efficiency with fewer components. Key waveforms, a thorough formulation of the steady-state operation concept, and an analysis of the voltage conversion ratio taking parasitic characteristics and leakage inductance into account are all provided in this study. The suggested converter is compared with conventional converters, and the strains that voltage and current place on power equipment are demonstrated. The advantages of the converter, such as its high voltage gain with smaller magnetic size, lower cost due to fewer components, and its ability to use low-voltage power switches to reduce on-state resistance and losses, are verified by the experimental results from a 200W prototype circuit, which show good agreement with theoretical analysis.

Wu *et al.* [10]

In their 2021 paper, Wu and Ke introduce a novel bidirectional isolated DC-DC converter that boasts high voltage gain and a wide input voltage range, aimed at bidirectional power conversion systems. By combining a forward-flyback converter and a bidirectional buck-boost converter, this novel architecture delivers numerous advantages like increased voltage gain and continuous current characteristics in both step-up and step-down modes. Leakage inductance energy recovery features are an important improvement to the design. These features improve efficiency by lowering voltage spikes on switches and enabling zero voltage switching (ZVS) on select switches. A 500-W prototype is used to verify the viability as well as effectiveness of the suggested converter. For low-side voltages of 24V, 48V, and 55V, respectively, the prototype achieves maximum efficiencies of 94.2%, 95.6%, and 96.9% in step-up mode and 92.6%, 94.2%, and 94.5% in step-down mode. The authors list several advantages of their topology, including lower design and development costs, increased safety, continuous current ripple on the low voltage side that lessens battery burden during energy transmission, higher voltage gain with galvanic isolation suitable for applications like electric scooter batteries, and the elimination of the need for specific converters for different battery voltages. The study demonstrates the high conversion efficiency and potential to decrease power conversion losses of the suggested converter and validates its viability both theoretically and experimentally.

Silveira *et al.* [11]

In their 2014 publication, Silveira et al. explain a non-isolated DC-DC boost converter that may be applied to motor drives, split-capacitor inverters, uninterruptible power supply (UPS), and renewable energy systems since it produces balanced output voltage with substantial voltage gain. Utilizing the 3-State Switching Cell (3SSC), the suggested topology guarantees balanced output voltage even in the presence of unbalanced load conditions. The authors discuss the design process, present an experimental prototype to show the viability, and provide both quantitative and qualitative analysis. The performance of this prototype is in line with theoretical predictions, especially when it involves efficiency, waveforms, current and voltage stress on semiconductor elements, and static gain curves. The converter is noteworthy because it reduces the voltage stress on active switches, allowing the use of less expensive switches and increasing overall efficiency. As the magnetic components operate at twice the switching frequency, the design benefits from smaller size and volume, and efficiencies exceeding 92% over the entire load range. The converter's usefulness in preserving voltage balance in output capacitors is supported by experimental results, which

also show how well it works in a variety of high-performance power conversion settings.

Andrade *et al.* [12]

This article shows a novel hybrid DC-DC converter that is especially designed for distributed photovoltaic (PV) generating systems. Because PV sources have a low voltage, these systems usually need major step-up converters. By combining coupled-inductor and switched capacitor approaches with the standard boost converter, the suggested converter creates a hybrid design that can achieve high voltage gain and efficiency with just one switch and doesn't require large duty cycle values. The components' stress from voltage and current is substantially reduced by this novel topology. A 200 W prototype has been evaluated experimentally, and outcomes showed a maximum efficiency of 97.6% at 40 V input voltage and 50 W output power, and 94% under nominal power parameters (30 V input, 400 V output, 200 W output power). Through an extensive CSF analysis, the converter's high efficiency and minimal component stress are further guaranteed. The converter's compatibility for power conversion in low-voltage renewable energy applications, especially distributed PV generation systems, is demonstrated by these results, which are backed by both theoretical and experimental analyses. The converter provides a high-efficiency, low-complexity solution with reduced operational stresses.

Mirzaee *et al.* [13]

In this paper, an advanced high step-up DC-DC converter optimized for renewable energy applications has been introduced. This converter is suitable for renewable energy sources because it uses a linked inductor design to provide ultra-high voltage gain and continuous input current with minimal ripple. The converter's clamped circuit is a crucial component that prevents voltage spikes during the active switch's turn-off operation, permitting the adoption of low R_{DS-on} switches to lower conduction losses and total costs. Zero voltage switching (ZVS) is made possible for both main and auxiliary switches by using the energy from leakage inductance, which raises efficiency and lowers switching losses. Additionally, the reverse-recovery problem with the output diode is resolved by the regulated dropping rate of the output diode current, which is made practicable by the leakage inductance. The research presents a comprehensive steady-state analysis and design considerations that confirm the theoretical performance promises through experimental validation using a 250 W prototype. The proposed structure shows better voltage gain and less voltage stress on switches when compared to conventional high step-up converters, highlighting its effectiveness and affordability for renewable energy systems.

Cao *et al.* [14]

This paper addresses the challenge of integrating low-voltage outputs from non-polluting resources such as fuel cells and photovoltaic panels into conventional systems. In the article headed "A Novel Nonisolated Ultra-High-Voltage-Gain DC–DC Converter with Low Voltage Stress," The problem of incorporating low-voltage outputs from non-polluting resources like fuel cells and solar panels into conventional systems is addressed by Y. Cao, V. Samavatian, K. Kaskani, and H. Eshraghi. The study highlights the need for a high voltage gain, low input voltage handling, and efficient DC-DC converter. The authors propose a brand-new, ultra-high voltage gain DC-DC converter combining a circuit for a voltage doubler with a circuit for a switched capacitor. To enhance performance in low-voltage applications, this novel technique seeks to maintain high efficiency and low voltage stress throughout the switching components. In addition to providing a thorough efficiency analysis, the research describes the converter's operation modes, including continuous and discontinuous conduction. The converter's capabilities have been confirmed by experimental findings from a 250 W prototype with a 400 V output, which demonstrate notable gains in performance and efficiency even with a higher component count. Because of its high voltage ratio and efficiency, this converter is especially well-suited for use with fuel cell stacks and solar panels. Therefore, by enhancing DC-DC converter technology for low-voltage, high-efficiency applications, the research presents a significant achievement in the field.

Hassan *et al.* [15]

This work highlights a new high voltage gain DC–DC converter that is especially intended for use in renewable energy applications. With low voltage stress and great efficiency, the recommended converter achieves an ultra-high step-up voltage gain by strategically integrating coupled-inductor and switched-capacitor approaches. With the use of a symmetrical voltage multiplier network, a passive clamp circuit, and a voltage boost unit, the converter's architecture enables modularity and extendibility without the need for further windings. This design is essential for dependable operation since it not only lessens the voltage stress on the primary switch but also keeps it constant throughout the duty cycle. In addition, the coupled inductor's leakage inductance reduces the problems associated with diode reverse recovery. With experimental data indicating a peak efficiency of 96.70%, the report presents a thorough investigation of the converter's working principle and steady-state performance. The converter is especially well-suited for DC nanogrid applications due to its capacity to maintain low voltage stress and high efficiency. The report also suggests incorporating the interleaved approach to improve power capacity and reduce ripples in voltage and current for higher power needs. By offering an acceptable approach for high

step-up voltage conversion with superior performance metrics, this work advances the area.

Ardi *et al.* [16]

This paper proposed a non-isolated bidirectional DC-DC converter designed to achieve high voltage gain. Two boost converters, four power switches with integrated body diodes, two inductors, a capacitor, and four power switches are used by the converter. In step-up mode, this configuration produces a higher voltage gain than conventional cascaded bidirectional buck/boost converters (CCBC); in step-down mode, however, the voltage gain is smaller. When compared to the CCBC, the suggested converter gets praise for its higher efficiency and less complicated control structure, even if the active switches experience similar amounts of stress. The converter's efficiency and device stress are compared to those of the CCBC in this paper's detailed steady-state analysis. A prototype circuit that works at 250 V for the high side and 25 V for the low side illustrates the practical application of the converter. The impact of synchronous rectification is also evaluated theoretically and experimentally in the study, showing the viability and efficiency of the suggested converter in delivering high voltage gain with less complexity.

Literature Survey Related to Transformerless DC-DC Converters

Denniston *et al.* [17]

The authors of this paper examined an innovative approach to achieving high voltage gains in offshore wind technology. Traditional techniques usually depend on large, complex transformers and expensive, ineffective high-voltage AC-DC converters. To minimize semiconductor conduction losses and do away with the necessity for transformers, the authors propose using several modules of single-switch single-inductor DC-DC converters. With voltage gains of up to 29 p.u., their low-voltage prototype experimental results emphasize the approach's promise for high-gain DC-DC conversion in offshore wind applications. In order to demonstrate the advantages of the suggested multiple-module approach which includes fewer devices, comparable isolation levels, and ease of interleaving for increased reliability—the study compares it to traditional high-voltage DC converters and theoretical full-bridge converters. The authors anticipate improved performance at greater power levels and a reduction in the consequences of diode reverse recovery due to developments in high-voltage SiC technology. They come to the conclusion that the multiple-module method is especially well-suited for high-power offshore wind energy applications because it has several advantages over standard HVDC systems, such as fewer device counts, more reliability, and better device ratings.

Andrade *et al.* [18]

In the publication a novel transformer-less DC-DC converter that combines switched capacitor cells and a voltage multiplier with a two-inductor boost converter has been shown. By using each component's unique capabilities, this hybrid technique minimizes voltage and current stresses on the converter's components while achieving a high voltage gain. A laboratory prototype of the suggested design, rated at 200 W and operating at 37.4 V/400 V and 100 kHz, displays outstanding effectiveness and operational simplicity, with a maximum efficiency of 98.24%. The boost converter's architecture can be enhanced by the incorporation of switched capacitor cells and a voltage multiplier. This minimizes component stress and keeps the converter's efficiency high throughout a wide range of input power levels. The efficiency, simple use, and good stress management of this hybrid converter make it a good choice for high-voltage gain applications, the report says.

Banaei *et al.* [19]

The authors of this paper defined a new transformer-less buck–boost DC–DC converter that outperforms other common converters like boost, buck-boost, CUK, SEPIC, and ZETA in terms of voltage gain. Through the use of a single power switch, this novel converter minimizes development complexity and lowers voltage stress across the switch, allowing lower on-state resistance switches to be used to reduce conduction losses and increase overall efficiency. The research illustrates the advantages of the converter in terms of simplicity and controllability by providing a thorough explanation of its working principle and mathematical analysis. The converter's high voltage gain and efficiency have been verified by experimental findings, which justify its performance. Applications requiring high efficiency and simplicity, like fuel-cell systems, notebooks, mobile phones, automotive electronics, and LED drivers, are the most appropriate for the suggested buck-boost converter.

Elsayad *et al.* [20]

The article presents a brand-new bidirectional buck-boost converter that can handle both buck and boost functions in either direction of the power flow. The converter makes use of no transformer. With a wide voltage gain range and a simple design with few components, this converter lessens the voltage stress on the power transistors. Zero-voltage switching (ZVS), made possible by synchronous rectification between complementary transistors, increases efficiency. With a focus on continuous conduction mode (CCM) performance, this research offers a comprehensive analysis of the converter's small-signal model, component parameter design, efficiency, and steady-state operation. A 1.6 kW prototype using Silicon Carbide (SiC) MOSFETs is presented to validate the converter's effectiveness and feasibility.

Applications requiring wide conversion ratios and bidirectional power flow, like energy storage systems, EVs, microgrids, and uninterruptible power supply, are ideally suited for the suggested design.

Saadatizadeh *et al.* [21]

In the paper introduces a novel DC-DC converter designed to achieve high voltage gain while maintaining low voltage stresses on switches and diodes. One notable feature of the proposed converter is that it does not use connected inductors and transformers, which usually cause design difficulties and elevated component stress. Rather, it uses a design in which two switches enable two inductors to charge for an extended amount of time, allowing for substantial voltage gain without the need for extraordinarily high-duty cycles. Due to the converter's architecture, fewer power circuit components are needed and the voltage pressures on semiconductor elements are reduced, enabling the use of less expensive, lower-rated components. The performance of the converter, including voltage gain, element stress, input current ripple, and efficiency, is thoroughly theoretically evaluated in this study. A 12V/380V, 520-W prototype is employed for experimental validation, showing real-world performance consistent with theoretical predictions. Because of its less complex design and less stressed components, the suggested converter performs better and is more economical when compared to existing high voltage gain boost converters.

Young *et al.* [21]

This paper describes a new high step-up DC-DC converter that works by using a Cockcroft-Walton (CW) voltage multiplier in place of a step-up transformer. By reducing voltage stress on switches, diodes, and capacitors, and ensuring continuous input current with minimal ripple, this design enables the converter to achieve large voltage gains. The suggested converter may supply a steady DC supply for an n + 1-level multilevel inverter and is particularly appropriate for low-input-level DC generation systems. The two different frequencies used in the control technique explained in the paper are a high frequency for inductor size reduction and a lower frequency for output voltage ripple management. The performance of the converter has been verified by simulation and experimental results on a 200-W prototype. According to the results of the research, the CW voltage multiplier-based converter provides a dependable and beneficial solution for high step-up applications by making it easier to manage component stress while reaching high voltage ratios.

Gupta *et al.* [22]

J. Gupta, R. Kushwaha, and B. Singh present a novel bridgeless switched inductor Cuk (BSIC) converter in their 2021 paper, which aims to improve efficiency and lower expenses

for chargers for light-duty vehicles (LEVs). compared with conventional chargers, which frequently need more converters in order to charge low-voltage batteries (24–72 V), the BSIC converter can achieve a significant step-down voltage gain in just one stage and does so without the use of a transformer. By using a discontinuous current mode, this solution not only reduces the size and cost of the magnetic components but also lowers the number of sensors needed. An 850 W laboratory prototype that has been evaluated with a 220V. 50 Hz supply voltage is shown in the paper. It shows improved power quality with a higher power factor, decreased total harmonic distortion, and increased efficiency. The converter's benefits over current LEV chargers are additionally discussed in the article, including its reduced cost, smaller size, and easier control, which make it an appealing choice for high-performance, transformerless charging applications.

2.2. Objective of the Present Work

In context to the literature review as mentioned in the section 2.1 this work is consideration of a numerical analysis on transformerless DC-DC converters in order to achieve the high gain at the output and also a comparative study on voltage gain, output power, efficiency and voltage stress of three proposed transformerless converters with simple boost converter for different duty ratio. The results will possibly unlock a new avenue for preparing and utilizing the proposed converters in innovative and demanding applications, contributing to the advancement across multiple industries.

In context to the above, it is worth to mention that the traditional trial and error based experimental approaches have encountered many difficulties in order to understand the basics of voltage gain, and the effect of duty ratio on other parameters like voltage and current of inductor(s), capacitor(s) and diode(s). This work, thus, considered a numerical study on transformerless high gain DC-DC converter. The study involves:

1. Study the relationship between voltage gain and duty ratio in a proposed converter to estimate the output voltage at different duty ratio.

2. Create mathematical models of proposed converters for MATLAB simulation to analyze the behavior and performance of the converters under varying duty ratio.

3. Validate the simulation results with experimental data to ensure the accuracy and reliability of the models.

4. Examine and compare the voltage gain, output power and voltage stress of the simple boost converter with the three proposed transformerless converters.

2.3. Layout of Thesis

Chapter − I: Introduction

Chapter − II: Literature Rivew

Chapter − III: Proposed Converters and Simulation Output

Chapter − IV: Comparison study based on simulation results

Chapter − V: Conclusion

2.4. Closure

The present chapter enlightened the literature review related to transformerless DC-DC converter, high voltage gain with high duty ratio, high voltage gain without high duty ratio, and the numerical and mathematical modelling. The objective of the work is also discussed in details and the layout of the whole thesis is done briefly.

CHAPTER – III

Proposed Converters and Simulation Output

3.1. Simple Boost Converter

3.1.1. Introduction

 The boost converter is a DC-to-DC converter designed to perform the step-up conversion of applied DC input. In the Boost converter, the supplied fixed DC input is boosted to adjustable DC output voltage. Output voltage of boost converter is always greater than the input voltage. So, a Boost converter is also called a step-up converter or step-up chopper. It is given the name "boost" because the obtained output voltage is higher than the supplied input voltage. It performs the reverse operation of the buck converter which converts higher DC input into lower DC output.

 The boost converter is used to step up an input voltage to some higher level as per the requirement of the load. This step-up conversion in the boost converter is achieved by storing energy in the inductor and releasing it to the load at a higher voltage. Boost converters are widely used in battery-powered devices where perhaps a pair of batteries deliver 3V but need to supply a 5V circuit.

As we know, the product of voltage and current results in power, the increase in voltage at the output of the boost converter means a decrease in the output current through the circuit.

There are at least two semiconductors (such as a diode and transistor) and at least one energy storage element (such as an inductor or capacitor or both). Other semiconductor devices like power MOSFET, power BJT, IGBT, etc. are used as a switch in boost converter circuits. Thyristors are not used generally for DC-to-DC converters because another external communication circuit is required when using thyristors.
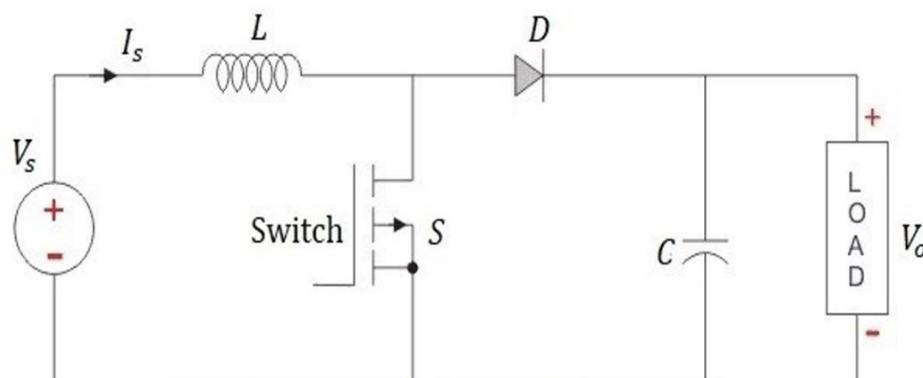
Figure 3.1: Circuit diagram of simple boost converter

3.1.2. Operating principle

The operation of the boost converter is based on the principle of storing energy in an inductor. The voltage drop across an inductor is proportional to the change in the electric current flowing through the device. The circuit arrangement operates in such a way that it helps in maintaining a regulated and increased dc output at the load.

In this circuit, the solid-state device such as power MOSFET which operates as a switch is connected across the source. A diode is used as a second switch. The diode is connected to the capacitor and the load. The capacitor and load are connected in parallel as shown in the above circuit diagram. The inductor is connected in series with the supply voltage source which leads to a constant input current so the boost converter acts as a constant current input source and loads act as a constant voltage source.

The controlled switch S is turned on and off by using PWM (Pulse Width Modulation). PWM can be time-based or frequency based. Time-based Modulation is mostly used for Boost Converter because it is simple to construct and use. The frequency remains constant in this type of PWM modulation. Whereas Frequency-based modulation has a wide range of frequencies to achieve the desired control of the switch and has a complicated design for the low-pass LC filter.

There are two modes of operation of the Boost converter. They are:

1. Mode I: Switch S is ON and Diode D is OFF

2. Mode II: Switch S is OFF and Diode D is ON

Mode I: Switch S is ON and Diode D is OFF

In this mode of operation, switch S is in closed condition i.e. ON state, and diode D is in open condition i.e. OFF state. Thus switch S allows the flow of current through it. All the current will flow through the closed path including inductor L, switch S, and back to the dc input source. The circuit diagram for this mode is shown in the figure below.

Here, the polarity of the inductor will be according to the direction of the flow of current. In this mode of operation, the diode D is in reverse biased condition so that diode does not allow the flow of current through it to the circuit. In this condition, the voltage across the switch S will appear across the load resistance and hence output voltage.
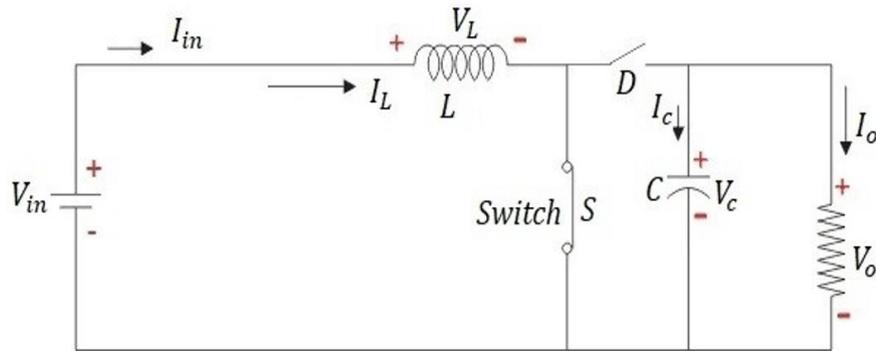
Figure 3.2: *ON state circuit diagram of simple boost converter*

Mode II: Switch S is OFF and Diode D is ON

In this mode of operation, switch S is in open condition i.e. OFF state and diode D is in closed condition i.e. ON state. Thus switch diode D allows the flow of current through it, whereas switching S blocks the current flow through it. The circuit diagram for this mode is shown in the figure below.
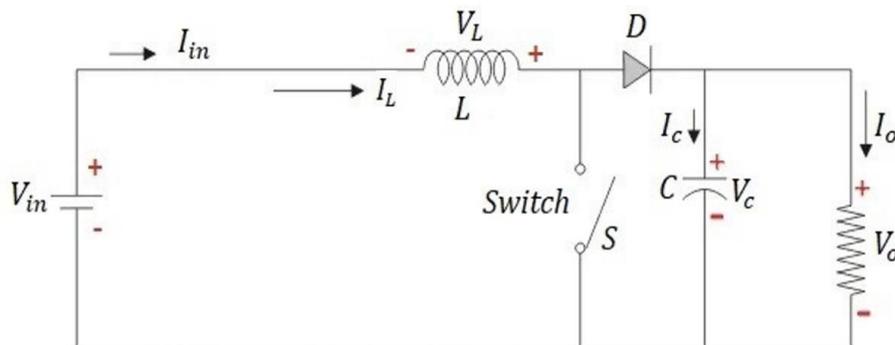
Figure 3.3: *OFF state circuit diagram of simple boost converter*

As we know, the inductor in the circuit store energy in the form of the magnetic field, the inductor acting as the source when the switch S is open. Hence diode D becomes closed. In this mode of operation, the inductor releases the energy stored in the previous mode when switch S was closed. During releasing of energy stored in the inductor, the polarity of the inductor gets reversed which causes the diode D to come in forward biased condition. So it allows the flow of current in the circuit through diode D. The way of current flow is shown in the above figure.

The released energy is ultimately dissipated in the load resistance which helps to maintain the flow of current in the same direction through the load and also steps up the output voltage.

The current through the inductor is of decreasing nature and will die out after the point in time.

3.1.3. Limitation of Simple Boost Converter

Conventional boost converters cannot operate at high efficiency with high voltage gain (G). For a simple boost converter the blocking voltage of the switch (during switch off condition) is equal to the output voltage. Therefore with high voltage gain boost switch, S has to block a large voltage. Usually for a MOSFET (popularly employed as the switch in simple boost converters) Drain to Source resistance RDS-ON is proportional to square of its blocking voltage capability. A high G, simple boost converter employs a MOSFET with high blocking voltage, hence with high R_{DS-ON}. As G, is high, input current would be high (G, times output current for 100% efficiency). This high current flows through the switch. A high G, requires high duty cycle (D). Extreme duty cycle operation drives short pulsed currents with higher amplitude to flow through output diode and capacitor which causes severe diode reverse recovery problem and increases conduction loss at the same time.

The high RDS-ON of the MOSFET causes high conduction loss when switch is on. This along with severe reverse recovery problem of the diode degrades efficiency of the converter and limit power level of simple boost converters. Besides, parasitic ringing present in the circuit induces additional voltage stress across the switch and necessities switch with high blocking voltage which leads to more loss.

Thus, limitations of conventional boost converter include-
(a) Low efficiency.
(b) High voltage stress on switch
These limit the use of boost converter at low power rating only.

3.1.4. Theoretical waveforms of simple boost converter:
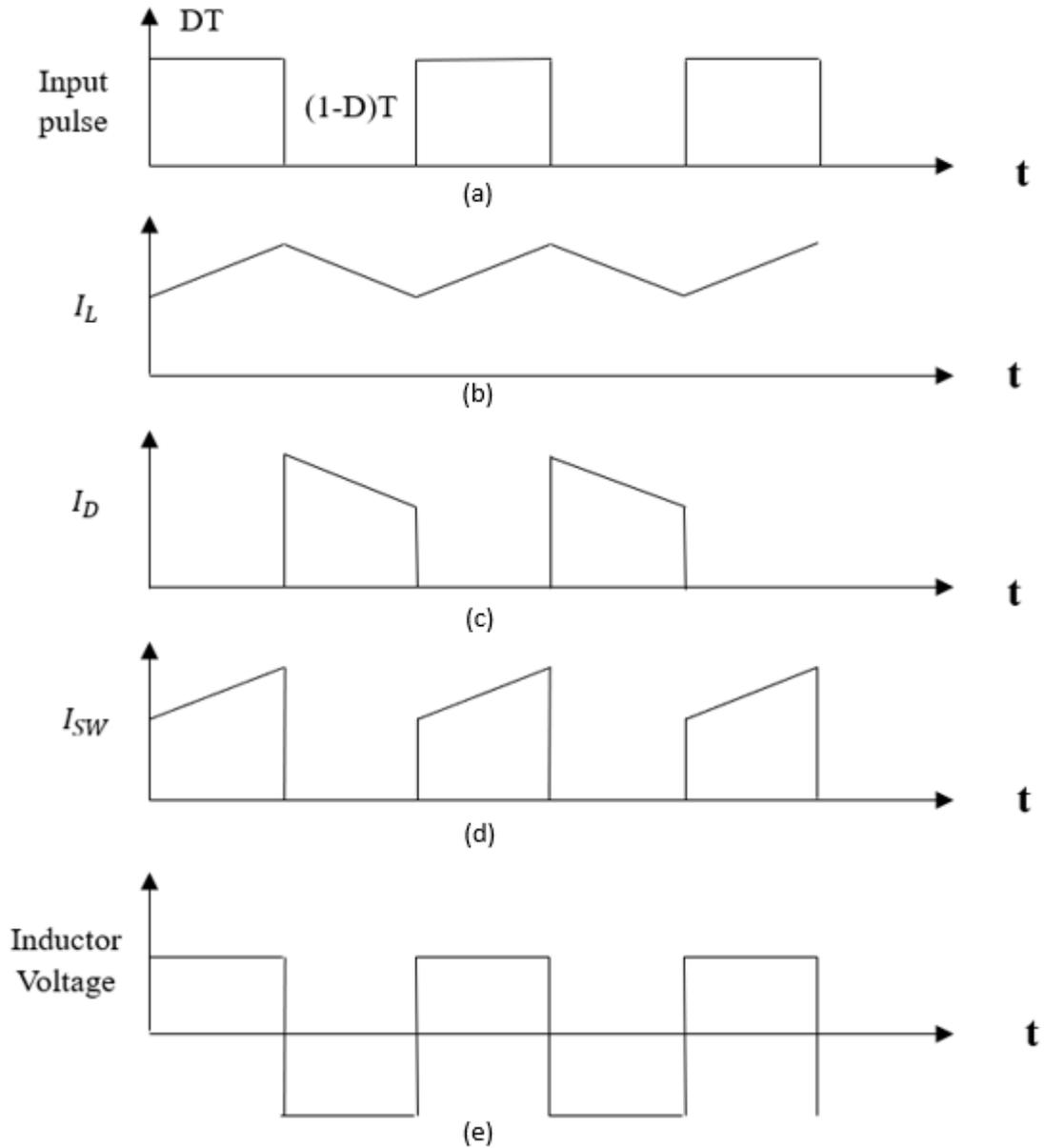
Figure 3.4: *Theoretical waveforms of simple boost converter (**a**) input pulse (**b**) inductor current (**c**) diode current (**d**) switch current (**e**) inductor voltage*

3.1.5. Mathematical analysis
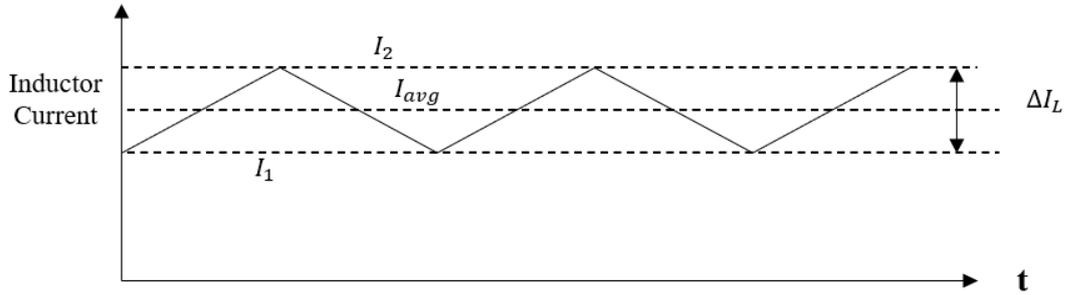
Figure 3.4(f): *Inductor current of simple boost converter*

Assuming CCM (Continuous Conduction Mode),

When switch is ON

$$V_{in} = L\frac{I_2 - I_1}{t_{on}} \qquad (1)$$

$$[where\ I_2 = maximum\ current\ and\ I_1 = minimum\ current]$$

$$V_{in} = L\frac{\Delta I_L}{t_{on}}, \qquad as\ I_2 - I_1 = \Delta I_L$$

During switch off duration, inductor voltage along with input voltage makes the output voltage,

$$V_{in} + L\frac{I_2 - I_1}{t_{off}} = V_o$$

$$V_{in} + L\frac{\Delta I_L}{t_{off}} = V_o$$

Replacing ΔI_L

$$V_{in} + \frac{L}{t_{off}}\left(\frac{V_{in}t_{on}}{L}\right) = V_o$$

$$V_{in}\left(1 + \frac{t_{on}}{t_{off}}\right) = V_o$$

$$V_{in}\left(\frac{T}{t_{off}}\right) = V_o, \qquad as\ t_{on} + t_{off} = T$$

$$V_o = V_{in}\left(\frac{T}{T - t_{on}}\right)$$

$$V_o = V_{in}\left(\frac{1}{1 - D}\right), \qquad (2) \qquad as\ D = \frac{t_{on}}{T}$$

$$\frac{V_o}{V_{in}} = \left(\frac{1}{1 - D}\right) = G_v$$

This is the relation between voltage gain and duty cycle in simple boost converter,

Now,

$$\Delta I_L = \left(\frac{V_{in}t_{on}}{L}\right) = \left(\frac{V_{in}DT}{L}\right)$$

$$\Delta I_L = \frac{V_{in}D}{L_1 f}, \qquad as\ f = \frac{1}{T} \qquad (3)$$

Power transferred to inductor during switch on period,

$$P_1 = \frac{1}{2} \times L(I_2^2 - I_1^2)f \times D$$

$$= 0.5 \times L \times (I_2 + I_1)(I_2 - I_1)f \times D$$

$$= L \times I_{av} \times \Delta I_L \times f \times D \qquad (4)$$

This power is transferred to the output during the t_{on} duration. Rest of the power is transferred directly from the source during t_{off} period.

$$P_2 = 0.5 \times V_{in} \times (I_2 + I_1) \times (1 - D) \qquad (5)$$

Calculation of Input Power:

$$P_{in} = V_{in}I_{av}$$

$$= L\left(\frac{\Delta I_L}{t_{on}}\right)\left(\frac{I_2 + I_1}{2}\right)$$

$$= L\left(\frac{I_2 - I_1}{D}\right)f\left(\frac{I_2 + I_1}{2}\right)$$

$$P_{in} = \frac{Lf I_{av}\Delta I_L}{D} \qquad (6)$$

Calculation of output Power:

If the converter output power is P_o

Then,

$$P_o = V_o I_o \qquad (7)$$

Calculation of Duty Ratio:

$$V_o = V_{in}\left(\frac{1}{1-D}\right)$$

$$\Rightarrow 1 - D = \frac{V_{in}}{V_o}$$

$$\Rightarrow D = 1 - \frac{V_{in}}{V_o} \qquad (8)$$

Calculation of efficiency:

If the converter efficiency is η

Then,

$$\eta = \frac{P_o}{P_{in}} \qquad (9)$$

Design Example:

A simple Boost converter is designed and simulated in MATLAB to study its various parameters.

Specifications:

Input Voltage: $V_{in} = 12\ V$

Switching frequency: $f = 100\ kHz$

Load Resistance: $R = 10\ \Omega$

3.1.6. Simulation waveforms for Simple Boost Converter:
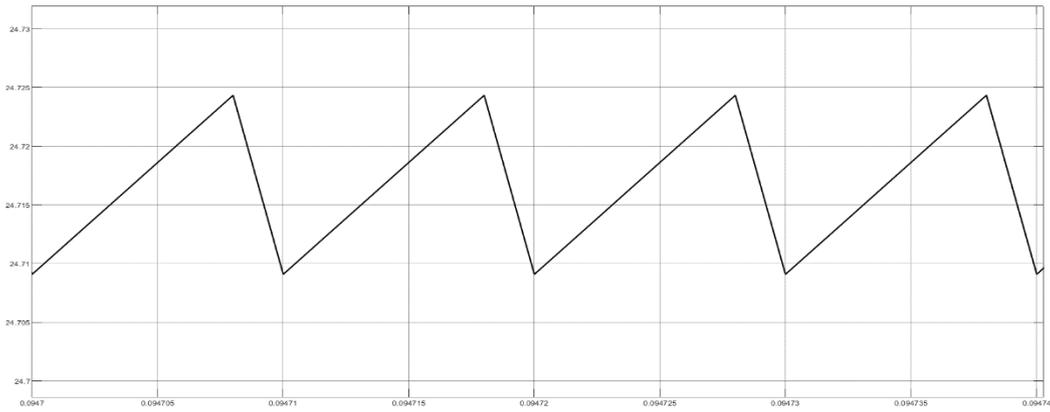
(a)
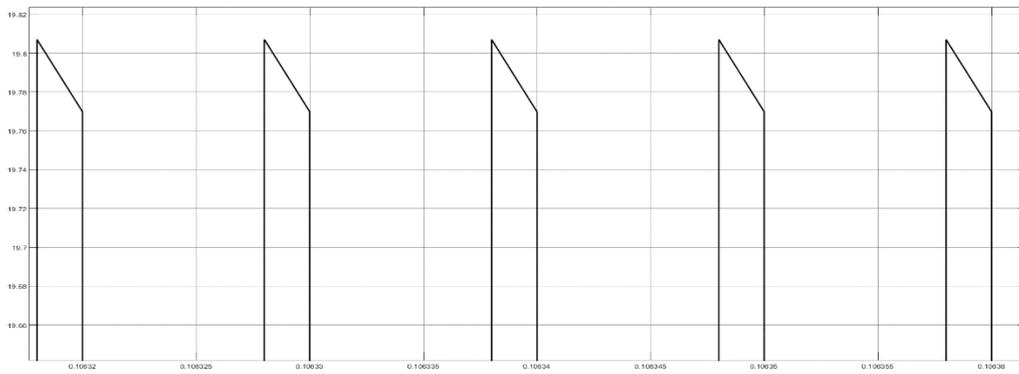
(b)
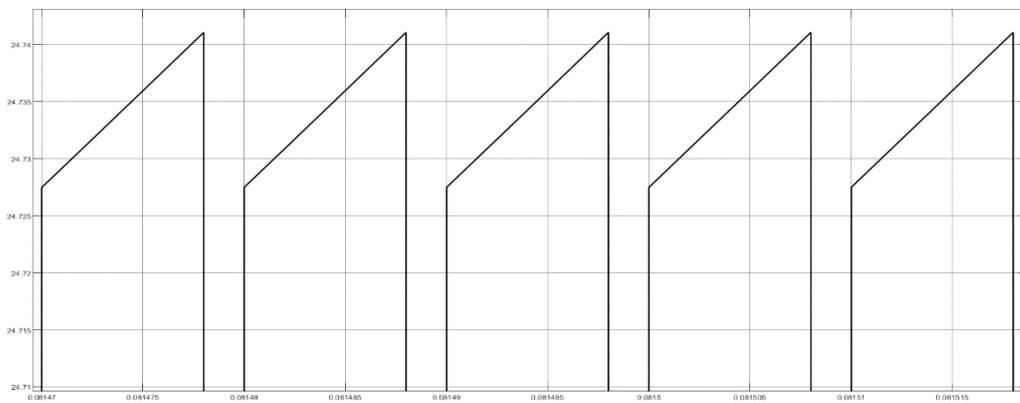
(c)
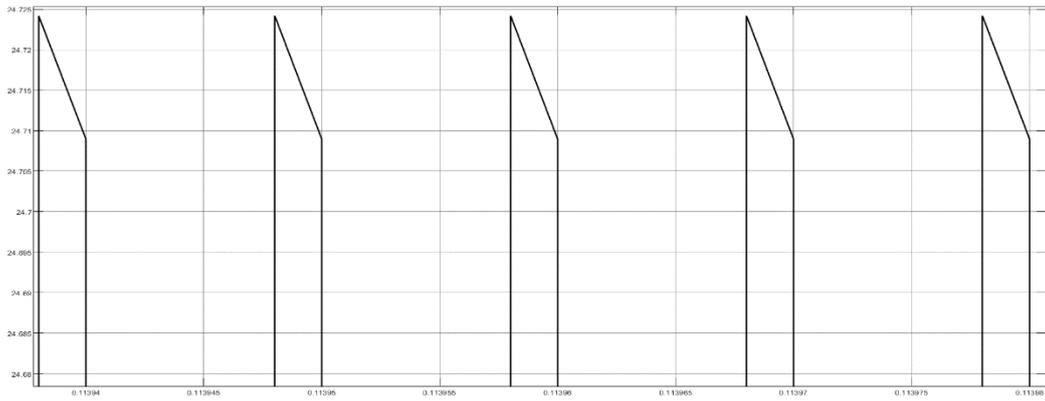
(d)
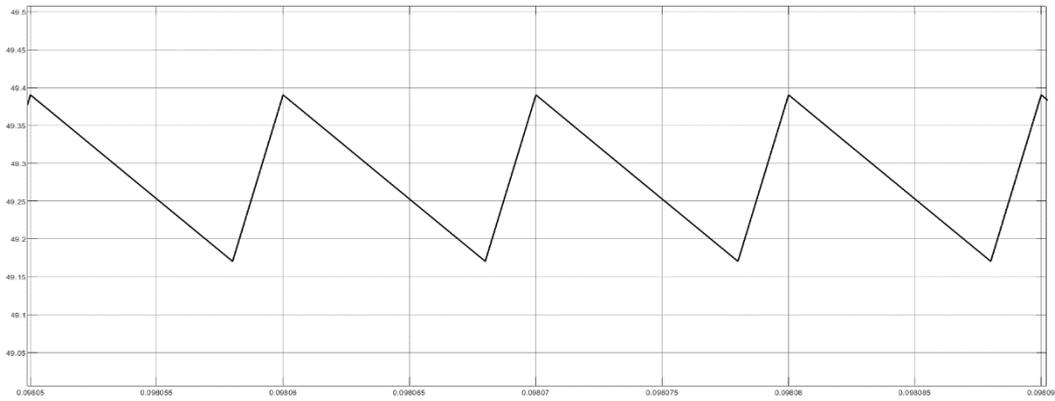
(e)
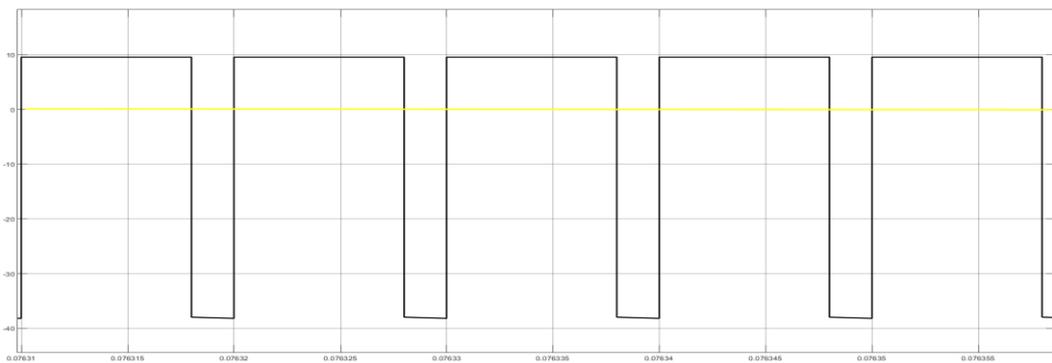
(f)

Figure 3.5*: Simulation waveforms of simple boost converter (a) Inductor Current, (b) Capacitor current (c) Switch current (d) Diode current, (e) output voltage, (f) Inductor voltage*

3.2. Proposed Converter I

Due to the effect of power switches, rectifier diodes, and the equivalent series resistance of inductors and capacitors, conventional dc-dc boost converters are unable to offer high step-up voltage gains.

Two inductors with the same level of inductance are charged in parallel during the switch-on time and discharged in series during the switch-off period in the proposed converters. The proposed converters have very simple architecture. There is only one power stage in use. Furthermore, the steady-state assessments of voltage gains and boundary operating conditions are thoroughly examined.

3.2.1. Operating Principle and Mathematical Analysis

The circuit layout of the proposed converter I is shown in Fig. 3.6(a), which comprises of two active switches (S_1 and S_2), two inductors with the same level of inductance (L_1 and L_2), one output diode, D_0, and one output capacitor C_0. S_1 and S_2 switches are operated simultaneously by a single control signal.

This proposed converter has been operated in Continuous Conduction Mode (CCM) only.
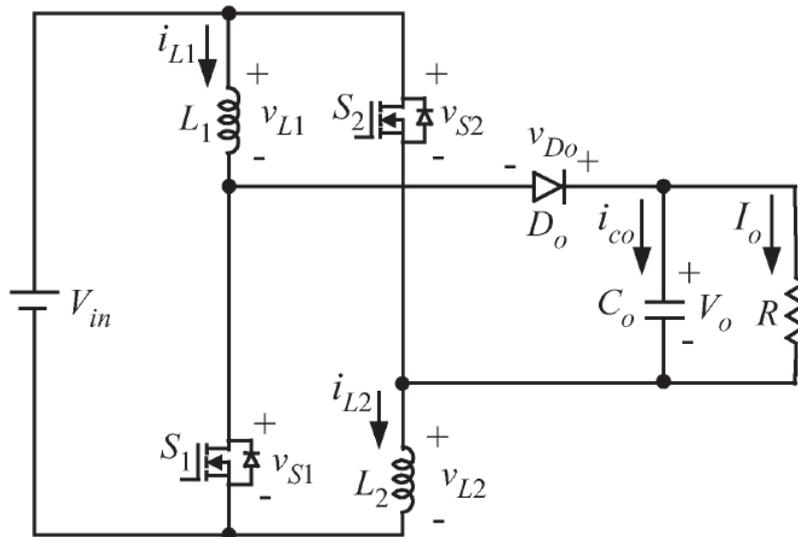
Figure 3.6(a): Proposed Converter I

In Continuous conduction mode (CCM) the operating modes are classified into two categories: mode 1 and mode 2. The operational principles and steady-state analyses of CCM are detailed here.

MODE I $[t_0 \, to \, t_1]$

Switches S1 and S2 are turned on during this time span. The equivalent circuit is depicted in Figure 3.6(b). The dc source charges inductors L_1 and L_2 in parallel, and the energy stored in the output capacitor C_0 is released to the load. As a result, the voltages between L_1 and L_2 are as follows:
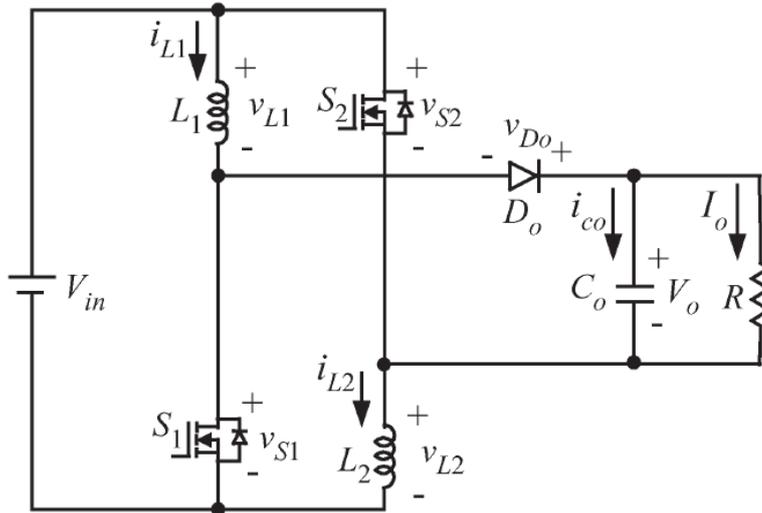
Figure 3.6(b): Proposed Converter I (Switch ON)

$$V_{L1} = V_{in} \qquad (10)$$

$$V_{L2} = V_{in} \qquad (11)$$

MODE II $[t_1 \, to \, t_2]$

S_1 and S_2 are turned off during this time interval. The equivalent circuit is depicted in Figure 3.6(c).

The dc source, L_1, and L_2 are linked in series to deliver energy to C_0 and the load. As a result, the voltages across L_1 and L_2 are calculated as

$$V_{L1} = \frac{V_{in} - V_o}{2} \qquad (12)$$

$$V_{L2} = \frac{V_{in} - V_o}{2} \qquad (13)$$

Using the voltage outputs of the both waveform we can say that

$$\int_0^{DT} V_{in} dt + \int_{DT}^{T} \frac{V_{in} - V_o}{2} dt = 0$$
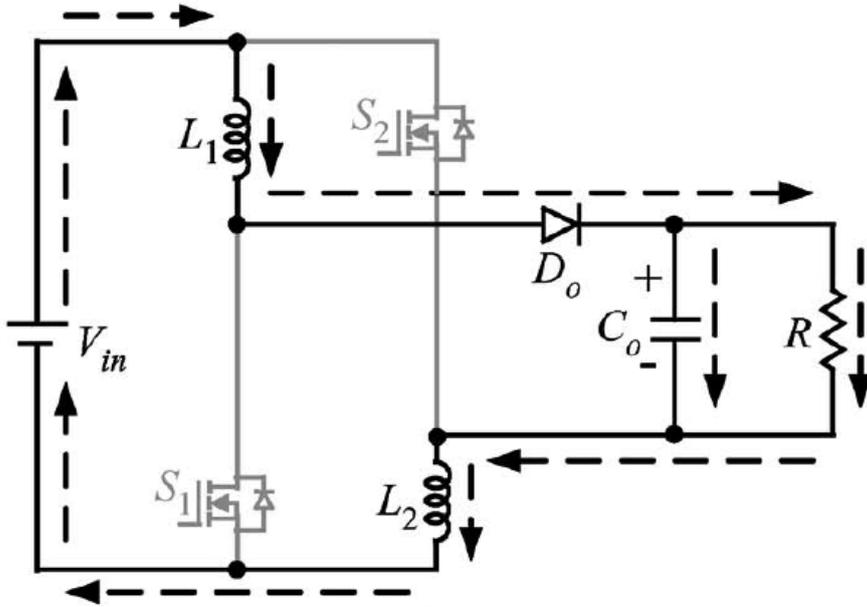
Figure 3.6(c): *Proposed Converter I (Switch OFF)*

$$\Rightarrow \quad V_{in}[DT] + \frac{1}{2}[V_{in}T - V_{in}DT] - \frac{1}{2}[V_oT - V_oDT] = 0$$

$$\Rightarrow \quad \frac{V_{in}[DT + T]}{2} = \frac{V_o[T - DT]}{2}$$

$$\Rightarrow \quad \frac{V_o}{V_{in}} = \frac{1+D}{1-D} \qquad\qquad (14)$$

Equation 14 shows the voltage gain of the DC-DC Converter in the Continuous Conduction Mode (CCM).
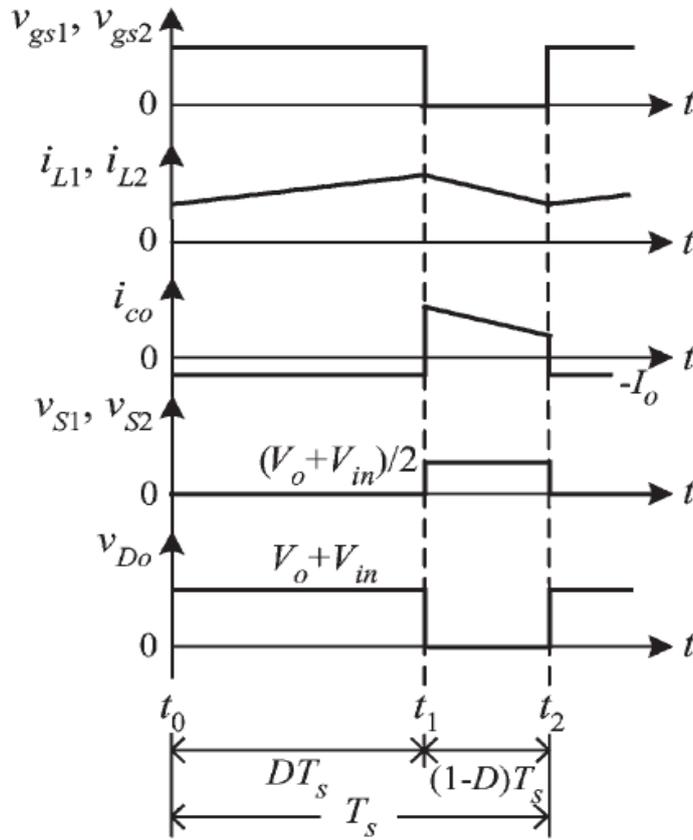
Voltage stresses of the switches S_1 and S_2 are

$$V_{S1} = \frac{V_o + V_{in}}{2} \qquad\qquad (15)$$

$$V_{S2} = \frac{V_o + V_{in}}{2} \qquad\qquad (16)$$

And voltage stress of Diode is

$$V_{D0} = V_{in} + V_o \qquad\qquad (17)$$

3.2.2. Theoretical waveforms of Proposed converter I:

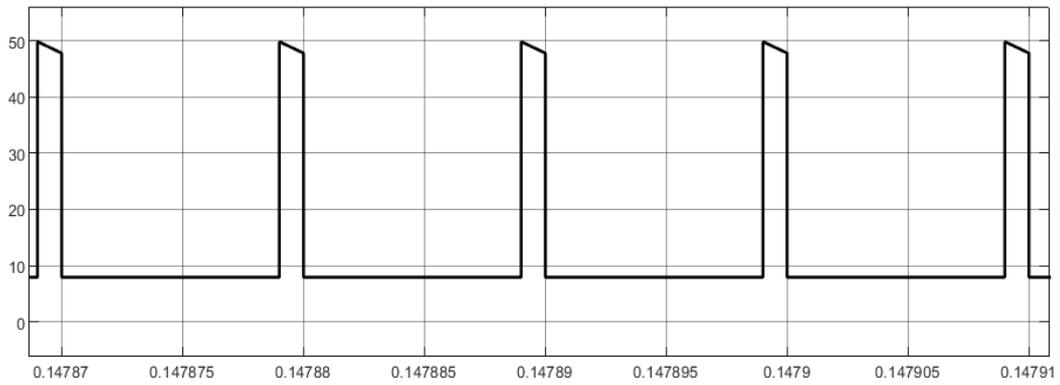***Figure 3.7:*** *Theoretical waveforms of proposed converter*

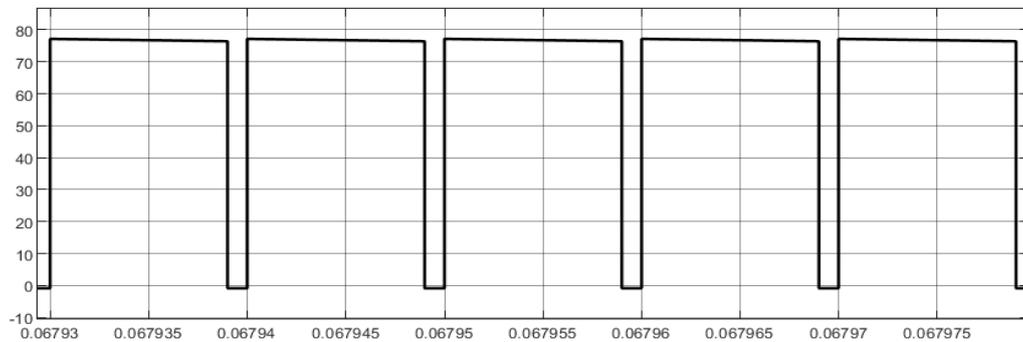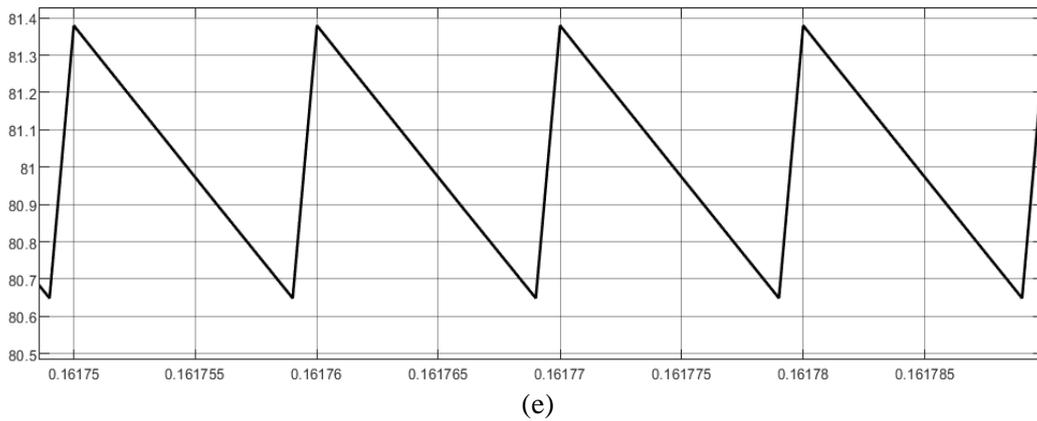### 3.2.3. Simulation waveforms of Proposed Converter I


(a)

(b)

(c)

(d)

(e)
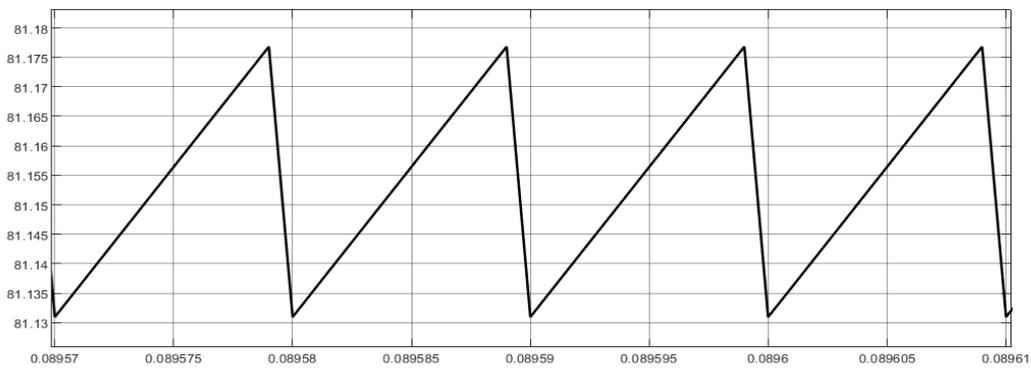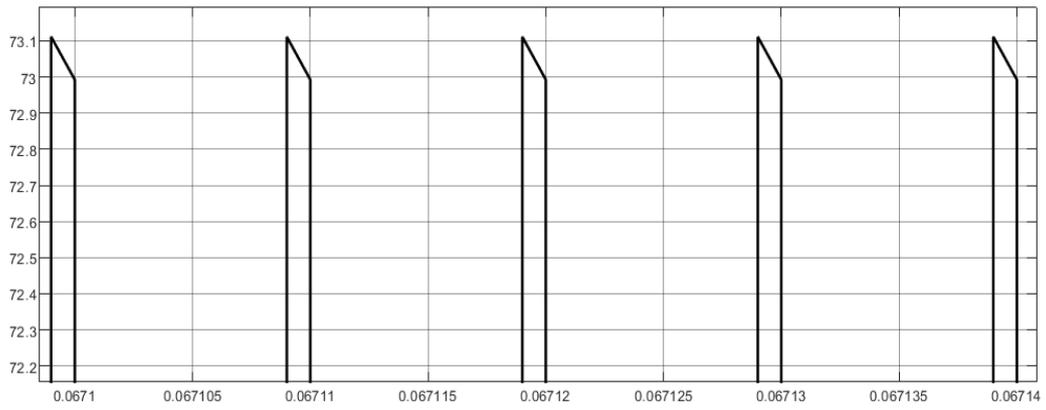
Figure 3.8: *Simulation waveforms of proposed converter I -(a) inductor current (b) capacitor current (c) switch voltage (d) diode voltage (e) output voltage*

3.3. PROPOSED CONVERTER II

3.3.1. Operating Principle and Mathematical Analysis

Figure 3.9(a) illustrates the setup of the suggested Converter II, an enhanced version of Converter I with the integration of a single voltage-lift circuit. In this configuration, two inductors (L_1 and L_2) of identical inductance values are also employed.

The states of switches S_1 and S_2 are synchronized and governed by a single control signal. The operational principles and the analysis of the steady-state behavior of both CCM are outlined below.
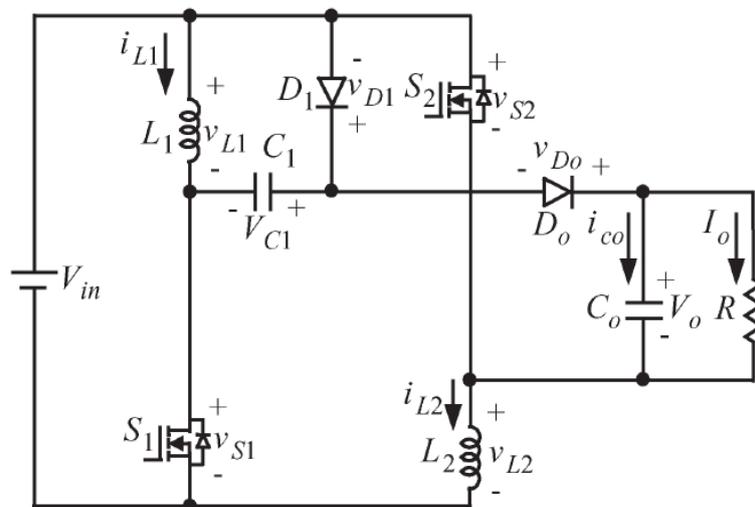
Figure 3.9(a): *Proposed Converter II*

Continuous Conduction Mode (CCM)

This CCM mainly two modes. They are discussed below

MODE I $[t_0 \, to \, t_1]$

In the specified timeframe, S_1 and S_2 are activated, as depicted in Figure 3.9(b). Both L_1 and L_2 receive a parallel charge from the direct current (DC) source, while the energy stored in capacitor Co is discharged into the load. Furthermore, capacitor C_1 undergoes charging from the dc
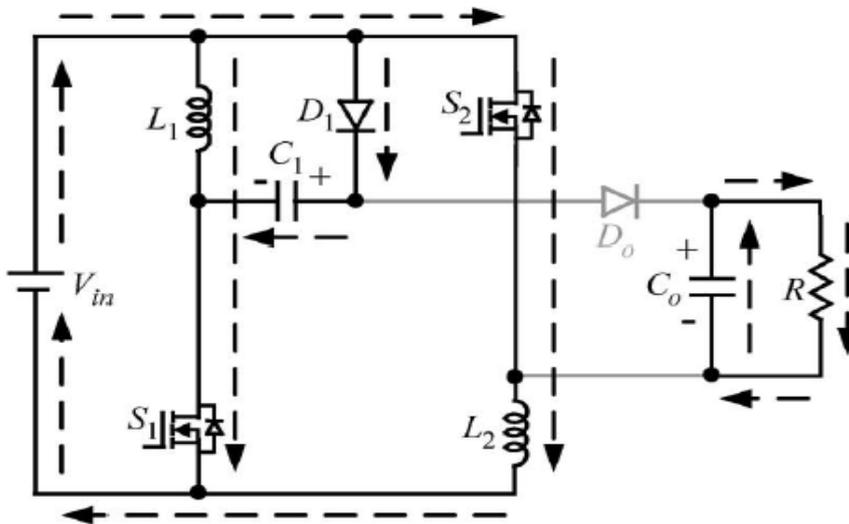

Figure 3.9(b): *Proposed converter II (MODE I)*

The voltages across the L_1, L_2 and C_1 are given as

$$V_{L1} = V_{in} \qquad (18)$$

$$V_{L2} = V_{in} \qquad (19)$$

$$V_{C1} = V_{in} \qquad (20)$$

MODE II $[t_1 \, to \, t_2]$

In this specific time period, S_1 and S_2 are deactivated, as illustrated in Figure 3.9(c). The direct current (DC) source, L_1, L_2 and C_1 are connected in series to facilitate the transfer of energy to C_0 and the load.
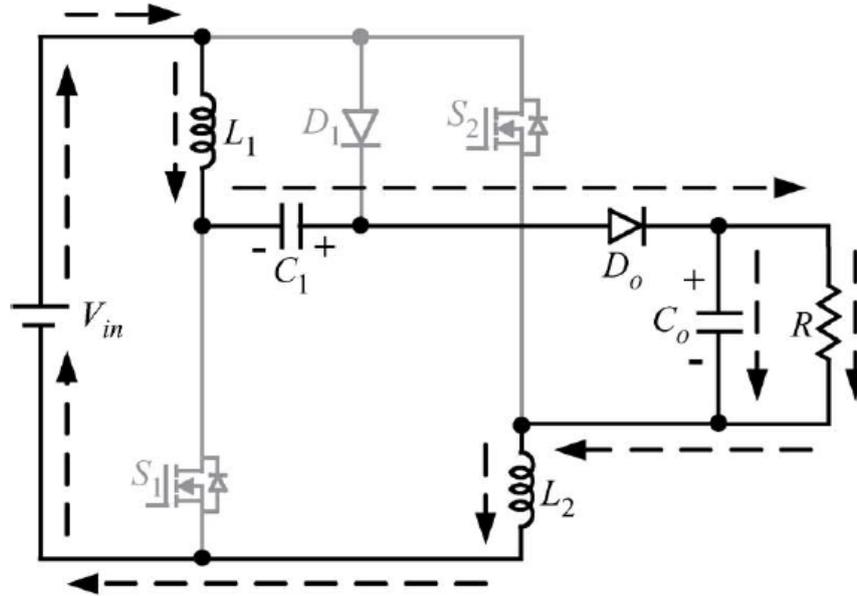
Figure 3.9(c): *Proposed Converter II (MODE II)*

Thus,

voltages across L_1 *and* L_2 are derived as

$$V_{L1} + V_{L2} = V_{in} + V_{C1} - V_0$$

$$\Rightarrow V_{L1} = V_{L2} = \frac{V_{in} + V_{C1} - V_0}{2}$$

$$\Rightarrow V_{L1} = V_{L2} = \frac{2V_{in} - V_0}{2} \qquad (21)$$

Using the voltage balance equation of L_1 *and* L_2 we can say that

$$\int_{0}^{DT} V_{in}dt + \int_{DT}^{T} \frac{2V_{in} - V_0}{2} dt$$

$$\Rightarrow V_{in}DT + V_{in}[T - DT] - \frac{V_0}{2}[T - DT]$$

$$\Rightarrow V_{in}T = \frac{V_0}{2} T[1 - D]$$

$$\Rightarrow M_{CCM} = \frac{V_0}{V_{in}} = \frac{2}{1 - D} \qquad (22)$$

Equation 22 shows the voltage gain of the DC-DC Converter in the Continuous Conduction Mode(CCM)

Now, voltage stresses of D_1, D_0, S_1 *and* S_2 can be written as

$$V_{S1} = \frac{V_0}{2} \qquad (23)$$

$$V_{S2} = \frac{V_0}{2} \qquad (24)$$

$$V_{D1} = \frac{V_0}{2} \qquad (25)$$

$$V_{D0} = V_0 \qquad (26)$$

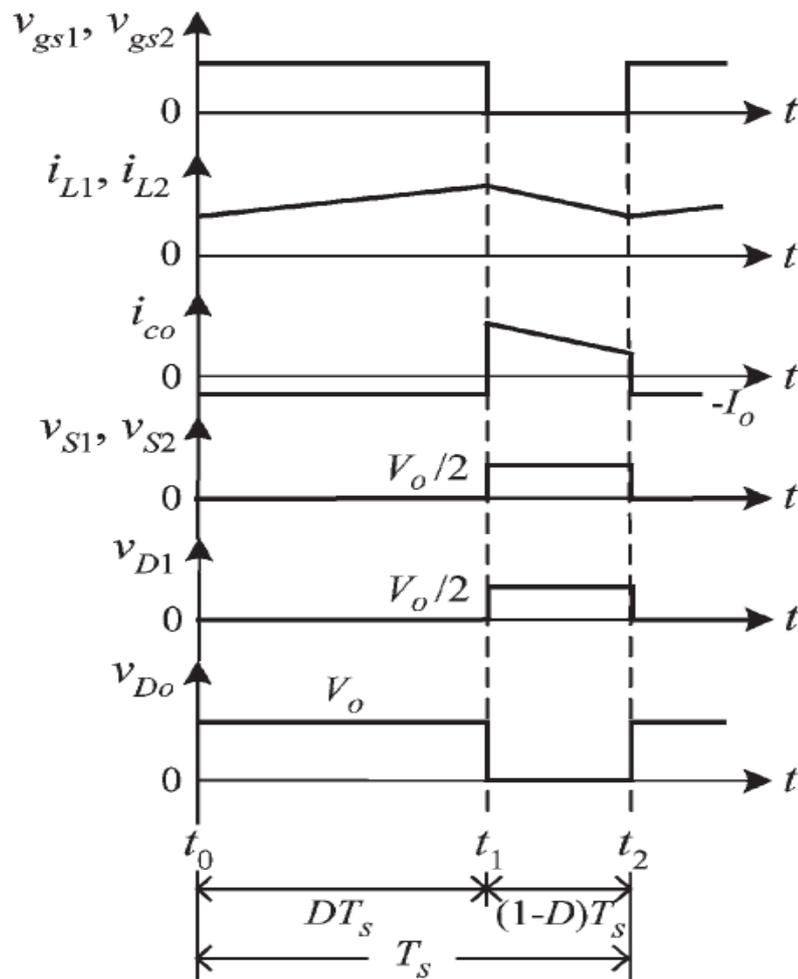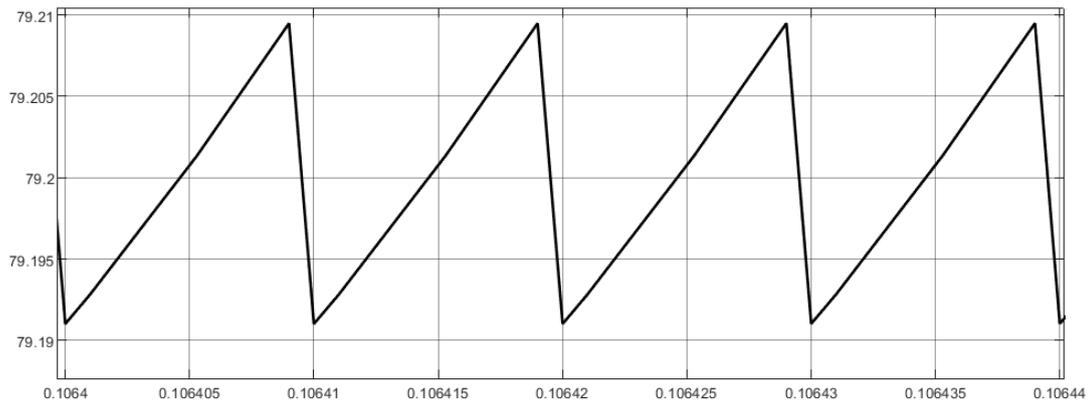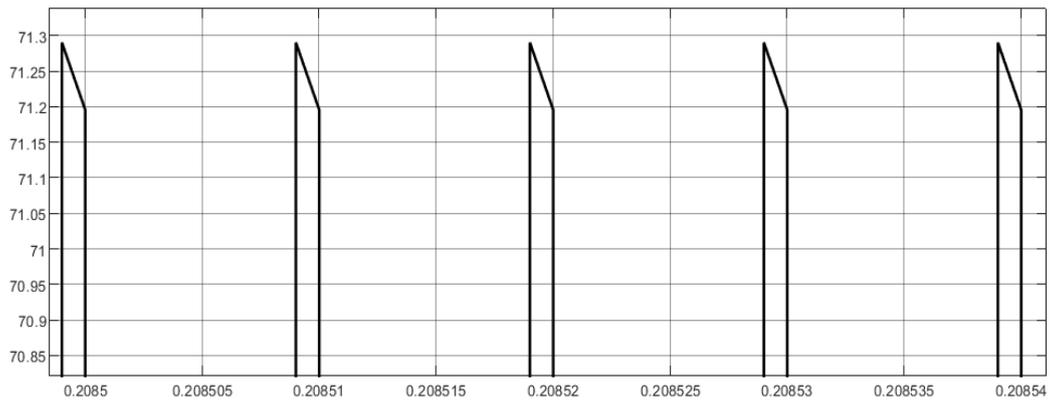### 3.3.2. Theoretical waveform of Proposed Converter II

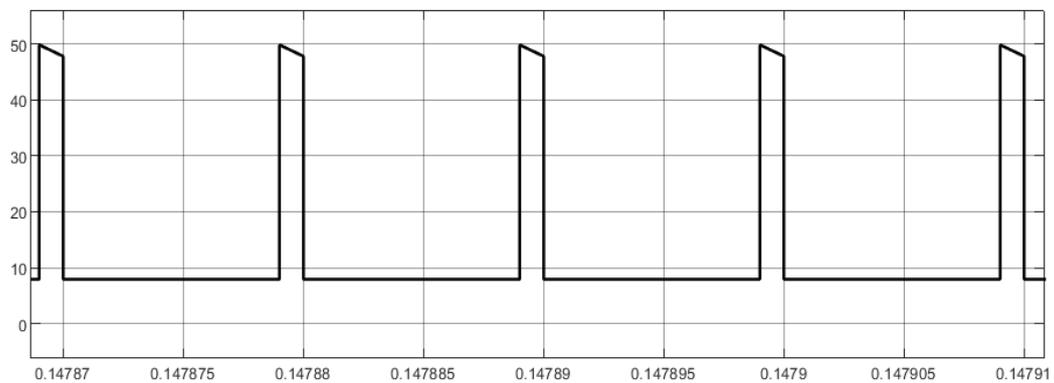***Figure 3.10:*** *Theoretical waveform of proposed converter II*

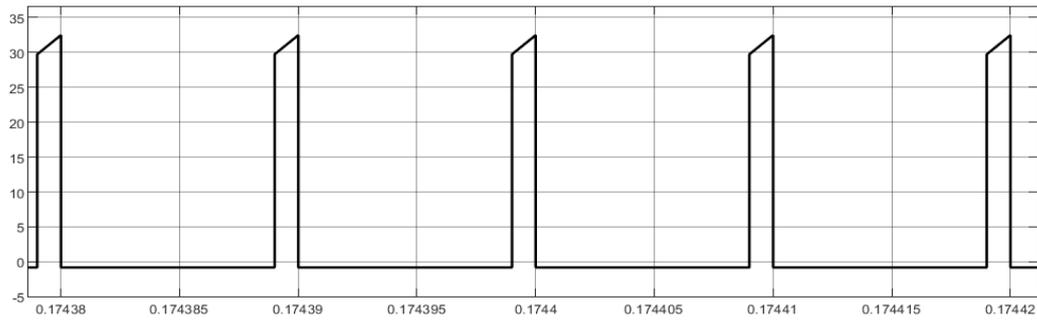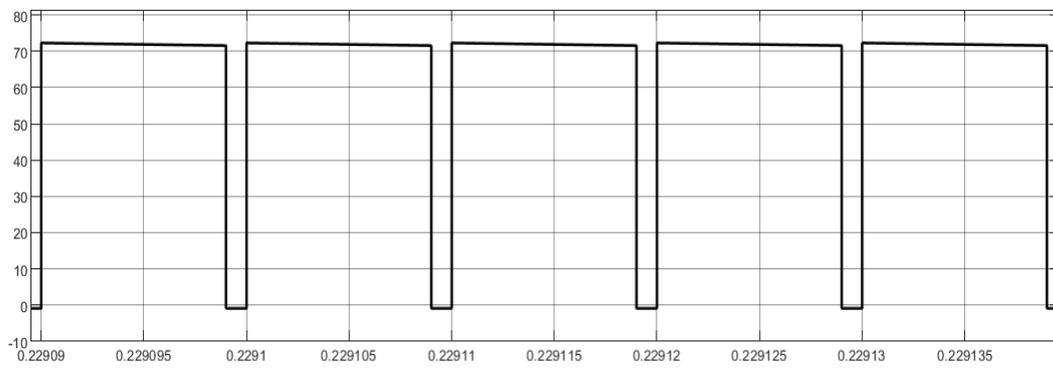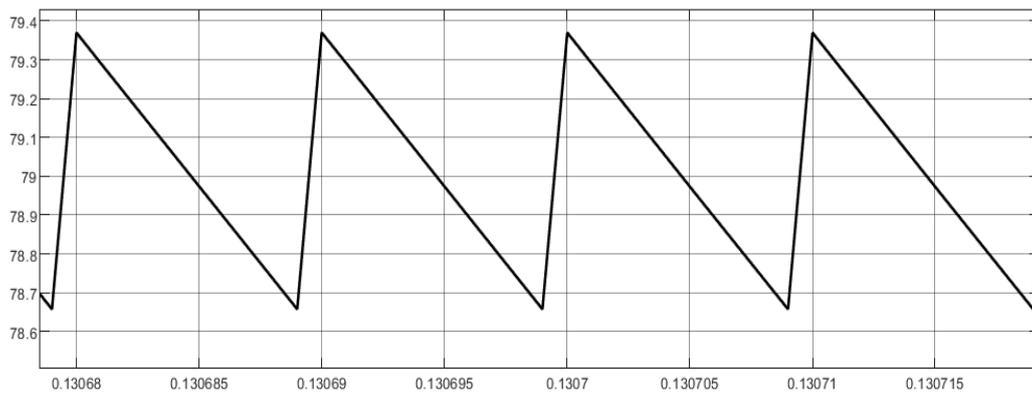### 3.3.3. Simulation waveforms of Proposed Converter II

(a)

(b)

(c)

(d)

(e)

(f)

Figure 3.11: *Simulation waveforms of proposed converter II -(a) inductor current (b) capacitor current (c) switch voltage (d) diode voltage (V_{D1}) (e) diode voltage (V_{D0}) (f) output voltage*

3.4. PROPOSED CONVERTER III

3.4.1. Operating Principle and Mathematical Analysis

Figure 3.12.(a) illustrates the circuit arrangement of the newly introduced Converter III, which is essentially Converter I integrated with two voltage-lift circuits. Consequently, this configuration also includes a pair of inductors (L_1 and L_2) having identical inductance values. Switches S_1 and S_2 are jointly controlled by a single control signal.
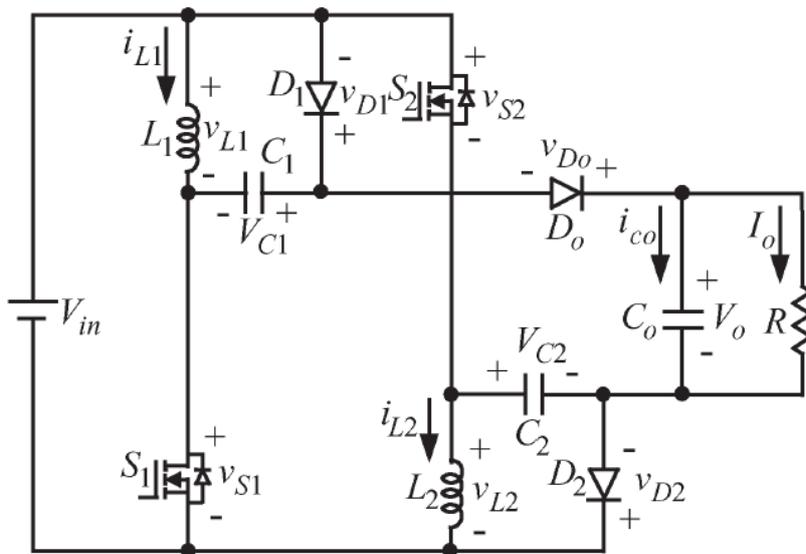
Figure 3.12(a): *Proposed Converter III*

It has two modes in continuous conduction mode (CCM). They are

MODE I $[t_0$ to $t_1]$

While in this specific time interval, both S_1 and S_2 are activated, resulting in the equivalent circuit depicted in Figure 3.12(b). Inductors L_1 and L_2 receive a simultaneous charge from the DC source, subsequently discharging the stored energy in capacitor C_0 to the load. Furthermore, capacitors (C_1 and C_2) undergo charging from the dc source.

Now capacitors (C_1 and C_2) inductors (L_1 and L_2) can be calculated as

$$V_{C1} = V_{in} \qquad (21)$$

$$V_{C2} = V_{in} \qquad (22)$$

$$V_{L1} = V_{in} \qquad (23)$$

$$V_{C2} = V_{in} \qquad (24)$$

Figure 3.12(b): *Proposed Converter III (Mode I)*

MODE II $[t_1\ to\ t_2]$

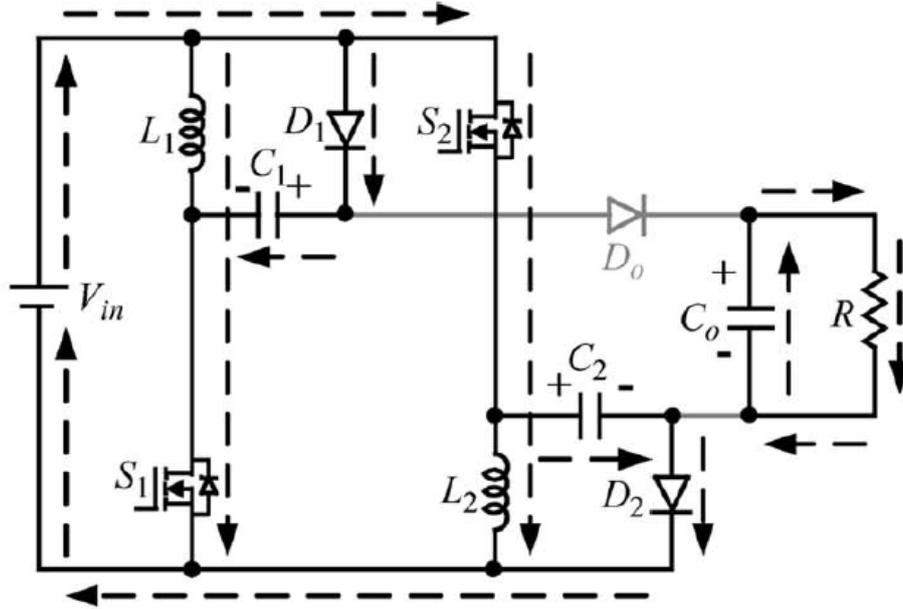In this specific time frame, both S_1 and S_2 are deactivated, leading to the representation of the equivalent circuit displayed in Figure 3.12(c). The DC source, along with $L_1, L_2, C_1\ and\ C_2$ are interconnected in series to facilitate the transfer of energies to C_0 and subsequently to the load.

Now the voltages across the $L_1\ and\ L_2$ can be calculated as

$$-V_{in} + V_{L1} - V_{C1} + V_{C0} - V_{C2} + V_{L2} = 0$$

$$\Rightarrow V_{L1} + V_{L2} = V_{in} + V_{C1} + V_{C2} - V_{C0}$$

$$\Rightarrow V_{L1} = V_{L2} = \frac{V_{in} + V_{C1} + V_{C2} - V_{C0}}{2}$$

$$\Rightarrow V_{L1} = V_{L2} = \frac{3V_{in} - V_{C0}}{2} \qquad (25)$$

Using the voltage balance equation of $L_1\ and\ L_2$ we can say that

$$\int_0^{DT} V_{in}\, dt + \int_{DT}^{T} \frac{3V_{in} - V_{C0}}{2} = 0$$

$$\Rightarrow V_{in}DT + \frac{3V_{in}T - V_{C0}T - 3V_{in}DT + V_{C0}DT}{2}$$
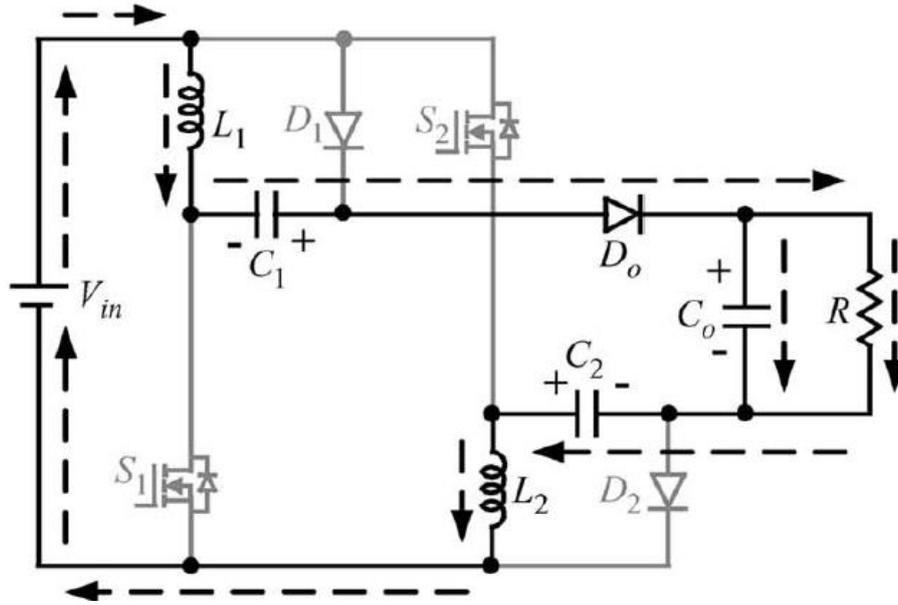
Figure 3.12(c): *Proposed Converter III (Mode II)*

$$\Rightarrow V_{in}\left[D + \frac{3}{2} - \frac{3}{2}D\right] = V_{C0}\left[\frac{1}{2} - \frac{D}{2}\right]$$

$$\Rightarrow V_{in}\left[\frac{2D + 3 - 3D}{2}\right] = V_{C0}\left[\frac{1 - D}{2}\right]$$

$$\Rightarrow M_{CCM} = \frac{V_{C0}}{V_{in}} = \frac{3 - D}{1 - D} \qquad (26)$$

Equation 26 shows the voltage gain of the DC-DC Converter in the Continuous Conduction Mode (CCM).

3.4.2. Theoretical waveforms of Proposed Converter III
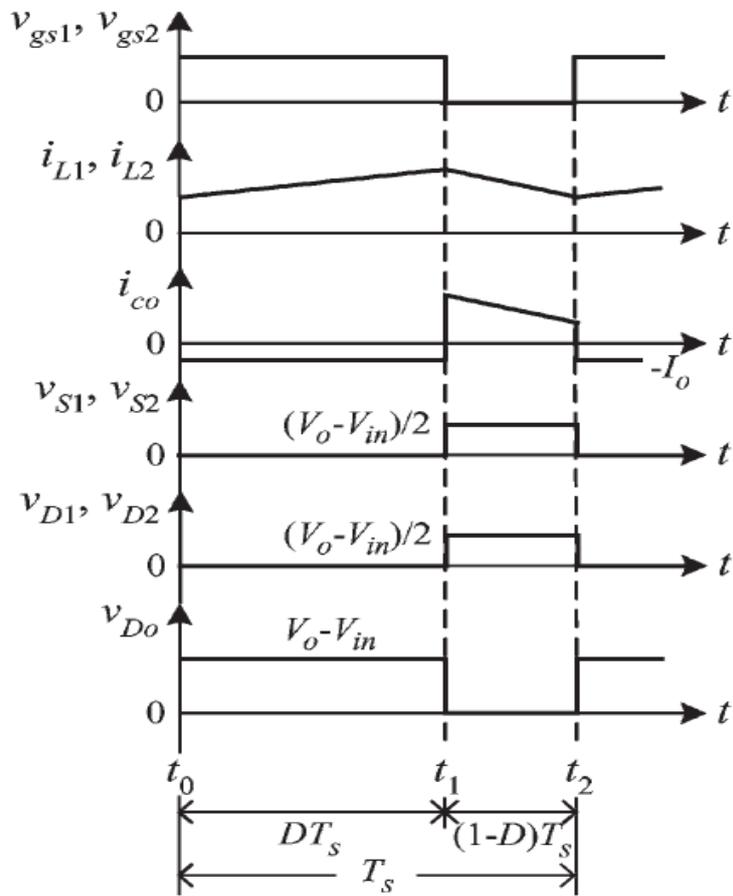
Figure 3.13: *Theoretical waveforms of proposed converter III*

3.4.3. Simulation waveforms of Proposed Converter III
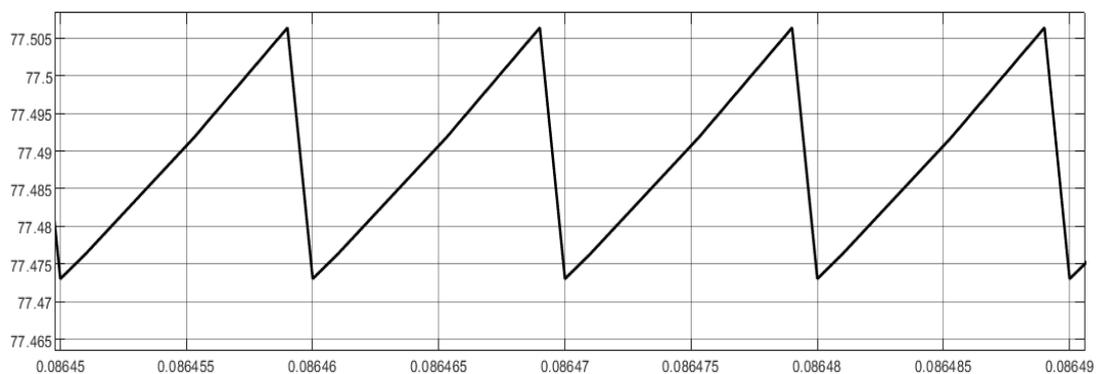
(a)
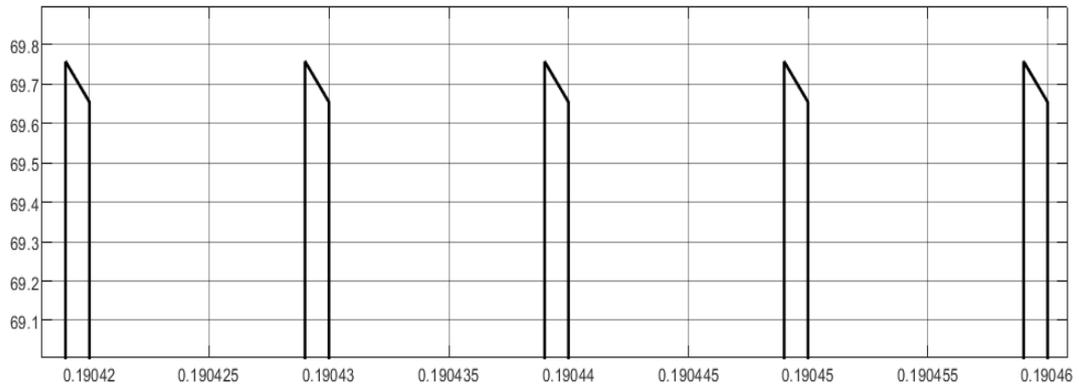
(b)

(c)
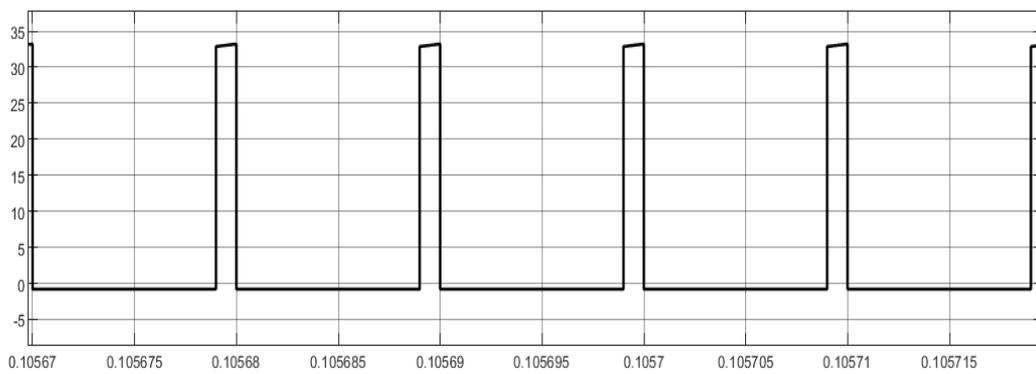
(d)
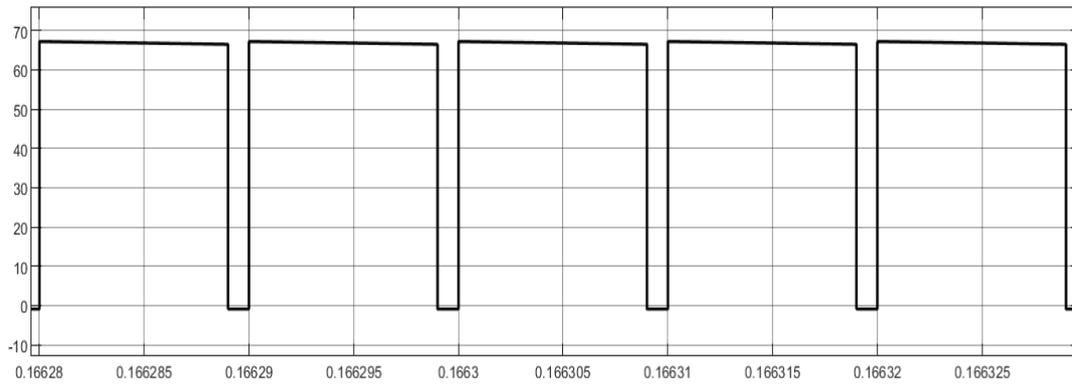
(e)
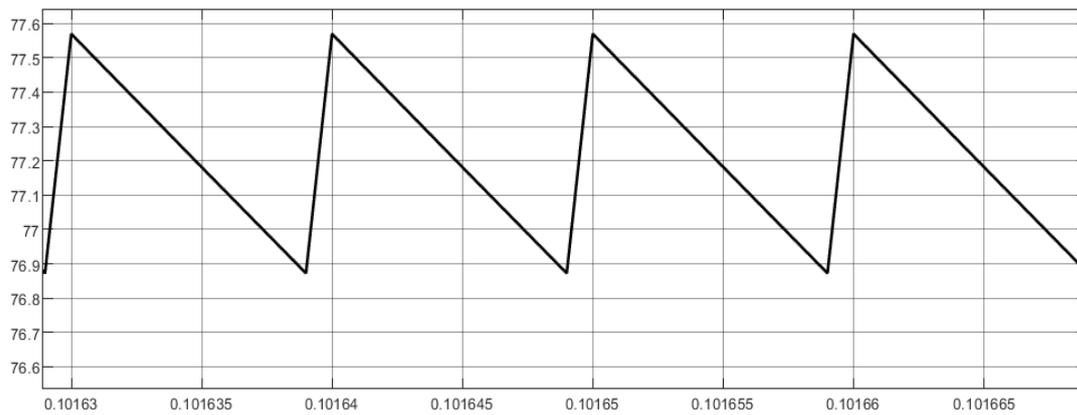
(f)

Figure 3.14: *Simulation waveforms of proposed converter III -(a) inductor current (b) capacitor current (c) switch voltage (d) diode voltage (V_{D1} and V_{D2}) (e) diode voltage (V_{D0}) (f) output voltage*

CHAPTER – IV

Comparison Study Based on Simulation Results

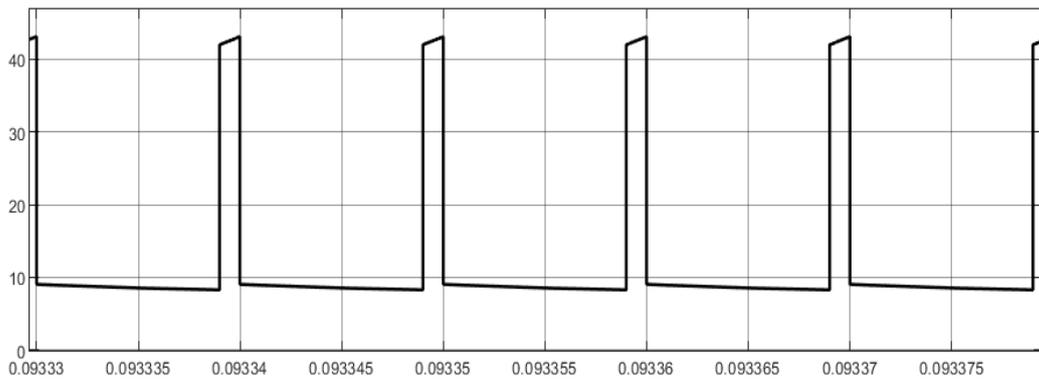## 4.1. Comparison Study of Different Converters:

Similar Specifications has been taken for a simple boost converter and three proposed converters. Duty cycle of the converters has been changed to observe the change in various parameters.

4.1.1. Comparison study on Simple Boost Converter:

A simple Boost converter is designed and simulated in MATLAB to study its various parameters.

Specifications:

Input Voltage: $V_{in} = 12\ V$

Switching frequency: $f = 100\ kHz$

Load Resistance: $R = 10\ \Omega$

D	V_{in}	I_L	I_o	V_0	Voltage stress $(V_s = V_0)$	Gain $\left(V_o/V_{in}\right)$	Gain (Theoretical)
0.1	12	1.39	1.26	12.56	12.56	1.04	1.11
0.2	12	1.77	1.42	14.22	14.22	1.19	1.25
0.3	12	2.32	1.64	16.36	16.36	1.36	1.43
0.4	12	3.17	1.9	19.1	19.1	1.59	1.67
0.5	12	4.56	2.28	22.79	22.79	1.9	2
0.6	12	7.06	2.83	28.21	28.21	2.35	2.5
0.7	12	12.16	3.647	36.47	36.47	3.04	3.33
0.8	12	24.54	4.94	49.39	49.39	4.11	5
0.9	12	62.54	6.28	62.81	62.81	5.23	10

Table 4.1: Comparison of parameters of simple boost converter

D	P_{in}	P_o	η
0.1	16.68	15.83	94.9
0.2	21.24	20.19	95.06
0.3	27.84	26.83	96.37
0.4	38.04	36.29	95.4
0.5	54.72	51.96	94.96
0.6	84.7	79.83	94.25
0.7	145.92	133.01	91.15
0.8	294.48	243.99	82.85
0.9	751.56	394.45	52.48
0.95	1195	249.55	20.88

Table 4.2: *Simple boost converter- comparison of input power, output power and efficiency with different duty cycles*

Figure 4.1: *Simple boost converter graph for duty ratio vs voltage gain*

Simple Boost Converter (100 kHz)
Duty Ratio vs Output Power

Figure 4.2: Simple boost converter graph for duty ratio vs output power
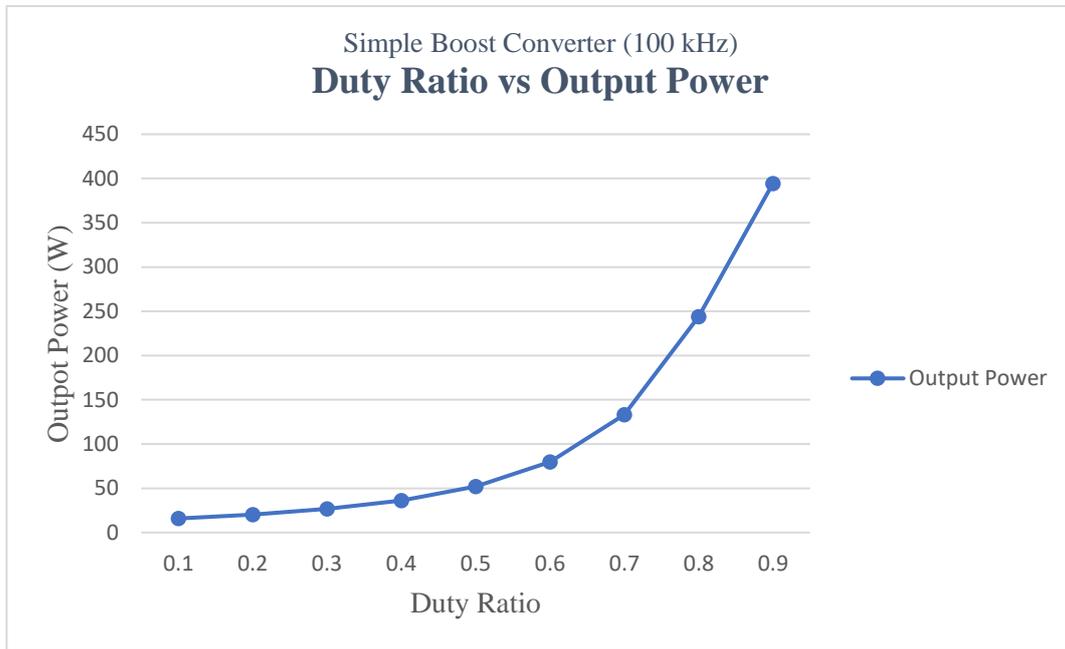
Simple Boost Converter (100 kHz)
Duty Ratio vs Efficiency
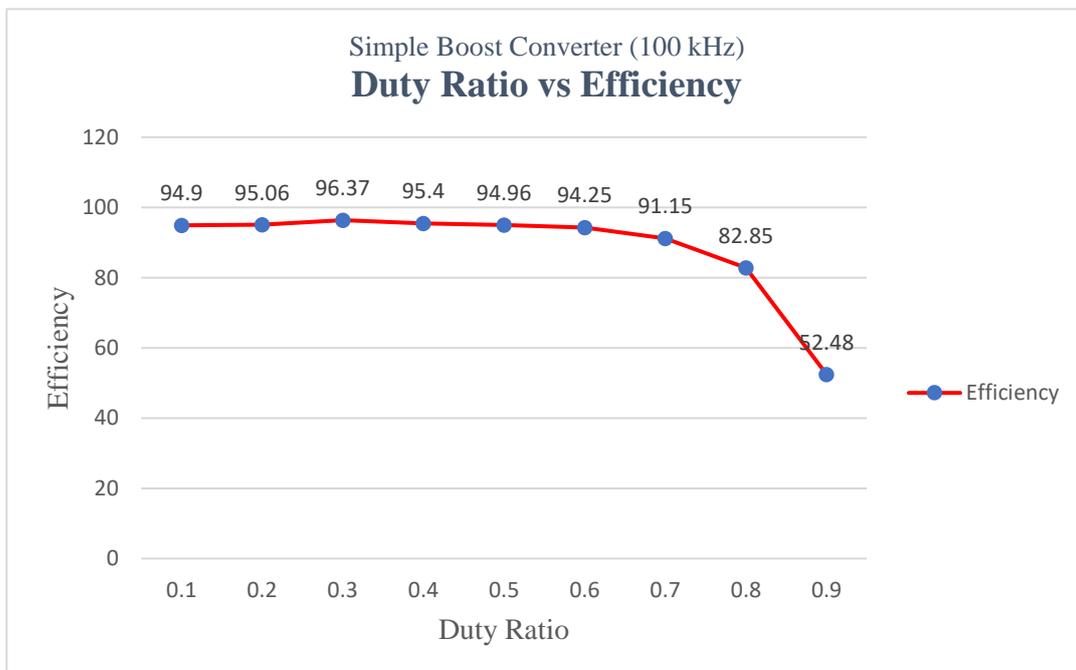
Figure 4.3: Simple boost converter graph for duty ratio vs efficiency

4.1.2. Comparison study on Proposed Converter I

A Proposed Converter is designed and simulated in MATLAB to study its various parameters.

Specifications:

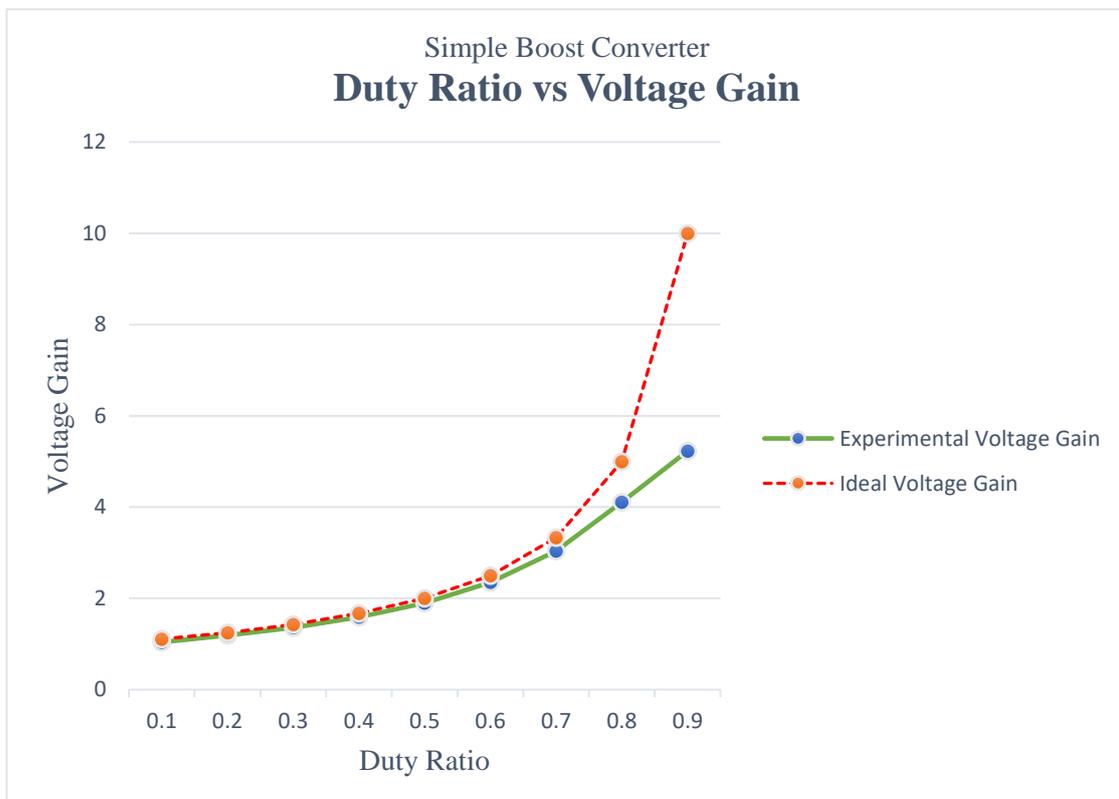Input Voltage: $V_{in} = 12\ V$

Switching frequency: $f = 100\ kHz$

Load Resistance: $R = 10\ \Omega$

D	V_{in}	I_L	I_o	V_0	Voltage stress $\left(V_S = \dfrac{V_o + V_{in}}{2}\right)$	Gain $\left(V_o/V_{in}\right)$	Gain (Ideal)
0.1	12	3.07	1.39	13.84	12.92	1.15	1.22
0.2	12	4.26	1.72	17.2	14.6	1.43	1.5
0.3	12	6.05	2.13	21.25	16.62	1.77	1.85
0.4	12	8.86	2.67	26.65	19.31	2.22	2.33
0.5	12	13.55	3.39	33.91	22.95	2.82	3
0.6	12	21.98	4.4	44	28	3.67	4
0.7	12	38.22	5.83	58.3	35.15	4.86	5.67
0.8	12	76.63	7.68	76.76	44.38	6.4	9
0.9	12	162.3	8.14	81.38	46.69	6.78	19
0.95	12	217.2	5.46	54.53	33.26	4.54	39

Table 4.3: *Comparison of parameters of proposed converter I*

D	P_{in}	P_o	η
0.1	36.82	19.17	52.06
0.2	51.12	29.58	57.87
0.3	72.6	45.26	62.34
0.4	706.32	71.16	66.93
0.5	162.6	114.95	70.69
0.6	263.76	193.6	73.4
0.7	465.84	339.89	72.96
0.8	919.56	589.52	64.05
0.9	1947.6	662.43	34.01
0.95	2606.4	297.73	11.42

***Table 4.4****: Proposed converter I- comparison of input power, output power and efficiency with different duty cycles*

Figure 4.4: *Proposed converter I graph for duty ratio vs voltage gain*
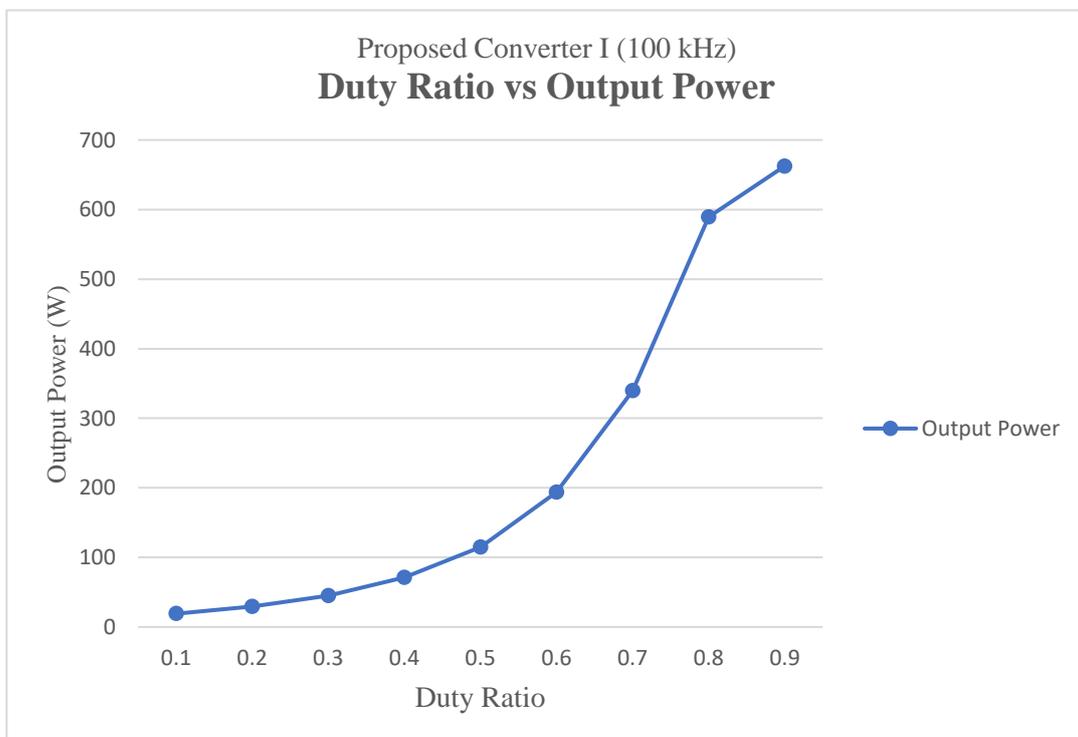
Figure 4.5: *Proposed converter I graph for duty ratio vs output power*

Figure 4.6: Proposed converter I graph for duty ratio vs efficiency

4.1.3. Comparison study on Proposed Converter II

A Proposed Converter is designed and simulated in MATLAB to study its various parameters.

Specifications:

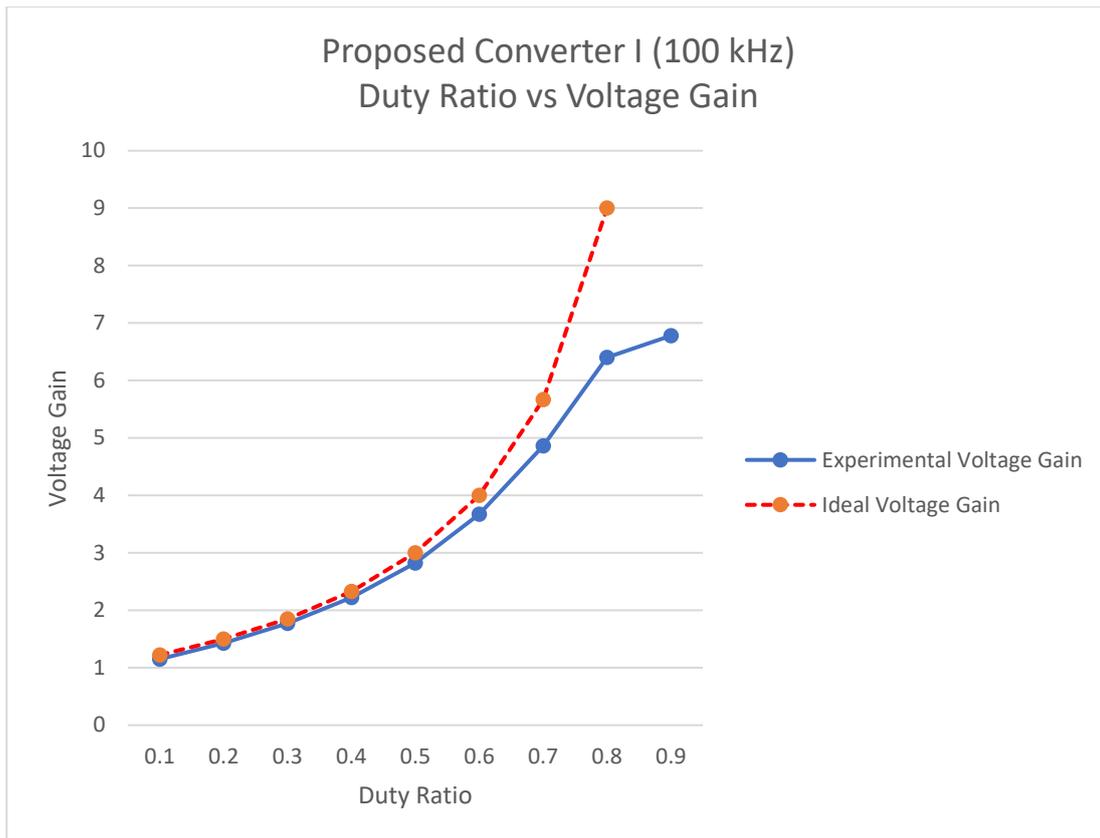Input Voltage: $V_{in} = 12\ V$

Switching frequency: $f = 100\ kHz$

Load Resistance: $R = 10\ \Omega$

D	V_{in}	I_L	I_o	V_0	Voltage Stress $\left(V_S = \dfrac{V_o}{2}\right)$	Gain $\left(V_o/V_{in}\right)$	Gain (Theoretical)
0.1	12	4.95	2.23	22.27	11.13	1.85	2.22
0.2	12	6.58	2.63	26.26	13.13	2.19	2.5
0.3	12	8.72	3.05	30.44	15.22	2.54	2.85
0.4	12	11.89	3.56	33.57	16.78	2.78	3.33
0.5	12	16.95	4.22	42.24	21.12	3.52	4
0.6	12	25.68	5.12	51.22	25.61	4.27	5
0.7	12	42.4	6.35	63.49	31.74	5.29	6.67
0.8	12	78.42	7.84	78.42	39.21	6.53	10
0.9	12	158.4	7.94	79.37	39.68	6.61	20
0.95	12	212.4	5.33	53.28	26.64	4.44	40

Table 4.5: *Comparison of parameters of proposed converter II*

D	P_{in} (W)	P_o (W)	η (%)
0.1	59.4	49.66	83.6
0.2	78.96	69.06	87.46
0.3	104.64	92.84	88.72
0.4	142.68	119.51	83.76
0.5	203.4	178.25	87.71
0.6	308.16	262.25	85.1
0.7	508.8	403.22	79.25
0.8	941.04	614.81	68.2
0.9	1900	630.2	33.17
0.95	2544	283.98	11.16

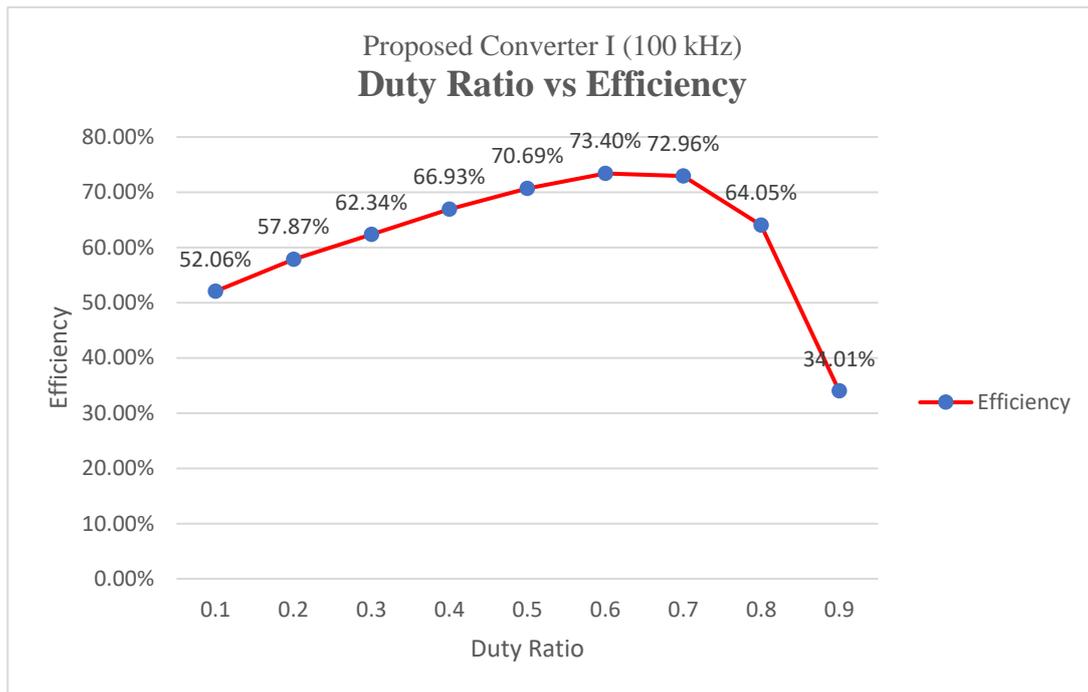***Table 4.6****: Proposed converter II- comparison of input power, output power and efficiency with different duty cycles*

Figure 4.7: *Proposed converter II graph for duty ratio vs voltage gain*
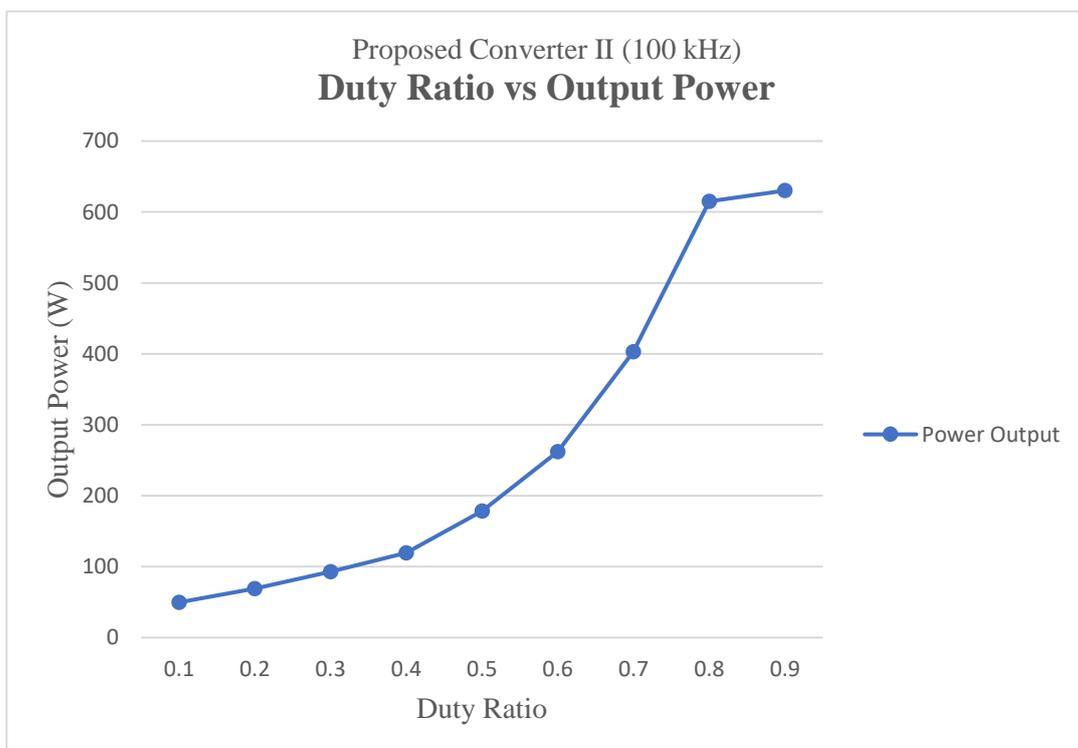
Figure 4.8: *Proposed converter II graph for duty ratio vs output power*
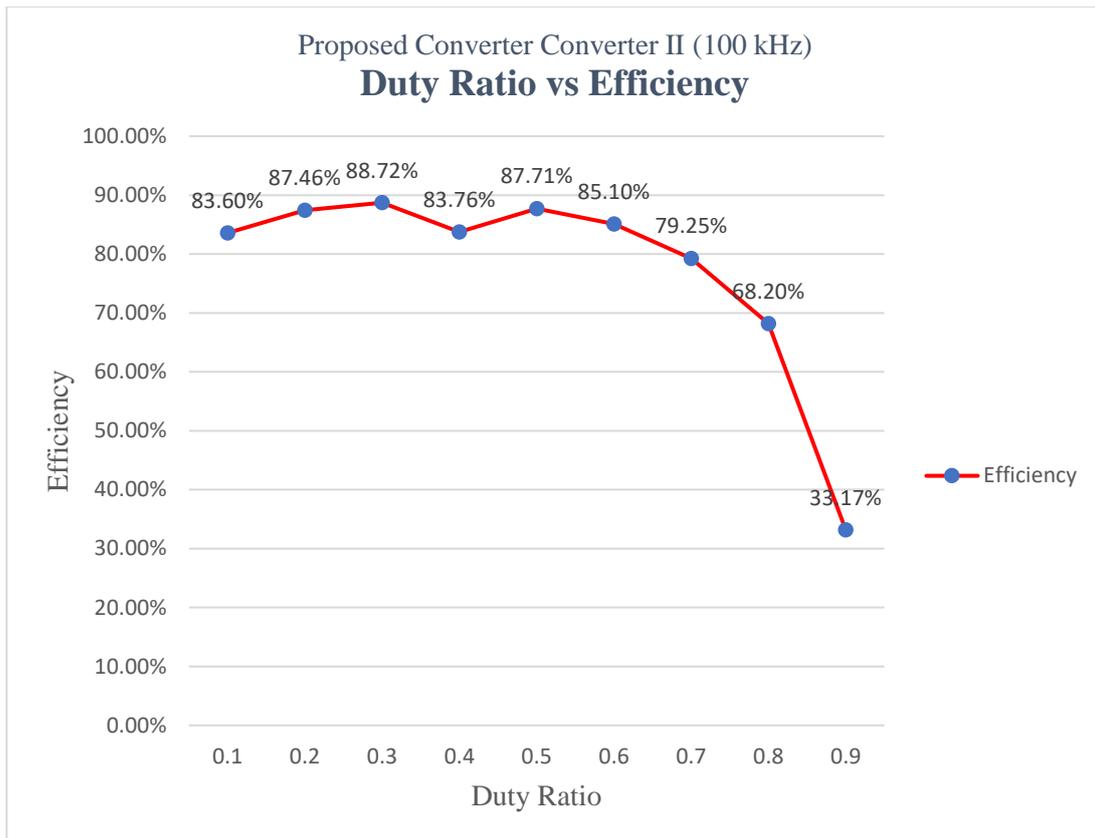
Figure 4.9: Proposed converter II graph for duty ratio vs efficiency

4.1.4. Comparison study on Proposed Converter III

A Proposed Converter is designed and simulated in MATLAB to study its various parameters.

Specifications:

Input Voltage: $V_{in} = 12\ V$
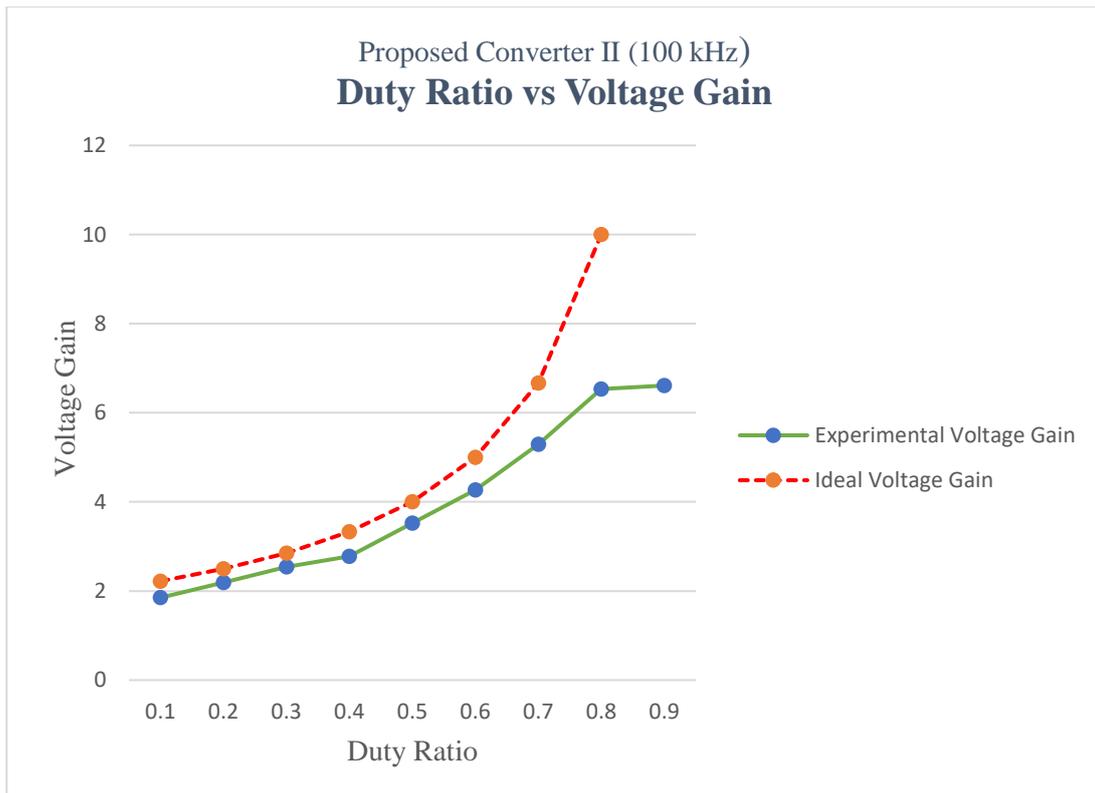
Switching frequency: $f = 100\ kHz$

Load Resistance: $R = 10\ \Omega$

D	V_{in}	I_L	I_o	V_0	Voltage Stress $\left(V_S = \dfrac{V_o - V_{in}}{2}\right)$	Gain $\left({V_o}/{V_{in}}\right)$	Gain (Theoretical)
0.1	12	8.19	2.9	29.04	8.52	2.42	3.22
0.2	12	11.02	3.42	34.24	11.12	2.85	3.5
0.3	12	13.6	3.86	38.64	13.32	3.22	3.86
0.4	12	16.97	4.36	43.58	15.79	3.63	4.33
0.5	12	21.22	4.97	49.71	18.85	4.14	5
0.6	12	28.82	5.77	57.66	22.83	4.81	6
0.7	12	45.39	6.81	68.09	28.04	5.67	7.67
0.8	12	79.83	7.98	79.84	33.92	6.65	11
0.9	12	154.9	7.76	77.57	32.78	6.46	21
0.95	12	207.9	5.21	52.08	20.04	4.34	41

Table 4.7: *Comparison of parameters of proposed converter III*

| D	P_{in} (W)	P_o (W)	η (%)
0.1	98.3	84.22	85.67
0.2	132.27	117.1	88.53
0.3	163.24	149.3	91.46
0.4	203.68	190.01	93.29
0.5	254.7	247.06	97
0.6	345.84	332.69	96.2
0.7	544.68	463.69	85.13
0.8	957.96	637.12	66.51
0.9	1858.8	601.94	32.38
0.95	2494.8	271.34	10.88

Table 4.8*: Proposed converter III- comparison of input power, output power and efficiency with different duty cycles*
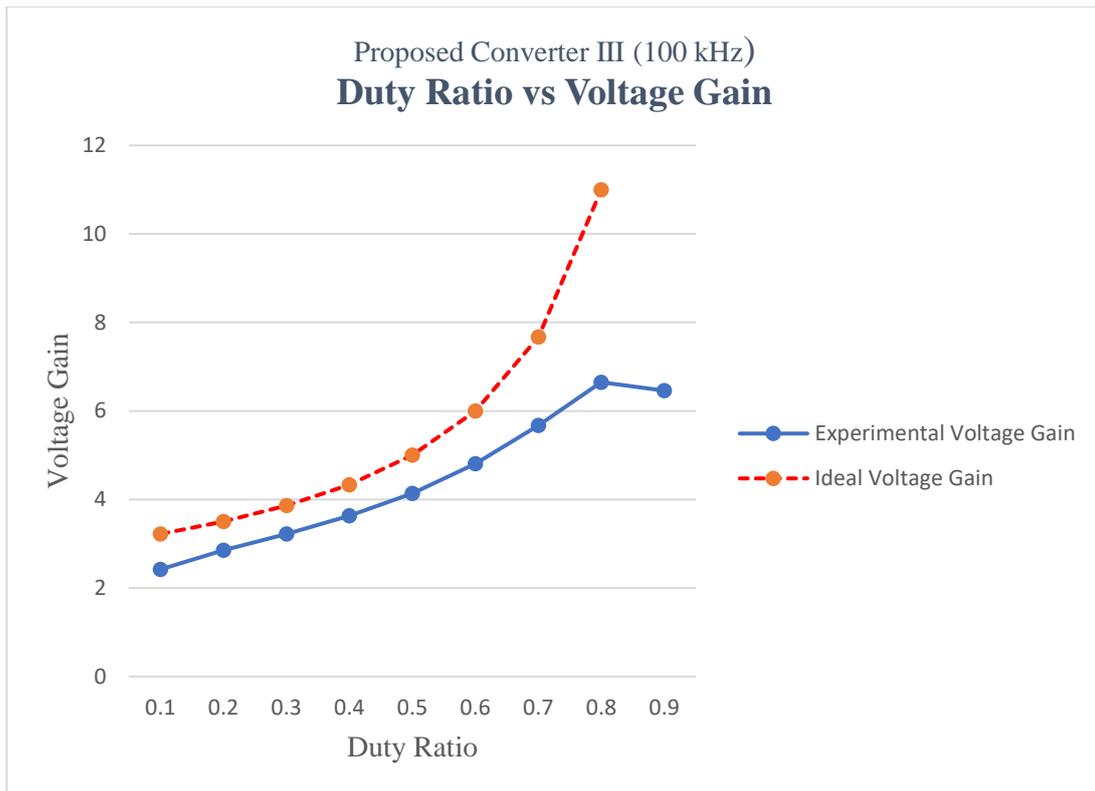
Figure 4.10: *Proposed converter III graph for duty ratio vs voltage gain*
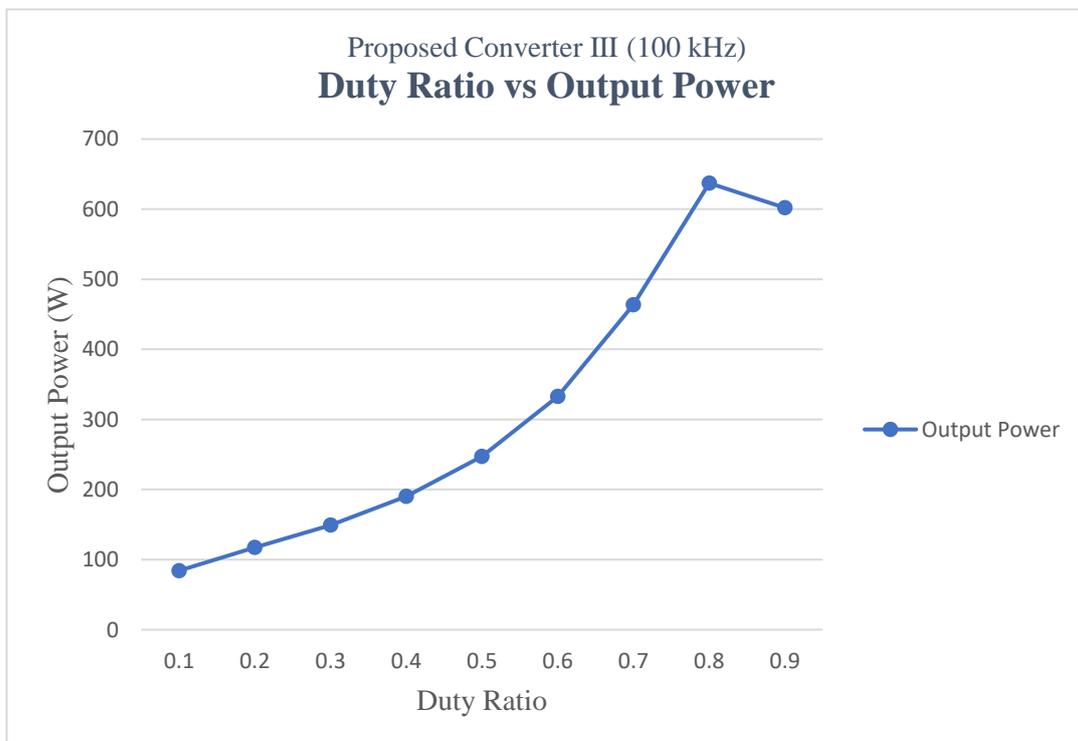
Figure 4.11: *Proposed converter III graph for duty ratio vs output power*
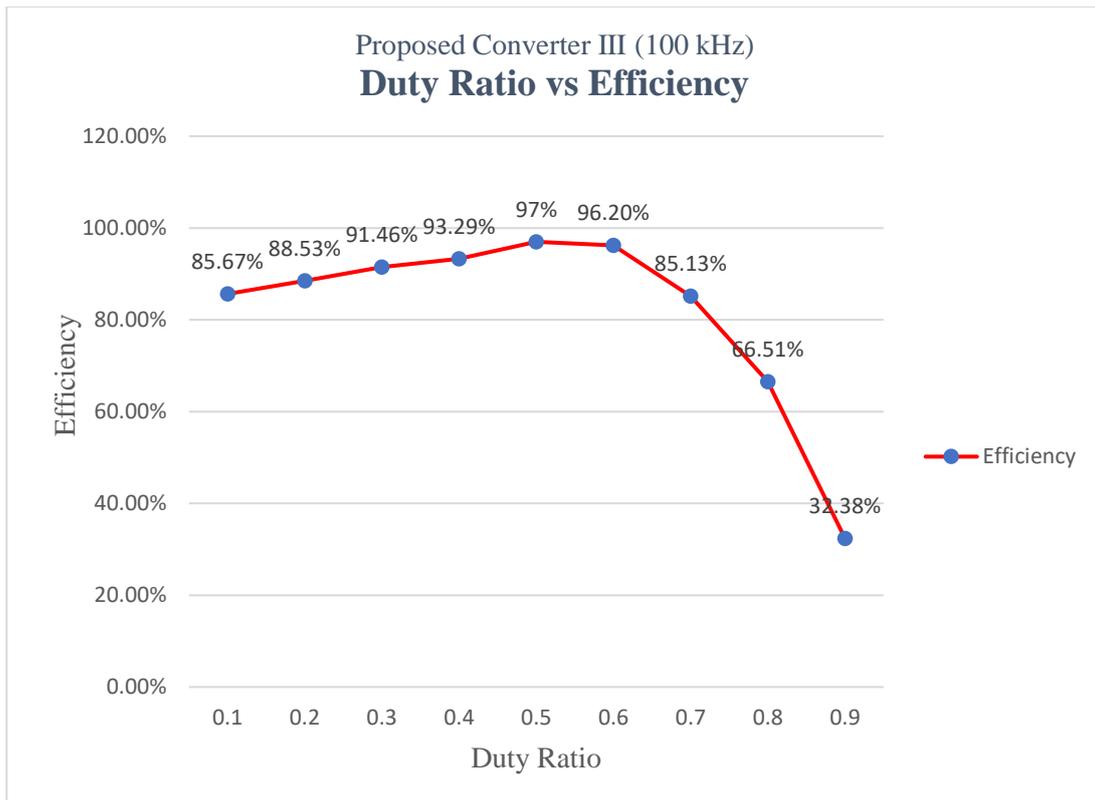
Figure 4.12: *Proposed converter III graph for duty ratio vs efficiency*

4.2. Comparison Study on Voltage Gain:

Duty Ratio (D)	Voltage Gain (Experimental)			
	Simple Boost Converter	Proposed Converter I	Proposed Converter II	Proposed Converter III
0.1	1.04	1.15	1.85	2.42
0.2	1.19	1.43	2.19	2.85
0.3	1.36	1.77	2.54	3.22
0.4	1.59	2.22	2.78	3.63
0.5	1.9	2.82	3.52	4.14
0.6	2.35	3.67	4.27	4.81
0.7	3.04	4.86	5.29	5.67
0.8	4.11	6.4	6.53	6.65
0.9	5.23	6.78	6.61	6.46

Table 4.9: Voltage gain comparison of different converters
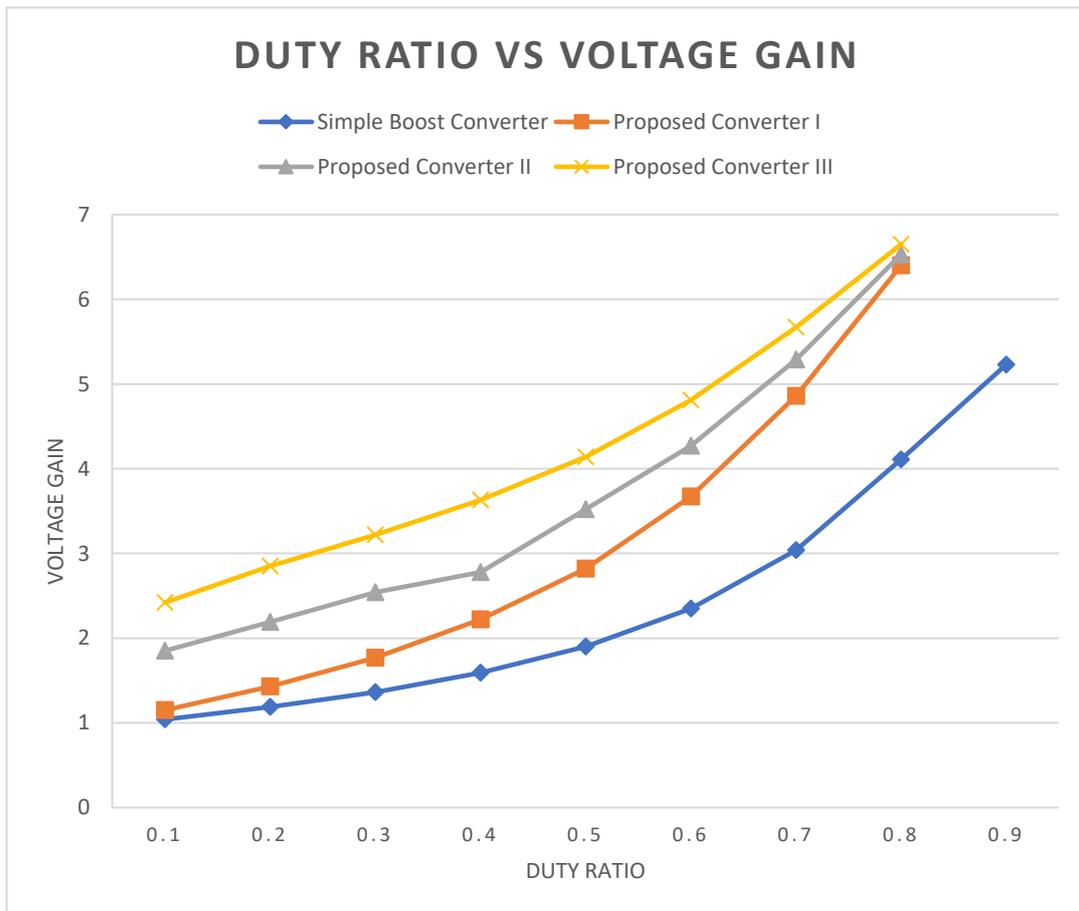
Figure 4.13: Voltage gain comparison of different converters

4.3. Comparison Study on Output Power

Duty Ratio (D)	Output Power (Experimental)			
	Simple Boost Converter	Proposed Converter I	Proposed Converter II	Proposed Converter III
0.1	15.83	19.17	49.66	84.22
0.2	20.19	29.58	69.06	117.1
0.3	26.83	45.26	92.84	149.3
0.4	36.29	71.16	119.51	190.01
0.5	51.96	114.95	178.25	247.06
0.6	79.83	193.6	262.25	332.69
0.7	133.01	339.89	403.22	463.69
0.8	243.99	589.52	614.81	637.12
0.9	394.45	662.43	630.2	601.94

Table 4.10: *Output power comparison of different converters*
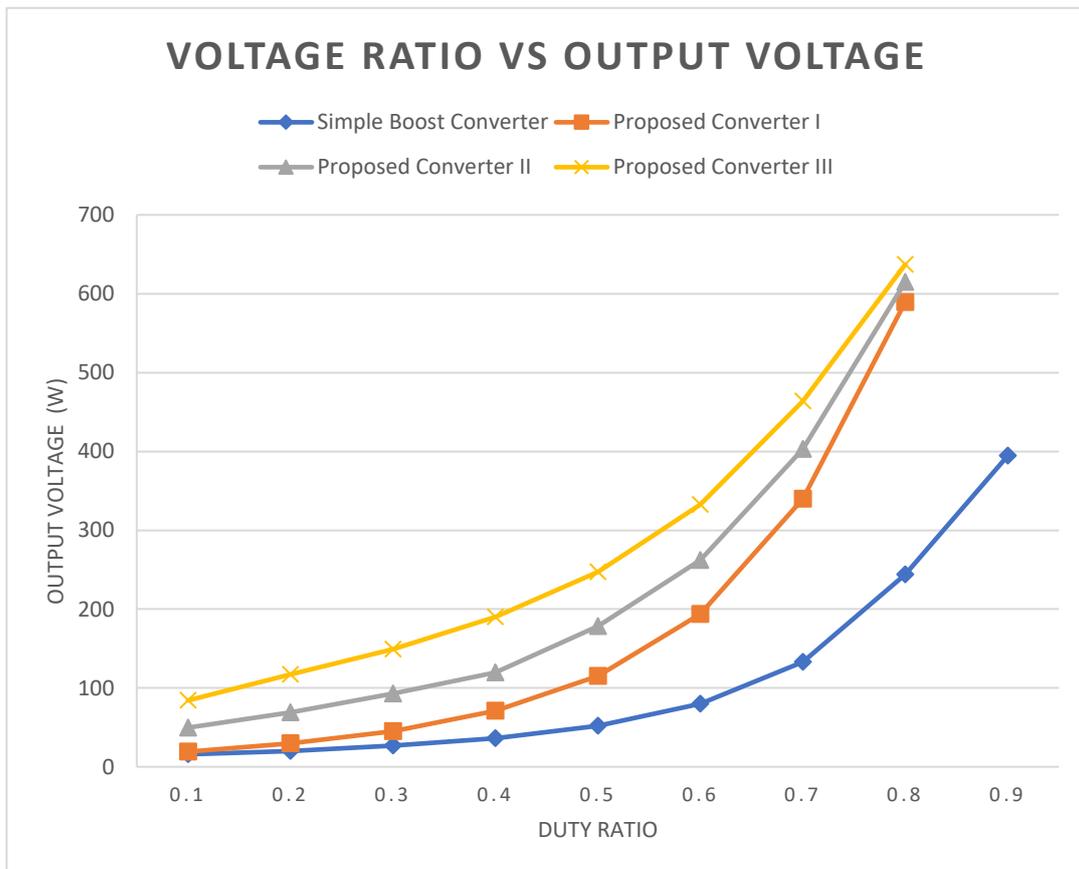
Figure 4.14: Output voltage comparison of different converters

4.4. Comparison Study on Voltage Stress

Duty Ratio (D)	Voltage Stress Voltage Stress (V_s)			
	Simple Boost Converter	Proposed Converter I	Proposed Converter II	Proposed Converter III
0.1	12.56	12.92	11.13	8.52
0.2	14.22	14.6	13.13	11.12
0.3	16.36	16.62	15.22	13.32
0.4	19.1	19.31	16.78	15.79
0.5	22.79	22.95	21.12	18.85
0.6	28.21	28	25.61	22.83
0.7	36.47	35.15	31.74	28.04
0.8	49.39	44.38	39.21	33.92
0.9	62.81	46.69	39.68	32.78

Table 4.11*: Voltage stress comparison of different converters*
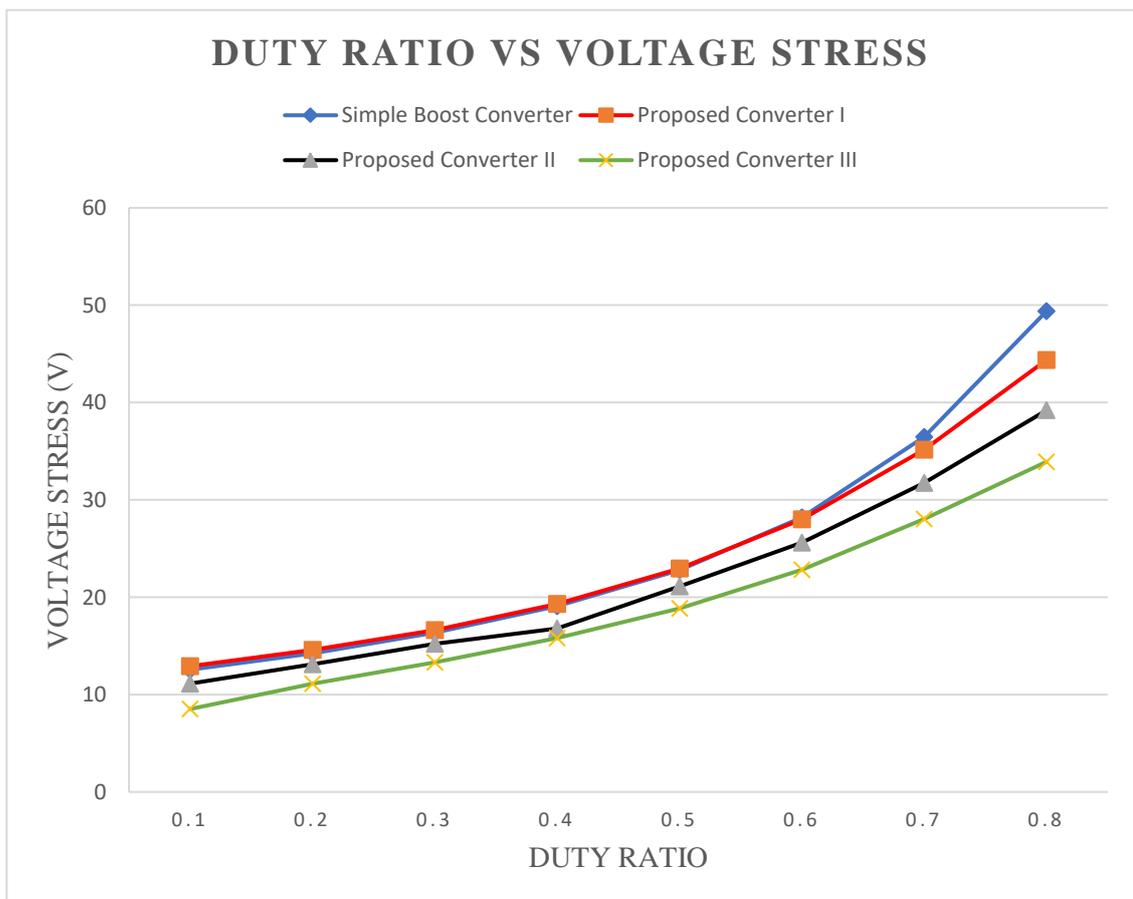
Figure 4.15: *Voltage stress comparison of different converters*

CHAPTER – V

Conclusion

5.1. Conclusion

The Simple Boost Converter and three proposed transformerless converters (Proposed Converter I, Proposed Converter II, and Proposed Converter III) have been studied here. This study involves creating mathematical models, running MATLAB simulations, and validating the results through experimentation. The voltage gain, output power, efficiency, and voltage stress of these three transformerless converters have been thoroughly examined by varying the duty ratio of the converters. The same specifications have been used for each transformerless converter to conduct a comparative study by observing changes in various parameters with changes in duty ratio. Although no single topology can be declared the best overall, it is evident that these types of converters have their places. Ultimately, the designer's decision is to select a topology that offers maximum benefits.

However, the proposed transformerless converters show clear advantages over the simple boost converter in various aspects. Firstly, by examining the changes in parameters, it is clear that the proposed converters achieve a higher voltage gain compared to the simple boost converter and this indicates their ability to efficiently step up the input voltage to a higher level. This is beneficial in applications where a significant step up voltage is required without relying on bulky transformers. Secondly, experimental results have been compared with output power at different duty ratios and the results show that the proposed transformerless converters consistently deliver higher power output than the simple boost converter. This suggests that these converters are more efficient in converting input power to output power. Additionally, when comparing voltage stress at various duty ratios, it is observed that the proposed converters experience lower voltage stress compared to the simple boost converter. This reduction in voltage stress helps to improve reliability and longer lifespan of the components used in the converter. Components can be optimized for lower voltage ratings, which not only reduces the size and weight of the converter but also enhances its overall efficiency.

Therefore, the proposed transformerless converters not only offer better performance in terms of voltage gain and power output but also contribute to improved reliability, efficiency, and design optimization compared to the simple boost converter.

5.2. Future scope of the work

The study on Transformerless DC-DC converters can be effective in renewable energy systems such as solar and wind energy applications due to their capability to efficiently

manage power conversion without transformers. This study is vital for renewable energy systems that require effective power management. These converters can be very much beneficial in stepping up the voltage for electric vehicle battery management system because of compact and lightweight design.

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