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ROBUST CONTROL OF BUCK-BOOST CONVERTER USING SLIDING MODE CONTROLLER

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By Salah Hilo Mohammed AL-ATTWANI

August 2023

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science

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ABSTRACT

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A comprehensive comparative analysis of Sliding Mode Control (SMC) and Proportional-Integral-Derivative (PID) controllers is conducted by this thesis study to determine the optimal strategy for robust control in buck-boost converters. A particular focus is placed on enhancing the performance and reliability of these converters, which are recognized as crucial elements in several industries, including renewable energy systems, electric vehicles, and variable-speed drives. Due to an ever-increasing demand for higher efficiency and reliability in these applications, a critical need for control systems that can effectively manage uncertainties, parameter variations, and external disturbances without compromising on performance is identified. In response to this need, the theoretical foundations and mechanisms underlying both SMC and PID controllers are first examined by the study. SMC is renowned for its robustness against system uncertainties and disturbances. The operation of this controller in two phases, the reaching phase and the sliding phase, is studied, ensuring that stability is maintained and the desired output is followed even under challenging conditions. On the other hand, the use of a three-component strategy—proportional, integral, and derivative by PID controllers, which are traditionally favored in industrial applications, is analyzed. These controllers are found to often suffer from performance degradation when subjected to uncertainties and parameter variations. The construction and assessment of a sliding mode controller that can be robust against these challenges is aimed for by the study. This construction is benchmarked against a well-tuned PID controller, traditionally considered the choice in industrial applications. Designing, modeling, and tuning of both controllers to specific performance criteria are then undertaken. Subsequently, an evaluation of the controllers based on a series of performance indices that include stability, robustness, dynamic responsiveness, tracking precision, and disturbance rejection capacity is performed by the study. Support for the theoretical evaluations is provided by mathematical proofs and simulation models, establishing the grounds for experimental validation. The strengths and weaknesses of both SMC and PID controllers is achieved by the results. Superior robustness and disturbance rejection are demonstrated by SMC but complexities in design and tuning may be involved. PID controllers, although easier to implement, are shown to have limitations in effectively handling uncertainties and parameter variations.

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Keywords: Proportional integral controller, Sliding mode controller, Dc-dc converter, Buck-boost converter

ÖZET

KAYAN KİPLİ DENETİM KONTROL KULLANARAK BUCK-BOOST DÖNÜŞTÜRÜCÜNÜN GÜRBÜZ KONTROLÜ

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Bu tez çalışması, buck-boost dönüştürücülerde sağlam kontrol için en uygun stratejiyi belirlemek amacıyla Kayan Kipli Kontrolü (SMC) ve Oransal-Entegral-Türevsel (PID) denetleyicilerin kapsamlı bir karşılaştırmalı analizini yapmaktadır. Özel bir odak, yenilenebilir enerji sistemleri, elektrikli araçlar ve değişken hızlı sürücüler gibi birçok endüstride hayati unsurlar olarak kabul edilen bu dönüştürücülerin performansını ve güvenilirliğini artırmak üzerinedir. Bu uygulamalarda daha yüksek verimlilik ve güvenilirlik için artan bir talep nedeniyle, belirsizlikleri, parametre değişikliklerini ve dış etkileşimleri performanstan ödün vermeden etkili bir şekilde yönetebilecek kontrol sistemleri için kritik bir ihtiyaç belirlenmiştir. Bu ihtiyaca yanıt olarak, çalışma öncelikle SMC ve PID denetleyicilerin altında yatan teorik temelleri ve mekanizmaları incelemektedir. SMC, sistem belirsizlikleri ve dış etkileşimlere karşı sağlamlığı ile tanınmaktadır. Bu denetleyicinin iki fazda, ulaşma fazı ve kayma fazı, çalışması incelenmiş, böylece istikrarın korunduğu ve istenen çıkışın bile zorlu koşullar altında takip edildiği garanti edilmiştir. Diğer yandan, endüstriyel uygulamalarda geleneksel olarak tercih edilen PID denetleyicilerin üç bileşenli bir strateji oransal, entegral ve türevsel kullanımı analiz edilmiştir. Bu denetleyicilerin, belirsizliklere ve parametre değişikliklerine maruz kaldıklarında sıklıkla performans kaybına uğradığı görülmüştür. Çalışma, bu zorluklara karşı sağlam olabilecek bir kayan mod denetleyicisinin inşası ve değerlendirmesini amaçlamaktadır. Bu inşa, endüstriyel uygulamalarda geleneksel olarak tercih edilen iyi ayarlanmış bir PID denetleyici ile karşılaştırılmıştır. Her iki denetleyicinin de özgül performans kriterlerine göre tasarımı, modellemesi ve ayarı yapılmıştır. Ardından, çalışma tarafından denetleyicilerin, stabilite, sağlamlık, dinamik tepki hızı, izleme hassasiyeti ve dış etkileşim reddetme kapasitesini içeren bir dizi performans indeksi temelinde değerlendirmesi yapılmıştır. Teorik değerlendirmelere, matematiksel kanıtlar ve simülasyon modelleri ile destek sağlanmış, deneysel doğrulama için temel oluşturulmuştur. Sonuçlar, SMC ve PID denetleyicilerin hem güçlü yönlerini hem de zayıf yönlerini aydınlatmaktadır. SMC tarafından üstün sağlamlık ve dış etkileşim reddetme yeteneği gösterilmiş, ancak tasarım ve ayarlama konusunda karmaşıklıklar olabileceği belirtilmiştir. PID denetleyiciler, uygulaması daha kolay olsa da, belirsizlikler ve parametre değişikliklerini etkili bir şekilde ele alamadıkları gösterilmiştir.

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Anahtar Kelimeler: Oransal integral türev, Kayan kipli denetleyici, Dc-dc dönüştürücü, Buck-boost dönüştürücü

PREFACE AND ACKNOWLEDGEMENTS

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Salah Hilo Mohammed AL-ATTWANI
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CONTENTS

LIST OF ABBREVIATIONS

BBC	Buck-boost converter
CCM	Continuous conduction mode
CSL	Currently senseless
DC	Direct current
DCM	Discontinuous conduction mode
DSM-CC	Discrete time sliding mode current control
DBB	Double buck-boost
DIDC	Dual input dc-dc converter
EV	Electric vehicle
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
FFT	Fourier Transform
FOMCON	Fractional order modelling and control
HIL	Hardware in the loop
HIL	Hardware-in-the-loop
IC	Integrated circuit
IDOC	Integrated dual output converter
KVL	Kirchhoff's voltage law
MPPT	Maximum power point tracker
P&O	Perturb and observe
PID	proportional integral derivative
RE	Renewable energy
STBUM	Saw tooth based unipolar modulation
SMC	Sliding mode control
TEG	Thermoelectric generator
THD	Total harmonic distortion
TSBB	Two switch buck-boost
TSBB	Two-switch buck-boost
VBB	Versatile buck-boost

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1. INTRODUCTION

Adjustable speed drives, electric cars, and renewable energy systems all rely heavily on the precise regulation of power electronic converters. Because of its versatile voltage conversion capacity, the buck-boost converter is a popular architecture in various applications.

To guarantee the buck-boost converter functions effectively and reliably, it is essential to design a control system that can deal with uncertainties, parameter variations, and disturbances. Sliding mode control (SMC) is widely used because of its reliability and high performance.

When applied to a nonlinear system, SMC that the system's states travel to and stay on a specified sliding surface. Force the system dynamics to "slide" over this surface to achieve resilient performance even in the face of uncertainty; this is the core principle underPIDnning SMC. SMCs are resistant against model uncertainties and disturbances because they use switching control actions to keep the system on the sliding surface.

When controlling a buck-boost converter using SMC, the goal is to keep the output voltage or current regulated regardless of the input voltage or load. Sliding surface definition often involves converter state variables like output voltage error and inductor current error. The system states are made to follow this sliding surface by the control signals generated by the controller.

Choosing the right sliding surface characteristics and coming up with the right switching control law are the two most important parts of designing a sliding mode controller for a buck-boost converter. Specifying the intended behavior and the system's reaction to uncertainties with the sliding surface settings. For the system to be forced to slide over the surface, control signals must be created in accordance with the switching control rule.

SMC's robustness, which can manage uncertainties and disturbances that can impact the converter's functioning, is a key benefit. However, the controller's switching operation has the potential to create high-frequency harmonics, which might result in unfavorable consequences like EMI or extra losses. To address these problems, great thought must be put into the design and implementation of the SMC. The use of a SMC for robust control of a buck-boost converter allows for efficient and reliable operation, even in the presence of uncertainties and disturbances. The SMC technique provides a robust control strategy by forcing the system to follow a predefined sliding surface. By carefully designing the sliding surface and control law, the controller can regulate the converter's output voltage or current, ensuring stable and accurate performance.

1.1 Introduction to dc-dc Converter

To ensure that the entire output of each module is delivered to the load notwithstanding incompatibilities in the system, dc-dc converters may be used at the module level to convert each module from a current source to a power source. There are several possible strategies and organizational structures towards this goal. To accomplish these aims, we will look at the most common topologies to learn more about their pros and cons and how they affect the total system. Common topologies include buck converters, boost converters, and buck-boost converters, which combine the features of both.

A DC-to-DC converter is an electronic device that converts direct current, voltage from one level to another. These converters are essential components in many electronic systems, as they help stabilize and adapt voltage levels for different parts of a circuit or application. Examples of where dc-dc converters are used include battery-powered devices, automotive systems, and renewable energy systems. Here's an introduction to dc-dc converters, covering their basic principles, types, and applications.

1.1.1 Basic principles

A dc-dc converter takes an input dc voltage and filters and modulates it, often using switching techniques, to produce an output dc voltage that is stable and at the required level. The effectiveness of a dc-dc converter is crucial to the functionality and reliability of any electronic system.

1.1.2 Types of dc-dc converters

There are several types of dc-dc converters, which can be broadly categorized into the following groups:

- Non-isolated converters

These converters do not provide electrical isolation between the input and output and are generally simpler and more compact than isolated converters. Common types include:

1) Buck converters (step-down): These converters reduce the input voltage to a lower, regulated output voltage.
2) Boost converters (step-up): These converters increase the input voltage to a higher, regulated output voltage.
3) Buck-boost converters: These converters can either step up or step down the input voltage, depending on the desired output voltage.

- Isolated converters

These converters provide electrical isolation between the input and output, which can be important for safety and noise reduction. Common types include:

1) Fly back converters: These converters use a transformer to provide isolation and can step up or step down the input voltage.

2) Forward converters: These converters also use a transformer for isolation, but tyPIDcally have a simpler topology and are more efficient than fly-back converters.

1.1.3 Applications of dc-dc converters

Dc-dc converters are used in a wide range of applications, including:

1) Power supplies: Many electronic devices require multiple voltage levels, and dc-dc converters help provide these levels from a single power source.
2) Battery-powered devices: Portable devices often require voltage regulation to ensure consistent performance as the battery voltage drops during discharge.
3) Automotive systems: Vehicles have numerous electronic systems that require different voltage levels, making dc-dc converters essential for proper operation.
4) Renewable energy systems: Solar panels and wind turbines generate varying voltage levels that need to be converted and regulated for use in grid-connected or off-grid applications.

1.2 Background and Motivation

The buck-boost converter is a fundamental power electronic topology used in a wide range of applications. It provides the capability to convert and regulate voltage levels, making it essential for renewable energy systems, electric vehicles, and adjustable speed drives. However, the performance and robustness of the buck-boost converter can be compromised by uncertainties, parameter variations, and disturbances commonly encountered in practical applications.

In the face of these difficulties, conventional control methods like proportional-integral-derivative (PID) control or proportional-resonant control may not provide enough resilience and performance. Due to this constraint, researchers are investigating more sophisticated control techniques, such as SMC, to enhance buck-boost converter control.

The motivation behind using SMC for the control of buck-boost converters lies in its inherent robustness properties. SMC is a nonlinear control technique that can handle uncertainties and disturbances by forcing the system states to slide along a predefined surface. This characteristic makes it particularly well-suited for power electronic systems where uncertainties and disturbances can have a significant impact on the system's performance.

Even in the face of parameter fluctuations, load changes, and disturbances, the buck-boost converter's output voltage or current may be tightly regulated using the SMC approach. The SMC actively pushes the system states to follow the intended sliding surface by applying to switch control actions, assuring stability and precision in the control process.

Additionally, SMC has benefits including ease of use, quick reaction, and insensitivity to model uncertainty. Due to its advantages over traditional control methods in terms of transient responsiveness, tracking precision, and disturbance rejection, it is a desirable option for regulating buck-boost converters.

The research on the robust control of buck-boost converters using SMCs aims to overcome the limitations of traditional control methods and explore the potential of SMC in achieving high-performance control in challenging operating conditions. By developing an effective and robust control strategy, researchers seek to enhance the efficiency, reliability, and overall performance of buck-boost converter-based systems, ultimately advancing the field of power electronics and its applications in renewable energy, transportation, and industrial sectors.

1.3 Research Objectives

The electronic switches in dc-dc converters are power semiconductor devices. Since switching devices are used to operate dc-dc converters, including the buck converter, it might have a nonlinear feature. Simply using a buck converter results in an output voltage that is often unstable, oscillates, has a significant overshoot, and is slow to settle. When the input voltage and load change, it also fails to provide the necessary voltage. So, this converter needs a controller with a lot of dynamic reactivity. PID controllers are often employed in converters because they regulate voltage easily.

In the case of non-linear systems, however, PID controller implementations fail to provide reliable and appropriate results. As a consequence, the rising and settling periods of the buck converter's output voltage are affected negatively, and it's hard to account for fluctuations in the system's characteristics. Therefore, in this thesis, a SMC for buck-boost converters will be developed to improve the performance of the converter.

The following goals may be taken into account while performing research on the reliable control of a buck-boost converter using a SMC:

1. Controller design: To manage the output voltage or current of the buck-boost converter, create a reliable SMC. Uncertainties, parameter changes, and disruptions often seen in real-world applications should all be taken into account while designing the controller.
2. Stability analysis: completely examine the suggested SMC system's stability. Look at the stability requirements and robustness characteristics to make sure the controlled system maintains stability and performs well under a variety of operating scenarios.
3. Performance Evaluation: Evaluate the SMC-based control system's performance in terms of dynamic reaction, tracking precision, and disruption rejection power. To illustrate the benefits of SMC, contrast the performance of the suggested control strategy with those of already-in-use control strategies like PID control or proportional-resonant control.
4. Analysis of robustness: Examine how resistant the SMC system is to ambiguities and parameter changes. Take into account relevant elements including component tolerances, temperature fluctuations, and load shifts. Analyze the controller's capacity to continue operating steadily and precisely in the midst of these interruptions.
5. Comparative study: Perform a comparison with various regularly used control systems for buck-boost converters. Consider the SMC approach's performance, robustness, and complexity in comparison to other control systems to identify its benefits and drawbacks.

Reliable control methods for buck-boost converters using sliding-mode controllers can be promoted by focusing on these research objectives. This will enhance the effectiveness, reliability and performance of electronic power systems in a variety of applications.

1.4 Thesis Organization

The thesis is structured into five main chapters, detailed as follows:

Chapter 1 delves into the dc-dc Converter, covering its foundational concepts, historical context, and the rationale behind its application in power electronics.
Chapter 2 offers a concise background, exploring the literature, defining the problem, and outlining the research methodology.
Chapter 3 explores various dc-dc converter topologies, evaluating their respective pros and cons. This chapter also delves into a comprehensive analysis of the design requirements for the proposed device.
Chapter 4 stands as the pivotal segment of the thesis, showcasing the experimental system setup and outcomes using two control theories: PID and SMC.
Chapter 5 recaps the research and offers insights into potential future developments in this field.

2. LITERATURE REVIEW

2.1 Overview of Buck-Boost Converters and Applications

A dc-dc converter known as a buck-boost converter can adjust the output voltage by stepping up or down the input voltage level. It is a flexible power electrical gadget that has uses across a range of sectors. An overview of buck-boost converters and their uses is given below:

2.1.1 Principle of operation for buck-boost converter

1) A buck-boost converter converts dc voltage by using a mixture of inductors, capacitors, and switches. It has two modes of operation: boost mode and buck mode.
2) Buck Mode: The input voltage is greater than the output voltage in this mode. With the converter acting as a step-down (buck) regulator, the load is supplied with a lower voltage.
3) Boost Mode: The input voltage is less than the output voltage in this mode. The converter serves as a step-up (boost) regulator, supplying the load with a greater voltage.

2.1.2 A buck-boost converter applications

Buck-boost converters are widely used in various industries due to their ability to provide regulated voltage levels desPIDte variations in input voltage. Some common applications include:

- Battery powered devices: To manage the battery voltage to the necessary levels in portable electronic devices like smartphones, tablets, and laptops, buck-boost converters are often utilized.

- Automotive electronics are utilized in systems for numerous components, including infotainment systems, LED lights, and sensors, to step up or step down the battery voltage.
- Renewable energy systems: By altering the voltage levels to meet the demands of the grid or the associated energy storage system, buck-boost converters play a significant role in solar power systems and wind turbines.
- LED lighting: Buck-boost converters are often used in LED drivers to control the input voltage and current to ensure the dependable and efficient functioning of LED lights.
- Electric vehicles: To control the voltage levels between the battery pack, motor, and other components, buck-boost converters are utilized in the powertrains of electric vehicles.
- Power banks: These on-the-go chargers use buck-boost converters to control voltage while charging a variety of gadgets, including Bluetooth earbuds, tablets, and smartphones.

2.1.3 Advantages of buck-boost converters

Buck-boost converters offer several advantages, including:

- Voltage regulation: DesPIDte changes in the input voltage, they can maintain a constant output voltage.
- Flexibility: Buck-boost converters are appropriate for a variety of applications since they can step up or step down the voltage.
- Effectiveness: Contemporary buck-boost converters have great conversion effectiveness, minimizing power losses.
- Small size: They are suited for portable and limited-space applications since they may be made to be small.

2.2 Review of control techniques for Buck-Boost Converters

PID Control and SMC are control techniques used in various engineering applications to achieve desired system behavior. Here's an introduction to each of these control methods.

2.2.1 PID control system

PID Control is a well-known control method that is used in a broad range of applications. It offers control measures based on the proportional, integral, and derivative terms of the difference between the intended set point and the measured process variable. By integrating these three terms, the PID controller determines the control output:

1) Proportionate Term: This term results in a control action proportionate to the present mistake.
2) Integral Term: It gathers the previous mistakes to get rid of steady-state errors and enhance the system's reaction to ongoing disruptions.
3) Derivative Term: It forecasts the future trend in mistakes and generates a control action to thwart the error's quick alterations.

PID control delivers resilience, simplicity, and ease of application in a variety of control settings.

2.2.2 Sliding mode control

SMC is an effective control method that makes sure the system's state trajectory arrives and maintains itself on a preset "sliding surface" The control rule changes the dynamics of the system to drive the trajectory onto this surface, providing precise control even when there are uncertainties and disruptions. The main attributes of SMC include:

1) Sliding Surface: It establishes the intended system behavior and aims to direct the system's state towards a predetermined trajectory.
2) Switching Control Law: It directs the system in the direction of the sliding surface and maintains the action of sliding.
3) Robustness: SMC has a reputation for being resistant to parameter changes and disturbances, which makes it a good choice for managing nonlinear and unpredictable systems.

2.3 Previous Studies on Buck-Boost Converters

The literature review of the study, as well as the literature review for converters based on photovoltaic applications, including historical dc-dc converter system research, will be covered in this section. According to the literature review, knowledge should be expanded, and the suggested system should be better understood.

Naresh and Peddapati (2021), proposed a unique continuous input quadratic buck-boost converter created using two diodes, two active switches that can be controlled concurrently, and two fourth-order energy storage devices. This analysis explains the converter's operation through time-domain key waveforms, considering factors such as the voltage conversion ratio, electrical stress on the power switching devices, circuit design characteristics, boundary conditions, non-ideal voltage gain, and comparisons with other buck-boost converters. MATLAB is employed to model both the boost and buck modes of operation to evaluate performance. The novel converter is particularly suited for renewable energy production due to its continuous input, wide-range voltage gain, and enhanced power density.

Mahajan *et al.* (2017) analyze a DC-DC current buck-boost converter using the concept of duality. Similar to traditional buck-boost converters, this one also offers adjustable current regulation suitable for drives and SMPS. Detailed MATLAB models and mathematical analysis of the proposed circuit are presented. The findings confirm that the recommended circuit operates as expected.

Saodah and Utami (2018) focuses on developing and optimizing a nonlinear controller for a buck-boost converter to stabilize the output voltage of PV production in DC microgrids. The proposed controller design is twofold: linear and nonlinear. The PID controller is employed to regulate the output voltage loop, while hysteresis control is used for managing the inductor current ripple. The ON/OFF trigger points for the hysteresis control are set based on the magnitude of the ripple observed in the inductor current. The functionality of the proposed buck-boost converter controller was validated using a simulation in MATLAB®/SIMULINK®.

A buck-boost converter is designed to adjust the input dc voltage to deliver a specific output dc voltage. It can be employed to convert a fluctuating voltage into a stable one, based on user requirements. This research centers on three main components: the rectifier, boost converter, and inverter. The system begins with an inconsistent ac input linked to a rectifier. This rectifier then guides a buck-boost converter to generate a stable dc output. When this output is connected to an inverter, it produces a consistent ac voltage set to the desired level. Using both an AC-to-AC converter and the buck-boost converter, the standard 220 V AC from the sources can be reliably upheld (Suryadi *et al.* 2020).

López *et al.* (2021), assess the efficacy of three MPPT techniques: constant voltage (CV), perturb and observe (P&O), and incremental conductance (IncCond) in conjunction with the Buck and Buck-Boost dc-dc power converter configurations. Our findings indicate that the CV/Buck-Boost pairing exhibits superior transient behavior, whereas the IncCond/Buck pairing delivers optimal steady-state efficiency when the PV system operates under varied radiation and temperature conditions. This research is PIDvotal, as it facilitates a comprehensive comparison of the overall performance across different MPPT/converter pairings.

Farah *et al.* (2020), the behavior of a non-inverting buck-boost converter is improved by the design suggested in this study, which is based on peak current management. It makes use of LDMOS transistors with a low on-resistance and is made to work with changeable output voltage. The results demonstrate the suggested buck-boost converter's flawless performance in comparison to alternative designs and its successful implementation utilizing 0.18 m CMOS TSMC technology. At a load current of 4 A, the power conversion efficiency for the three operating modes is 97.6%, 96.3%, and 95.5%.

(Javed *et al.* 2021), the system pre-converter's transfer function with optimal current control served as the foundation for the construction of the voltage regulator. In order to find a potential regime solution for a sinusoidal power supply, the system equation must first be determined. The calculations are checked using MATLAB/Simulink on a system with two paralleled buck-boost converters. In the simulation, a feed-forward control mechanism is used.

(González *et al.* 2021) designed an innovative dc-dc bidirectional buck-boost converter for integration between the battery pack and the inverter to stabilize the dc-bus. This creation is anchored on the adaptive buck-boost converter, which has proven its mettle in various fuel cell applications, especially where low input voltage and swift switching times are paramount. To uphold the DC-bus voltage, we've deployed a digital two-loop control strategy. This strategy amalgamates a discrete-time sliding-mode current control (DSM-CC) inner feedback loop with a PID control outer feedback loop. The PIDvotal digital control loops, along with the transition mode methodology, are facilitated by a digital signal controller: the TMS320F28377S. Our prototype, rated at 400 V and 1.6 kW, underwent rigorous testing both in simulations and within an EV powertrain system, corroborating the theoretical projections.

To enhance the electric motor's efficiency, this research proposes using a versatile buck-boost dc-dc converter in an electric vehicle's composite design, which necessitates a wide voltage range in the dc link. This buck-boost converter features a flexible inductor core tailored for high-voltage applications. PLECS thermal simulations of the composite layout indicate that the proposed topology surpasses the traditional non-inverting buck-boost converter under identical operating conditions. To demonstrate the practical implications, a 4.4 kW hardware-in-the-loop (HIL) real-time simulation system is facilitated using a PLECS RT Box 1. The results from the HIL simulation corroborate both the theoretical analysis and the merits of the proposed design (González-Castaño *et al.* 2022).

The buck-boost converter control approach for maximum power point tracking (MPPT) photovoltaic applications proposed in this study is currently sensorless (CSL). The suggested control method derives a preset goal function for the MPPT control from the buck-boost converter's mathematical model. The suggested approach is implemented effectively in a MATLAB/Simulink/State flow system, and its efficacy is contrasted with that of perturb and observe (P&O) approach. For the digital implementation, an Arduino prototype platform is employed, and an experimental rig is used for the experimental validation. The installation costs for sensors and the computational load have been cut by 24.3% and 27.95%, respectively, using the suggested strategy (Obeidi *et al.* 2022).

Miao and Gao (2019), Two inverting buck-boost converters with a range of conversion ratios are suggested in this research. A high step-down gain is achieved by the IB2BC, a high step-up gain is achieved by the IBB2C. The fourth-order simple common-ground architecture, minimal component stress, and lack of abrupt changes in capacitor voltage are benefits of the IB2BC and IBB2C. They build extensional topologies with broader conversion ratios and enhanced single-switch topologies with fewer switches. The aforementioned buck-boost converters' operational concepts and associated comparisons are examined. To test the performance of the family of buck-boost converters, the step-down and step-up modes of the single-switch inverting buck-boost2 converter (SIBB2C) were tested.

Moon *et al.* (2017), a two-switch buck-boost non-isolated dc-to-dc converter (TSBB) may alter its mode by adjusting gate signals. In contrast to a traditional TSBB, the unique redesigned topology of the converter presented in this study includes fewer conduction components and switching semiconductors, which reduces power loss. A benefit of using a gate driver integrated circuit (IC) is that the metal-oxide-semiconductor field effect's source terminals transistors are directly linked to the ground. To assess the suggested converter's improvement, a printed circuit board was created.

In other research, a design proposition by (Li and Chen 2021) to enhance the system's static and dynamic performance, it's imperative to transform the initial nonlinear system into a hybrid of a linear subsystem and a nonlinear one. This involves applying the linear optimal control theory for the linear subsystem's control design and subsequently adjusting the output function's coefficient along with the feedback coefficient of the linear control directive. Simulations validate that this multi-index feedback linearization control method stands as a more effective and superior option when crafting the buck-boost converter's nonlinear control guideline.

Jung *et al.* (2018) boost, buck, and buck-boost modes are all possible with a conventional two-switch buck-boost converter (TSBB). In this research, a new design for a buck-boost converter with two switches and the identical operational modes is introduced. The power losses of the proposed TSBB converter are reduced because it uses fewer conductions and switching components than a conventional TSBB converter.

Babazadeh *et al.* (2022), present a novel interleaved bidirectional buck-boost DC-DC converter with reduced input current ripple. It may be used with solar panels and fuel cells, two sustainable energy sources. The advantages of the converter's reduced input current ripple are shown by its detailed operating principle and power loss computation. Results from a comparison show that the suggested converter provides continuous input current with reduced ripple, unlike traditional interleaved buck-boost converters and other similar designs. An experimental prototype is tested in the lab to ensure the reliability of theoretical research.

Agrawal *et al.* (2022), proposed dc-dc converter in this study has a wider gain range and can function as a buck-boost converter. The tyPIDcal buck-boost converter offers significant gain at duty ratios close to unity, however, because the inductor is connected to the source in a short circuit, a capacitor discharge takes place and impacts the connected load. The suggested converter solves this issue by using two MOSFETs and two diodes. The converter is given a thorough analysis, which covers switch realization, gain formulation, design considerations, and a controller for closed-loop operation. If the diodes are replaced with MOSFETs, The suggested converter might perform the synchronous conversion, and if all the semiconductor switches are replaced with four-quadrant switches, the converter can be utilized to drive an AC load. The converter is simulated using MATLAB, and associated waveforms are shown. The hardware arrangement for the suggested converter's practical validation is currently being developed.

Eya *et al.* (2022), analyze the total harmonic distortion (THD) of buck-boost dc-ac converters, comparing them with converters employing either triangle wave-based or saw-tooth unipolar-based modulation. Utilizing the powerful graphical user interface (GUI) Fast Fourier Transform (FFT) analysis tool in MATLAB Simulink, we assessed the output voltage and current of the buck-boost dc-ac converter. Our findings reveal that the triangle wave-based-unipolar modulation technique outshines the saw-tooth-based-unipolar modulation in power factor efficiency and power loss reduction, thereby enhancing the overall performance of the buck-boost converter system. The triangular wave-based-unipolar modulation (TWBUM) method is ideal for critical power electrical applications, such as those in the medical and communication sectors. Conversely, the saw-tooth-based-unipolar modulation (STBUM) is more apt for powering heavy machinery and power drives, given its capability to handle high current and maintain a low THD%.

Ammar (2020), the majority of applications, including solar systems and microgrids, need a power dc-dc converter. These applications call for steady output voltage under various load conditions. Therefore, dc-dc power converters are necessary for the controller's current and output voltage in order to increase the controller's resilience. For the load current buck-boost converter, PID controllers are constructed in this study. Additionally, PID controllers for buck-boost converters with output voltage are being researched. Additionally, this study takes into account varying input voltage and changing loads. This project's PID controller proposal increased robustness and accelerated the rate at which the system achieved a steady state.

Akram (2018), investigates the relationships between the Buck-Boost converter's non-minimum phase characteristics. The duty ratio $D>0.382$ of the converter with its pre-designed inductor and load are proven to be how the converter determines the negative regulation voltage. When the Buck-Boost converter operates in Buck mode. When the Buck-Boost converter operates in Boost mode, the duty ratio has a limited impact on the converter's negative regulatory voltage since the voltage undershoots will be more severe the higher the output voltage. The paper's conclusion provides advice on how to lower the negative regulatory voltage of the Buck-Boost converter. Finally, simulations and tests are used to confirm that the analysis for the non-minimum phase is valid.

Mohapatra *et al.* (2019), a hybrid model is an appealing and rather straightforward alternative for simulating a dc-dc converter since it does not need short simulation steps, is applicable across the whole converter's operating range, and supports both continuous and discontinuous conduction modes. This piece aims to persuade the reader to apply it in a few common circumstances. Using State chart approaches, the hybrid model of the DC-DC Buck-Boost converter is put into practice. This converter model may be used as a building block with appropriate interfaces to the SimPowerSystem and Simulink environments since it was created in the State flow language, a tool from the MATLAB®/Simulink environment. The block is verified by comparing calculations made using well-known and tested formulae to simulation results realized under various operating situations. The usage of a buck-boost dc-dc converter with voltage and current control loops is an illustration of how the block is put to use.

Ado *et al.* (2020), In order to use renewable energy (RE) in the transportation sector, a prototype impedance source buck-boost converter (BBC) is suggested. To get the gain curve of the BBC, it uses a dc-dc quasi–impedance source converter topology (q–ZSCs). The ability to efficiently buck-boost at the efficient duty ratio range of 0.35 to 0.65 as well as continuous and non-zero gain at the efficient duty ratio range provide these devices an edge over the two other types of non-isolated dc-dc q-ZSCs. The converter can use asymmetric components and high switching frequencies to obtain BBC gain while employing fewer components to lower cost, weight, and footprint. For certain specified requirements, its simulated response and a similar BBC's reaction were contrasted, presented, and analyzed. For testing purposes, a scaled-down prototype was also created. By examining the converters' answers, the prototype's second order filtering—as opposed to the first-order filtering in traditional BBC—was confirmed.

Andrade *et al.* (2022), In order to offer clean energy with minimal to no environmental effects, this study examines the usage of fuel cells in dc microgrids. The fuel cell voltage must be converted to the reference voltage of the dc microgrid using a power converter. In this kind of application, buck-boost topologies are often used, and the literature offers a number of dc-dc buck-boost topologies. In addition to listing, contrasting, and describing many dc-dc buck-boost topologies, this study also discusses certain design issues and suggests further research.

Chen *et al.* (2022), new energy vehicles are required by the carbon peak carbon neutral technique to balance the unpredictable energy in the lithium battery pack. This problem is recommended to be fixed by balancing the unequal energy in the battery pack using a cascaded buck-boost converter. A matrix equalization approach has been developed and refined, and this equalization circuit has two primary operational modes. The proposed converter and its control scheme outperformed the current equalization circuit in terms of performance. Because of its extreme scalability, the idea will probably be used for massive energy storage systems to aid in the creation of the global energy Internet.

González *et al*. (2021), delve into a comparative analysis of SEPIDC buck-boost converters and adaptable PFC single-phase rectifiers. With an input voltage set at 220 V rms and output voltage of 200 V, these converters are optimized for a power rating of 3.2 kW. Our thermal simulations highlight that the versatile buck-boost (VBB) converter potentially offers superior power conversion efficiency when juxtaposed with the synchronous rectification and boost (SEPIDC) and the non-inverting buck-boost (NIBB) converters. To further corroborate these insights, we employ the PLECS RT Box 1 for a hardware-in-the-loop (HIL) real-time simulation. The empirical results gleaned from the HIL testing reinforce the theoretical analysis, underscoring the efficacy of the proposed design. This is especially pronounced for achieving elevated power conversion efficiency and adeptly managing dc output voltage, even without the need for sensing when the input current exhibits sinusoidal behavior and aligns phase-wise with the grid voltage.

Naik (2015), delves into the design and control of a buck-boost converter, also known as a 1-plus-D converter that yields a positive output voltage. It ingeniously merges the characteristics of the 1-plus-D converter with the synchronous rectifier (SR) buck converter. Such integration effectively addresses the voltage bucking limitation inherent in the standalone 1-plus-D converter, thereby broadening its applicability. A notable feature of this combined system is its non-pulsating output current, which minimizes both the output voltage ripple and the current stress exerted on the output capacitor. Marrying the functionalities of the 1-plus-D converter with the SR buck converter results in a unified buck-boost converter devoid of a right-half plane zero. This synergy not only compacts the circuitry, reducing cost, but also repurposes the same power switches for both functions. Intriguingly, during the magnetization phase, the 1-plus-D converter draws its input voltage directly from the source, while in the demagnetization phase, it taps into the output voltage of the SR buck converter.

Electrical power at various levels is often transformed using dc-dc buck-boost converters. By adjusting the duty ratio of the switch, it may function in both stepping-down (buck) and stepping-up (boost) of the input voltage. However, the hard-switching and switching loss introduced by the switches in these circuits lowers the circuit's efficiency. In this study, a novel, more straightforward buck-boost converter with components to provide soft-switching for the switch is proposed. To verify the performance, a simulation of the suggested circuit is run using MATLAB Simulink Behera *et al.* (2019).

Zambrano-Gutierrez *et al.* (2022), in this study the operation of a Buck-Boost converter in continuous conduction mode is mathematically modeled. The fractional Riemann-Lowville (R-L) approach is utilized to assess a direct current study, and the non-adimensionalize technique is employed to drive the average duty-cycle representation in state space. The model is put into practice utilizing the MATLAB/Simulink environment's Fractional-order Modelling and Control (FOMCON) package. The model exhibits some oscillations when the fractional order is changed, but the output voltage response is six times quicker, and, on average, the overshoot is significantly reduced by 67%.

Kunstbergs *et al.* (2022), takes a look at a bidirectional cascaded buck and boost converter that can handle up to 19.8 kW of power and is non-isolated for use in fuel cell hybrid vehicles. The primary purpose of this research is to identify the optimum fixed duty cycle and maximize efficiency via the use of a novel critical conduction mode and a tuned switching frequency. Experimental measurements confirm the validity of the proposed modulation method using Si-IGBT half-bridge modules. The results demonstrate that a loss reduction of 39% is achievable via the combination of switching frequency modulation and the optimal duty cycle. As a result, the converter is able to maintain high efficiencies (up to 99%) while maintaining low device junction temperatures.

Abbasi *et al.* (2020), an inverting buck/boost converter, which varies from typical dc-dc converters in that one of the inductor terminals is linked to the ground rather than the input or output, is the subject of this paper's discussion of electromagnetic compatibility (EMC) analysis. In order to evaluate the circuit's EMC properties, a SPIDCE model was created. Depending on the switch's state, two electromagnetic interference (EMI-relevant resonances) were seen. Measurements utilizing a circuit made of discrete components verified simulations, and integrated, commercially available converters had EMC characteristics that were identical to those of the general model.

Abdel-Rahim *et al.* (2022), introduces a cutting-edge non-inverting buck-boost converter, distinguished by its superior bucking and boosting attributes. Among its standout features are its robust step-up and step-down capabilities, coupled with reduced voltage/current stress on the converter's switch components. Remarkably, the voltage gain of this proposed converter is double that of a conventional buck-boost converter, the latter of which typically achieves only half this value. The potential to employ components with minimal voltage drops is a boon for enhancing the system's overall efficiency. Comprehensive insights into the converter's steady-state performance, along with analyses for both continuous and discontinuous conduction modes, are provided. Empirical validation was achieved using a 1 kW hardware prototype in a laboratory setting. The outcomes were impressive, with the converter demonstrating an efficiency exceeding 95.4% at 1 kW with a step-up ratio of 3.5 and surpassing 91.5% at a step-up ratio of 8.

Jame *et al.* (2022) underline that the majority of the energy from gasoline used in vehicles is wasted as heat. They propose the use of a thermoelectric generator (TEG) combined with a buck-boost converter to harness this waste heat and convert it into useful electrical energy. Their TEG-buck-boost setup was capable of producing 12V, enough to power a PIDR sensor. An enhanced Maximum Power Point Tracking (MPPT) technique was introduced to further refine energy harvesting.

Alizadeh *et al.* (2023), a buck-boost dc-dc converter is recommended. Their comprehensive analysis covers the optimal performance in continuous conduction mode (CCM) while delineating the operational modes and theoretical correlations. Side-by-side comparisons showcase the merits and potential shortcomings of their proposed converter, supported by experimental results to substantiate their theoretical propositions.

Baolei *et al.* (2019) delve into a high-efficiency buck-boost converter and its control mechanism. They put forth an analogy-based three-mode control strategy for smooth transitions across the converter's operational modes. By connecting two standard units in series, they could achieve a consistent output across a wide voltage spectrum. This system particularly addresses the demands of near-spacecraft power systems requiring compact, high-power solutions.

Rong *et al.* (2022) sheds light on a novel current step-up converter, which is an amalgamation of a buck-boost converter and a Cuk converter sharing a single input terminal. The authors dissect the operational theory and performance, ultimately presenting a parameter design for this novel converter. Their empirical model, producing 150 W, verifies the theoretical insights they've provided.

Yamuna *et al.* (2015) present the Double Buck-Boost (DBB) converter. This innovative design comprises one regulated switch, two capacitors, and two inductors. The resistive load employed aids in achieving an excellent power factor, low total harmonic distortion (THD), and minimal ripple current. The longevity of the converter can be enhanced by trimming down the filter capacitances. Comparative analyses with the hysteresis current controller offer promising results for their DBB converter.

Mathematics (2017), a dc-dc converter known as the Integrated Dual Output Converter (IDOC) concurrently executes boost and buck operations with a single input. It developed from a boost converter by adding a pair of switches in place of one single switch. IDOC has fewer switches than traditional boost and buck converters, which is its principal benefit. It can function very effectively when shot through. IDOC's fundamental mode of operation is described and contrasted with traditional buck and boost converters. MATLAB/SIMULINK is used to create and simulate the 200W IDOC prototype model. Between buck, boost, and IDOC converter, performance is compared.

Achmad and Nugraha (2022), one of the fundamental necessities of contemporary living is electricity, however, coal is not renewable and its usage as a fuel for power plants is dwindling. Solar panels with a 30 W power output are used in solar power production technologies. Hybrid plant systems' output values are affected by the environment's dependency on the sun, which makes it simple to harm household and commercial equipment likewise battery backup systems. To feed the output voltage to the battery or load, a stabilizing device for the output voltage is necessary. With a 14.4 volt set of terminals, the buck-boost converter can stabilize the output from solar panels. The average efficiency of the buck-conversion converter tested was 85.4% in buck mode, 80% in boost mode, and 79.2% in buck-boost mode.

Zhu *et al.* (2020), this research suggests a coat circuit-based low-voltage stress buck-boost converter with a high voltage conversion gain. The suggested coat circuit increases the range for voltage conversion and lowers the voltage strains on the semiconductor components, much as a coat might increase a person's resilience to cold weather. In order to verify the theoretical analysis based on a 300W closed-loop prototype platform, experimental data are gathered and examined.

Manohar Reddy *et al.* (2022), Multi-Input dc-dc converters have grown in popularity over the last ten years along with power electronics equipment. A PVSC type Buck Buck-Boost Dual-Input dc-dc Converter (DIDC) for use with the dc grid is demonstrated in this study. The suggested converter is constructed of two passive elements L and C, as well as diodes D1 and D2, switches S1 and S2, and it is powered by two renewable energy sources of various amplitudes: a PV cell and a battery. By running simulations in various operating modes, the converter's applicability is verified. The decentralized PID controller is made to assure a load current and voltage loop controller that maintains a dc output voltage of 48 V, 4.8 A, and 230 W. It is also confirmed that the closed-loop converter is stable under all scenarios of source and load disturbance. MATLAB and PSIM tools are used to simulate and analyze the suggested converter.

Kim *et al.* (2023), improve the power efficiency of the two-switch buck-boost (TSBB) converter while reducing the number of active components. Like the typical TSBB converter, the proposed converter can switch between buck, boost, and buck-boost modes. While the power efficiency of the buck topology improves for the power range of 10-80 W, the power efficiency of the buck-boost topology step-down increases for the same power range for all modes. This holds true in both the constant current (CC) and constant voltage (CV) settings. The buck-boost topology step-up improves efficiency by an average of 1.65–2.00 percent for 10–80 watts in CV mode and 2.17–2.77 percent for 10–50 watts in CC mode.

Mohan (2021), In order to step up or decrease the voltage for PV applications, buck-boost dc-dc converters have been widely used. Traditional quadratic buck-boost converters' input and output port currents are discontinuous, which causes higher input and output current ripples and makes it more difficult to build the input and output filters. Due to the greater voltage conversion ratio and continuous current at the input and output ports provided by a modified quadratic buck-boost converter, these issues may be resolved. From a single input converter, two outputs may be produced for use in various applications. For this suggested converter to function better and more quickly, a fuzzy logic controller may also be created.

Alajmi *et al.* (2022), in contrast to the traditional architecture, the interleaved buck-boost converter shown in this study has fewer power electronics devices. The suggested converter comprises of n parallel interleaved boost converters after a single buck converter. Only when one of the boost switches is gated does the buck switch become active. The suggested converter has features including gentle start-up and shutdown, power electronics device safety, high voltage gain needs, quick dynamic performance, and seamless switching from buck mode to boost mode. The suggested three-phase interleaved buck-boost converter's eight separate operating zones for the operation of non-overlapping gate signals are examined in this study. To run the suggested converter as a dc-dc converter or ac-dc converter, a simple control scheme is described. To assess the various capacities of the suggested converter, several study cases are conducted.

Femia and Di Capua (2019), the bi-directional battery charger circuit shown in this article is managed by a PID controller. When it is discharging, the converter performs as a boost converter, and when it is charging, it performs as a buck converter. During battery charging and discharging mode, simulation results were validated in MATLAB/Simulink software by attaining reference levels. In solar power plants and battery charging stations, this is a crucial function.

It has been shown that nonlinear behavior in dc-dc converters may become rather complex under certain situations (Bactiyar *et al.* 2022). This makes them a kind of system known as highly nonlinear time-varying systems. We investigate the fractional-order (FO) buck-boost converter's nonlinear dynamics in direct current mode (DCM). This work's main contributions and outcomes include the investigation of the period-doubling bifurcation and chaotic behavior of the FO buck-boost converter and the application of the predictor-corrector approach in fractional calculus, as well as the production of bifurcation diagrams based on this model. The findings demonstrate that the FO buck-boost converter displays chaotic bifurcation tendencies under certain operating and parameter settings. The predictor-corrector technique may be used to design controllers and fine-tune the parameters of a wide range of FO power converters.

3. MATERIALS AND METHODS

3.1 Buck-Boost Converter Design and Modeling

A buck-boost converter in Figure 3.1 is a kind of dc-dc power converter that converts input power using a mix of switching components, inductors, and capacitors to produce a controlled output voltage that may be either lower or greater than the input voltage. It is often used in many electrical systems and devices to effectively control voltage levels and manage power flow.

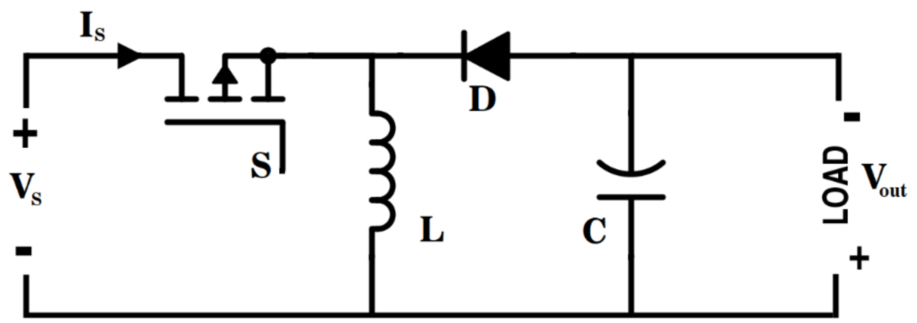

Figure 3.1 Buck-Boost Converter circuit

To understanding a buck-boost converter's operating principles, choosing appropriate components, and developing a mathematical model to replicate its behavior are all part of the design and modeling process.

3.1.1 Description of the buck-boost converter topology

The buck-boost converter is a type of dc-dc converter topology widely used in power electronic applications. It is a non-isolated converter that can step up (boost) or step down (buck) the input voltage to produce a regulated output voltage.

The basic buck-boost converter circuit consists of four main components:

1) Power Switch: The power switch regulates the circuit's current flow. It is often a MOSFET or a transistor. To control the output voltage, it functions as a switch that switches back and forth between the on and off states.

2) Inductor: The inductor, which is a component of the power switch that is linked in series with it, is essential for storing and transmitting energy. It allows for voltage conversion by storing energy when the power switch is turned on and releasing energy when the switch is turned off.

3) Capacitor: By filtering any ripple or high-frequency noise, the capacitor, which is linked in parallel with the load, aids in smoothing the output voltage.

4) Control Circuit: The control circuit monitors the output voltage and modifies the duty cycle of the power switch to maintain the desired output voltage level. It generally consists of a feedback loop and a control algorithm.

The operation of the buck-boost converter can be divided into two modes (Buck and boost mode)

- In buck, the word "buck" refers to the step-down (buck) action (Figure 3.2), in which the output voltage is lower than the input voltage. The buck-boost converter performs the same function as a standard buck converter in this mode, boosting current while lowering the voltage.

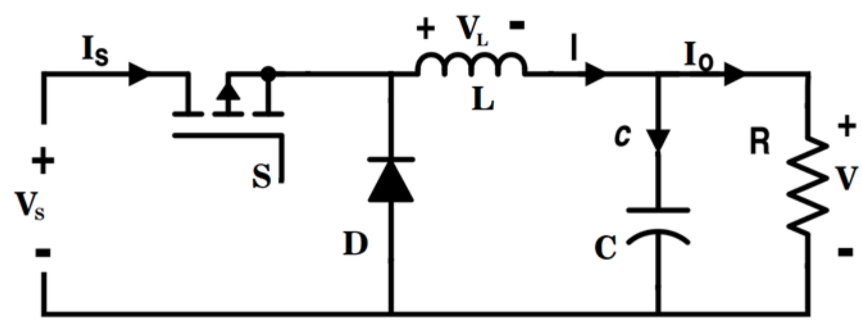

Figure 3.2 Buck converter circuit

- In Boost mode when we need to step up the voltage level, such as in battery-powered devices that demand a greater voltage than the available battery voltage, the boost mode of a buck-boost converter is very helpful. It is often utilized in applications like LED drivers, portable electronics, and energy storage systems and enables efficient voltage conversion.

The buck-boost converter in Figure 3.3 raises the input voltage to a higher output voltage level in boost mode. It does this by controlling the energy flow using an inductor and a switch (usually a transistor or a MOSFET). Energy is stored in the inductor while the switch is on, and it is transmitted to the load when the switch is off. The converter may modify the duty cycle of the switch to alter the output voltage.

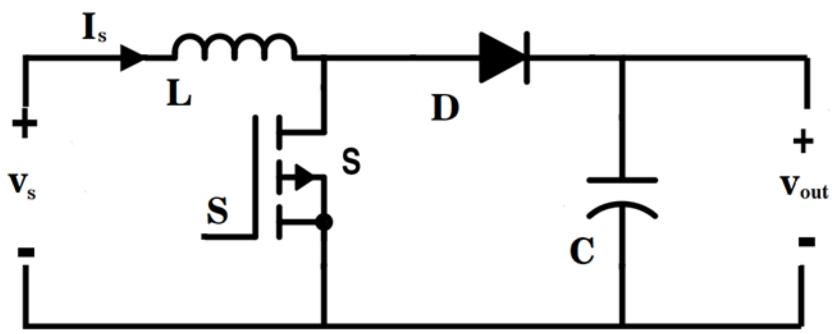

Figure 3.3 Boost converter circuit

By controlling the duty cycle of the power switch, the buck-boost converter can adjust the voltage conversion ratio, providing a regulated output voltage that is either higher or lower than the input voltage.

The buck-boost converter topology offers several advantages, including:

1) Wide input voltage range: It is excellent for a variety of power supply applications since it can handle a broad range of input voltages.
2) Polarity inversion: The buck-boost converter may produce an output voltage with a polarity opposite to the input voltage, unlike conventional dc-dc converters.

3) Efficiency: The buck-boost converter may reach great conversion efficiency with correct design and management.

The buck-boost converter is often used in battery chargers, portable electronics, renewable energy systems, and many other applications that need voltage management and conversion due to its adaptability and efficiency.

3.1.2 Mathematical modeling of the buck-boost converter

A buck-boost converter's mathematical modeling entails explaining the connections between the elements of the circuit and how the converter works. Assuming perfect components and steady-state circumstances, the modeling generally concentrates on the average continuous current mode (CCM) operation. The stages involved in mathematical modeling are as follows:

- Circuit description

1) Identification of circuit elements: Identifies the main components of a standby boost converter, including the inductor, capacitor, power switch (MOSFET or transistor), and load resistance.
2) Define operating conditions: Sets the input voltage Vin, output voltage Vout, switching frequency (fs), and duty cycle (D) of the power switch.

- Inductor current and voltage

1) Description of inductor current: Kirchhoff's voltage law (KVL) is applied to the inductor loop, taking into account the voltage across the inductor (V_L) and the input and output voltages.
2) Derivation of the inductor current equation: The relationship between the inductor current (I_L), the time derivative of the inductor current (d_{iL}/d_t), and the voltage across the inductor is used.

- Switching states

1) Definitions ON and OFF states: sets the conditions for the power switch to be in the on the state (conductive current) or off state (blocking current).
2) Derivation of switch equations: Generate equations that represent the behavior of the power switch in both cases.

- Inductor and capacitor energy

1) Evaluation of the energy stored in the inductor: integrates the energy flowing in and out of the inductor during a switching period.
2) Determine the energy stored in the capacitor: Calculate the average voltage across the capacitor and the energy stored in it.

- Steady-State Analysis

1) Equate the average power delivered to the load to the average power supplied by the input source.
2) Determine the relationship between the duty cycle, input voltage, output voltage, and other parameters to achieve steady-state conditions.

Equations explaining the connections between circuit variables such as the inductor current, capacitor voltage, and power switch behavior make up the resultant mathematical model. By taking into account non-idealities such as switching losses, component parasitic, and voltage dips, the model may be further enhanced. The output voltage's polarity differs from the input source since this converter is an inverted dc-dc converter. It is a buck-boost converter with a negative output as a result in Equation (3.1), Equation (3.2), Equation (3.3), Equation (3.4) and Figure 3.4.

$$-V_S + V_L = 0 \tag{3.1}$$

$$V_S = V_L = L\frac{di}{di} \tag{3.2}$$

$$-V_C + V_{out} = 0 \tag{3.3}$$

$$V_{out} = V_C \tag{3.4}$$

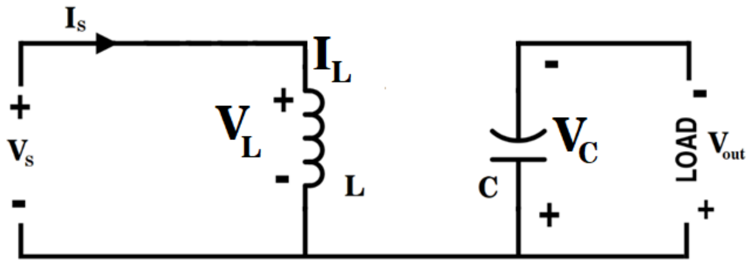

Figure 3.4 Buck-boost converter circuit when switch S is on

When the switch S is now opened as shown in Figure 3.5, Equation (3.5) to (3.7) presents the voltage and current across the inductance and capacitor.

$$+V_L + V_C = 0 \tag{3.5}$$

$$L\frac{di}{dt} + V_C = 0 \tag{3.6}$$

$$\frac{di}{dt} = -\frac{V_C}{L} \tag{3.7}$$

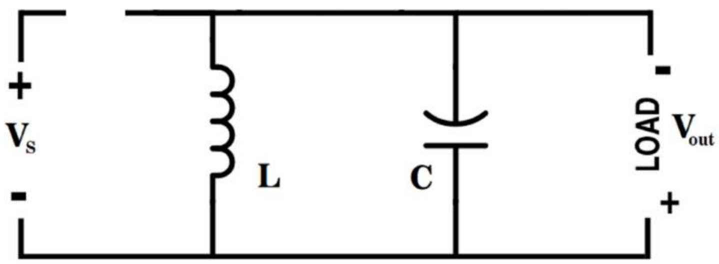

Figure 3.5 Buck-boost converter circuit when switch S is off.

Figure 3.6 displays the voltage and current waveforms for the buck-boost converter.

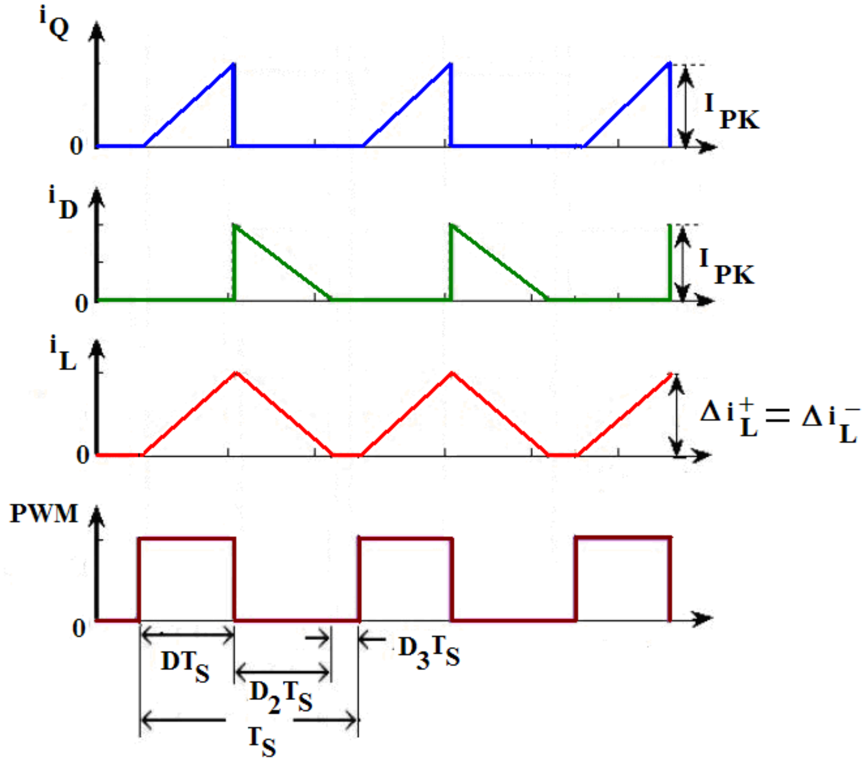

Figure 3.6 Buck-boost converter supply current, diode current, inductor current (Bendaoud *et al.* 2016).

From the waveforms given in Figure 3.6, when switch S is on, the rise in the inductor current is shown in Equation (3.8).

$$Rise\ in\ the\ Inductor\ Current = I_{max} - I_{min} = \frac{V_S}{L} DT \tag{3.8}$$

And, when switch S is OFF, a fall in the Inductor Current is shown in Equation (3.9).

$$Fall\ in\ the\ Inductor\ Current = I_{min} - I_{max} = -\frac{V_S}{L}(1 - D)T \tag{3.9}$$

When we combine Equations (3.7) and (3.8), we get, the average inductance current (I_L) is presented in Equation (3.10) to Equation (3.12).

$$\frac{V_S}{L}DT = \frac{V_C}{L}(1-D)T \tag{3.10}$$

$$V_{out} = V_C = \frac{D}{1-D}V_S \tag{3.11}$$

$$Average\ Inductor\ Current(I_L) = \frac{I_{min}+I_{max}}{2} \tag{3.12}$$

As there is no supply current during the switch-off condition, the input power is shown in Equation (3.13) and Equation (3.14) presents the output power.

$$Input\ Power\ (P_{IN}) = \frac{I_{min}+I_{max}}{2}DV_S \tag{3.13}$$

$$Output\ Power\ (P_{OUT}) = \frac{{V_{out}}^2}{R} \tag{3.14}$$

If there is no switching loss, the output power is equal to the input power as in Equation (3.15) and Equation (3.16).

$$P_{OUT} = P_{IN} \tag{3.15}$$

$$I_{max} + I_{min} = 2D\frac{V_S}{R(1-D)^2} \tag{3.16}$$

From Equations (3.15) and (3.16), we can get, the minimum and maximum current as in Equations (3.17) and (3.18) sequentially

$$I_{min} = D\frac{V_S}{D(1-D)^2} - \frac{V_S}{2L}D \tag{3.17}$$

$$I_{max} = D\frac{V_S}{D(1-D)^2} + \frac{V_S}{2L}D \tag{3.18}$$

In the Continuous Conduction Mode (CCM) of operation for a buck-boost converter, $I_{min} = 0$ means that the minimum current flowing through the inductor during each switching cycle is zero. Equation (3.19) represented to minimum inductor, Equation (3.20) represents to ripple voltage capacitor and finally Equation (3.21) for output voltage.

$$L_{min} = \frac{(1-D)^2}{2} TR \quad (3.19)$$

$$Ripple\ voltage\ \ Capacitor = \Delta V_C = \frac{\Delta Q}{C} = \frac{DTI_{out}}{C} = \frac{DTV_{out}}{RC} = \frac{D^2TV_S}{(1-D)RC} \quad (3.20)$$

$$V_{out} = \frac{D}{(1-D)} V_S \quad (3.21)$$

When D < 0.5, it acts as a step-down converter or a buck converter.
When D > 0.5, it acts as a step-up converter or a boost converter.
And when D = 0.5, input and output voltages are the same i.e. $V_{out} = V_S$.

The buck-boost converter's analysis, control scheme, and simulation are all based on the mathematical model. It enables engineers to create control techniques to achieve the necessary output voltage regulation as well as to assess the converter's functionality, efficiency, and stability.

3.1.3 Design considerations for the converter circuit

To achieve the best performance and dependability of a buck-boost converter, many crucial factors must be taken into account while constructing it. The following are some crucial design factors:

1) Input and Output Voltage Range: To make sure the buck-boost converter can handle the needed voltage conversion, identify the required input voltage range and the intended output voltage range. Think about the converter's required minimum and maximum input and output voltage levels.

2) Understanding the load requirements: Know the specifications of the load that the buck-boost converter will be giving. Think about things like the load current range, transient responsiveness, and any need for precise voltage or current management.

3) Efficiency: To reduce power losses and maximize the converter's overall performance, design for high efficiency. Think about component choice, switching frequency, and control strategies that may increase efficiency by lowering heat production and power dissipation.

4) Component Selection: Select components that can withstand the appropriate amounts of voltage and current as well as the converter's switching frequency, such as inductors, capacitors, and power switches. When choosing components, take into account the trade-offs between price, size, and performance.

5) Control technique: Choose a control technique to be used to govern the output voltage. This can include using a control algorithm like SMC or PID control. Choose a suitable feedback mechanism while taking the control system's stability and transient responsiveness into account.

6) Switching Frequency: Select the buck-boost converter's ideal switching frequency while balancing switching losses, component sizes, and efficiency. Smaller passive components can be made with higher switching frequencies, although switching losses and component prices may rise.

7) EMI Considerations. To reduce electromagnetic interference (EMI), the buck-boost converter should be designed. Use the proper filtering methods and layout considerations to cut down on noise emissions and make sure that your system complies with EMC regulations.

8) Protection Mechanisms: Include safety measures to protect the associated components and the buck-boost converter. To stop damage in fault situations, this

may also comprise overcurrent protection, overvoltage protection, short-circuit protection, and heat protection.

9) Component arrangement and Heat Dissipation: Consider the component arrangement to minimize parasitic effects, minimize signal noise, and maximize heat dissipation. Use heat sinks or other cooling methods to maintain safe operating temperatures to ensure effective thermal management.

10) Reliability and Robustness: The buck-boost converter should be built to tolerate changes in temperature, input voltage fluctuations, and load variations. To assure the converter's dependability and resilience in real-world circumstances, do a comprehensive study and testing.

Engineers may create buck-boost converters that satisfy the needed performance criteria, efficiency requirements, and reliability standards for a variety of applications by taking these design aspects into account.

3.2 PID Control for Buck-Boost Converters

3.2.1 Introduction to PID control theory for buck-boost converters

In order to regulate Buck-Boost converters, PID control is a well-liked and reliable control method. In power electronics applications, buck-boost converters are often used to increase or decrease the input voltage and create a controlled output voltage. PID control gives the converter's control signal a way to be modified, guaranteeing precise and reliable voltage regulation.

Three parts make up the PID control algorithm: proportional (P), integral (I), and derivative (D). Each component makes a distinct contribution to the total control action, enabling the PID controller to react to different facets of the converter's behavior.

- Proportional (P) Control

1) The proportional term of the PID controller adjusts the control signal based on the current error between the desired output voltage and the measured output voltage.
2) The P term produces a control action that is proportional to the error. A higher error results in a stronger corrective action, helping to reduce the steady-state error.

- Integral (I) Control:

1) The integral term of the PID controller considers the cumulative effect of past errors.
2) It continuously integrates the error over time, producing a control action that eliminates the steady-state error and improves the system's response to loading changes.
3) The I term ensures that any long-term discrepancies between the desired and actual output voltage are corrected.

- Derivative (D) Control:

1) The derivative term of the PID controller takes into account the rate of change of the error.
2) It provides a damping effect by reacting to sudden changes in the error signal.
3) The D term helps to stabilize the system, prevent overshoot, and improve the transient response.

The PID controller may be tweaked to provide the appropriate control performance for the Buck-Boost converter by modifying the gains of the P, I, and D terms. The improvements have an impact on the control system's reaction time, stability, and robustness.

PID control for Buck-Boost converters comes with a number of benefits:

1) Accurate voltage regulation: The PID controller continuously adjusts the control signal to maintain the output voltage close to the desired set point.
2) Robustness: PID control can handle variations in input voltage, load changes, and other disturbances, ensuring stable and reliable operation.
3) Flexibility: The PID gains can be adjusted to suit different operating conditions and system requirements.
4) Simplicity: PID control is relatively simple to understand and implement.

PID control also has limitations. It may struggle with nonlinearities, time delays, or complex dynamics in the Buck-Boost converter. Careful tuning and consideration of the system's characteristics are essential for achieving optimal control performance.

In conclusion, PID control is a widely used and effective control technique for regulating the output voltage of Buck-Boost converters. It provides accurate and stable control, contributing to the overall performance and efficiency of the converter in various power electronics applications.

3.2.2 Design of the PID controller for the buck-boost converter

Designing a PID controller for a Buck-Boost converter involves determining the appropriate values for the proportional (P), integral (I), and derivative (D) gains. Here are the general steps for designing the PID controller:

- Proportional Gain (Kp):

1) Start by setting the integral (Ki) and derivative (Kd) gains to zero.
2) Increase the proportional gain (Kp) gradually until the system response becomes oscillatory or unstable.
3) Once instability is observed, reduce the proportional gain slightly to a stable region.
4) The proportional gain determines the strength of the control action based on the present error, influencing the response speed and steady-state error.

- Integral Gain (Ki)

1) Set the proportional and derivative gains to their determined values.
2) Increase the integral gain (Ki) gradually to eliminate the steady-state error and improve the system's response to load changes.
3) Be cautious not to set the integral gain too high, as it may introduce instability or overshoot in the system.
4) The integral gain integrates the past errors, continuously adjusting the control signal to eliminate long-term discrepancies.

- Derivative Gain (Kd):

1) Set the proportional and integral gains to their determined values.
2) Introduce a small derivative gain (Kd) to improve the system's transient response and reduce overshoot or oscillations.
3) Start with a low derivative gain and gradually increase it until the desired response is achieved.
4) Be cautious not to set the derivative gain too high, as it may amplify noise or introduce instability.

Additionally, advanced control techniques, such as anti-windup mechanisms, feed-forward control, or adaptive control, can be incorporated to further enhance the performance and robustness of the PID controller for the Buck-Boost converter.

The PID controller can be mathematically described in Equation (3.22) in the e-domain and Equation (3.23) in S-domain, and the main PID control method parameter in Time and S- Domain is shown in Table 3.1. Figure 3.7 shows the block diagram of the PID controller system.

$$PID\ Controler = K_P e(t) + K_I \int_0^1 e(x)\, d(x) + K_D \frac{d}{dt} e(t) \quad (3.22)$$

$$PID\ Controler = k_p + \frac{K_I}{s} + K_D S = \frac{K_P S + K_I + K_D S^2}{S} \quad (3.23)$$

Table 3.1 PID control method parameter in time and s- domain

COMPENSATION	TIME DOMAIN	S-DOMAIN
Proportional	$K_P e(t)$	K_p
Integral	$K_I \int_0^1 e(x)\, d(x)$	$\frac{K_I}{s}$
Derivative	$K_D \frac{d}{dt} e(t)$	$K_D S$

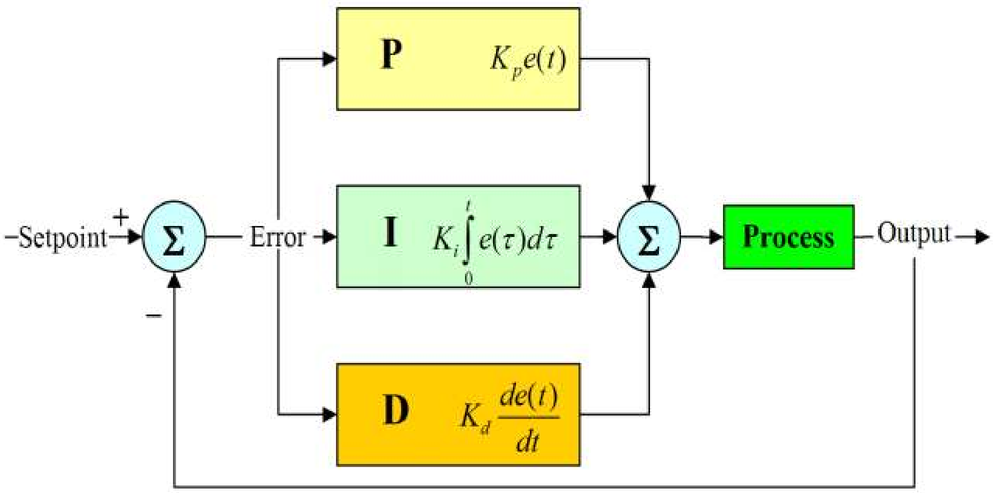

Figure 3.7 PID control Block diagram for closed loop (Mehta 2017)

3.2.3 Tuning methods for PID parameters

To obtain the required control performance, the PID parameters for a Buck-Boost converter must be tuned by choosing suitable values for the proportional (P), integral (I), and derivative (D) gains. These parameter values may be established using a variety of tuning techniques. Here are a few such approaches:

- Manual Tuning:

1) Start with all PID gains set to zero.

2) Gradually increase the proportional gain (Kp) until the system response becomes oscillatory.
3) Adjust the integral gain (Ki) to eliminate steady-state error and improve response to load changes.
4) Fine-tune the derivative gain (Kd) to reduce overshoot and improve transient response.
5) Iteratively adjust the gains based on system behavior until the desired performance is achieved.
6) Manual tuning is a simple but time-consuming method that relies on the designer's experience and understanding of the system.

- Ziegler-Nichols Method

1) Set all PID gains to zero initially.
2) Increase the proportional gain (Kp) until the system response exhibits sustained oscillations with a constant amplitude.
3) Measure the period of oscillation (Tu) and calculate the ultimate gain (Ku) as the value of Kp at which oscillations occur.
4) Use the calculated Ku value to determine the PID gains using specific tuning rules:
5) P control: Kp = 0.5 * Ku
6) PID control: Kp = 0.45 * Ku, Ki = 1.2 / Tu
7) PID control: Kp = 0.6 * Ku, Ki = 2 / Tu, Kd = 0.075 * Tu
8) Further fine-tune the gains if needed based on the system's response.

- Relay Feedback Method

Apply a relay control signal as input to the system, switching between two levels.
Observe the system's response, particularly the sustained oscillations that occur.
Measure the amplitude (Ar) and period (Tr) of oscillations.
Calculate the ultimate gain (Ku) as Ku = 4 * Ar / π.
Use the calculated Ku value to determine the PID gains using specific tuning rules (similar them to Ziegler-Nichols method).

Adjust the gains based on the system's behavior and performance requirements.

3.3 Sliding Mode Control for Buck-Boost Converters

3.3.1 Principle and theory of sliding mode control

SMC is a robust control technique widely used in various power electronic systems, including the buck-boost converter. The principle of SMC is to create a sliding surface that the system's states are forced to reach and stay on, ensuring robust and accurate control despite uncertainties and disturbances. Here's an overview of the principle and theory of SMC for the Buck-Boost Converter:

1) Sliding Surface: In SMC, a sliding surface is defined based on the system's state variables. For the buck-boost converter, the sliding surface is typically designed to ensure that the output voltage tracks a desired reference voltage accurately. The sliding surface is represented as a function of the system states and the reference voltage.
2) Control Law: A control law is designed to guide the system's states towards the sliding surface and maintain them on it. The control law consists of two terms: the reaching term and the sliding term.
3) Reaching Term: The reaching term drives the system's states towards the sliding surface. It introduces a high-gain control action that ensures fast convergence towards the sliding surface, even in the presence of disturbances or uncertainties. The reaching term is designed based on the dynamics of the buck-boost converter and the sliding surface.
4) Sliding Term: Once the system's states reach the sliding surface, the sliding term takes over to maintain the states on the sliding surface. The sliding term uses a discontinuous control action to keep the system's states following the sliding surface precisely. It ensures robustness to parameter variations and disturbances.
5) Control Signal Generation: The control signal is generated based on the control law to regulate the operation of the buck-boost converter. The control signal controls the

duty cycle of the power switch in the converter, adjusting the energy transfer and maintaining the output voltage at the desired level.

6) SMC Loop: The control loop for the buck-boost converter using SMC consists of the following steps:

- Measure the output voltage and compare it with the reference voltage.
- Based on the error between the measured and reference voltages, calculate the control signal using the control law.
- Apply the control signal to adjust the duty cycle of the power switch, regulating the energy transfer and output voltage.
- Continuously monitor the system's states to ensure they remain on the sliding surface, making rapi adjustments if they deviate.

The SMC technique for the buck-boost converter provides robustness to uncertainties, disturbances, and variations in the system parameters. It ensures accurate tracking of the desired output voltage, even in challenging operating conditions. The control law and sliding surface design can be customized based on specific requirements and constraints of the buck-boost converter system.

3.3.2 Sliding mode controller design in buck-boost converters

Designing a SMC for the buck-boost converter involves determining the sliding surface and designing the control law. Here's a step-by-step guide for designing the SMC for the buck-boost converter:

- Sliding surface design

1) Define the sliding surface to ensure accurate tracking of the output voltage. The sliding surface is typically chosen as the difference between the measured output voltage (Vout) and the reference voltage (Vref). The sliding surface can be represented as S = Vout - Vref.

2) Determine the desired behavior of the sliding surface, such as stability, convergence, and desired dynamics. The choice of the sliding surface design depends on specific control objectives and system requirements.

- Control law design

1) Reaching Term: Design the reaching term of the control law to drive the system's states toward the sliding surface. The reaching term introduces a high-gain control action to ensure fast convergence. It is typically designed using the system dynamics and stability analysis.
2) Sliding Term: Design the sliding term of the control law to maintain the system's states on the sliding surface. The sliding term uses a discontinuous control action to enforce robustness and accurate tracking. It can be designed using the SMC theory, such as the equivalent control or the SMC technique based on the sign function.

- Control signal generation

1) Combine the reaching term and sliding term to obtain the total control signal. The reaching term is active when the system's states are away from the sliding surface, while the sliding term becomes dominant when the system's states reach the sliding surface.
2) Calculate the control signal based on the control law and the system's states. The control signal is typically proportional to the sliding surface and its derivative, along with other control parameters.
3) Apply the control signal to adjust the duty cycle of the power switch in the buck-boost converter. The control signal determines the on and off periods of the switch, regulating the energy transfer and output voltage.

- Control Loop Implementation

1) Measure the output voltage of the buck-boost converter and compute the error between the measured output voltage and the reference voltage.
2) Use the control law and the error to calculate the control signal.
3) Apply the control signal to adjust the duty cycle of the power switch, regulating the energy transfer and output voltage.
4) Continuously monitor the system's states and adjust the control signal to keep the states on the sliding surface, ensuring accurate tracking and robustness.

The Block diagram of the SMC is shown in Figure 3.8

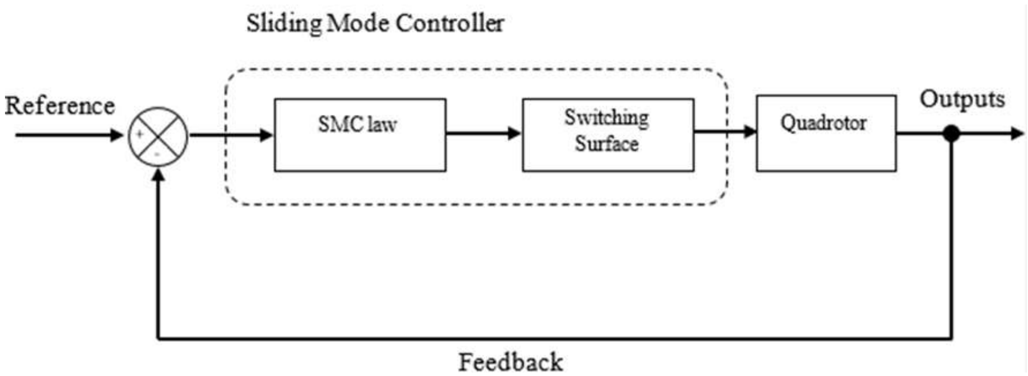

Figure 3.8 SMC control Block diagram for closed loop

SMC's goal is to specify a surface that will allow the system to glide to the desired ultimate value (Figure 3.9). Selecting the sliding surface to describe the system's overall behavior is the first step in designing this controller.

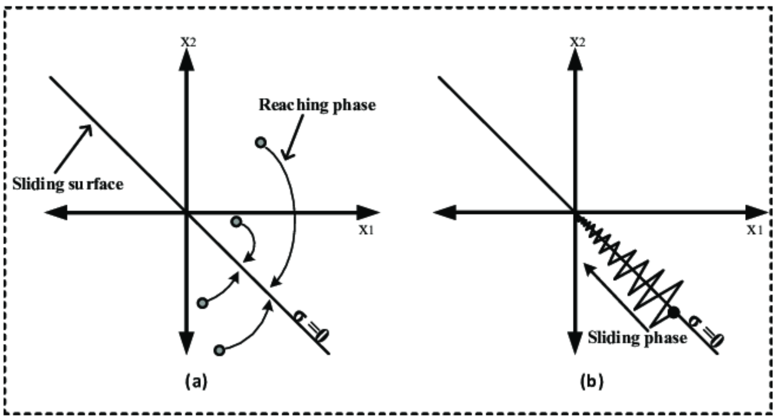

Figure 3.9 A) reaching mode and b) sliding phase mode (Yasin *et al.* 2018)

The step-down converter operates differently depending on whether the switch is in the ON or OFF position. The average state space model for the converter can be constructed using two distinct modes, as described in Equation (3.24) (Komurcugil 2021, Hisar *et al.* 2023).

$$\begin{aligned} \dot{I}_L &= \frac{1}{L}(uE - V_0) \\ \dot{V}_0 &= \frac{1}{C}\left(I_L - \frac{V_0}{R}\right) \end{aligned} \tag{3.24}$$

Where $\dot{I}_L$ represents the current in the inductor, and $\dot{V}_0$ is the output voltage. The control input denoted by *u*, determines the state of the switch: 0 a value of V_0 indicates the switch is off, while a value of 1 means it's on. Additionally, there are new terms derived from discrepancies in the output voltage and its associated derivatives as shows in Equation (3.25) to Equation (3.27) (Hisar *et al.* 2023).

$$x_1 = V_0 - V_{ref} \tag{3.25}$$

$$\dot{x}_1 = \dot{V}_0 - \dot{V}_{ref} = \dot{V}_0 = x_2 \tag{3.26}$$

$$\dot{x}_2 = -\frac{x_2}{RC} + \frac{1}{LC}\left(uV_{\text{in}} - V_{ref} - x_1\right) \tag{3.27}$$

The voltage error at the output terminal is represented as x_1 . Its derivative is signified by $\dot{x}_1$. Meanwhile, V_{ref} is the reference voltage at the terminal used as a benchmark.

Published materials have examined sliding surfaces. The traditional depiction of a sliding surface is as in Equation (3.28): (Komurcugil 2021).

$$S = \lambda x_1 + x_2, \qquad \lambda > 0 \tag{3.28}$$

Where λ is a positive constant.

The terminal SMC is a proposed nonlinear sliding surface designed to enhance performance, as in Equation (3.29) (Balta *et al*. 2022).

$$S_{TSMC} = \dot{x}_1 + \lambda x_1^{\gamma}, \qquad 0 < \gamma < 1 \tag{3.29}$$

Where λ represents to fractional power.

The design process of the SMC for the buck-boost converter often involves system modeling, analysis, and controller tuning. Advanced control techniques, such as gain scheduling or adaptive control, can also be employed to enhance the performance of the SMC. Simulations and experiments are typically performed to validate and fine-tune the controller design before implementing it in practical applications.

4. RESULTS AND DISCUSSION

In this chapter, the simulation results of the Buck-Boost converters will be presented using two methods (PID control and SMC).

4.1 Buck-Boost Converter Based PID Control

Figure 4.1 shows the final Buck-Boost converter circuit using the dc input power supply and use the PID for the control circuit.

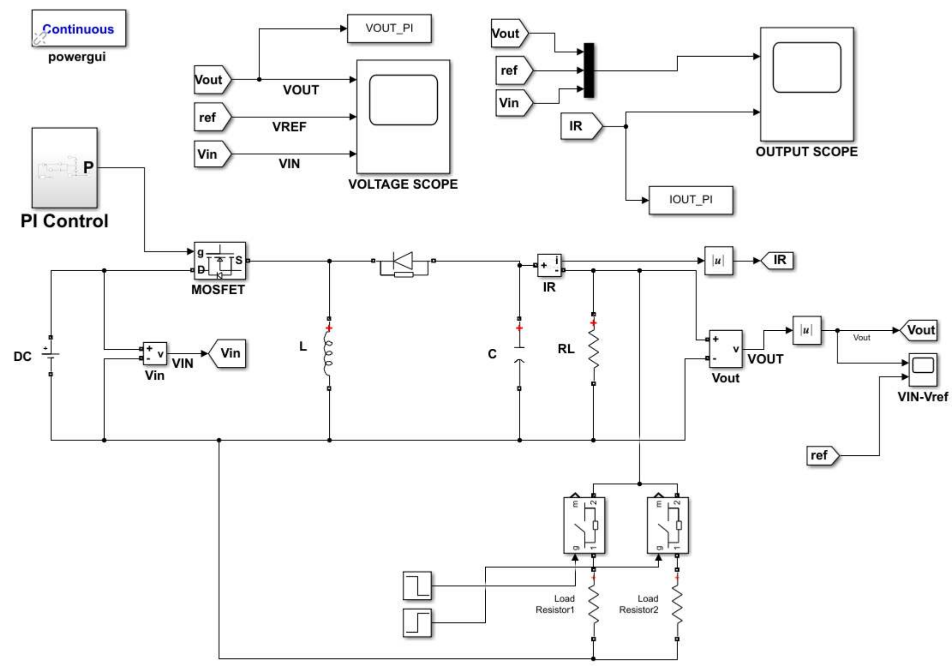

Figure 4.1 Final PID module and Buck-Boost converter circuit diagram

After determining all the values of the electronic elements and adjusting the variables for the PID (K_p= 0.324, K_i= 13 and K_d=0) as in Figure 4.2, also the result of the PWM shown in Figure 4.3.

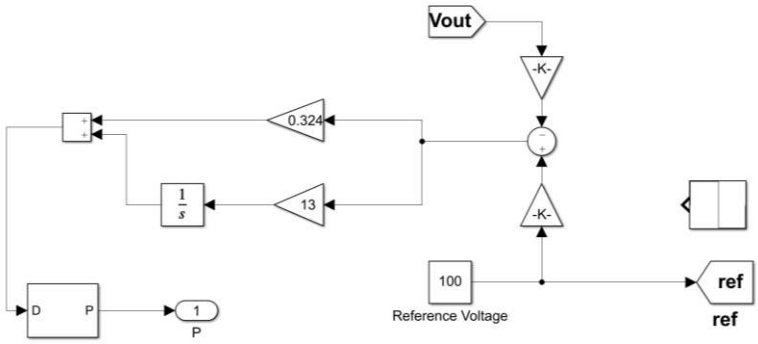

Figure 4.2 PID parameters and control for buck-boost converter circuit diagram

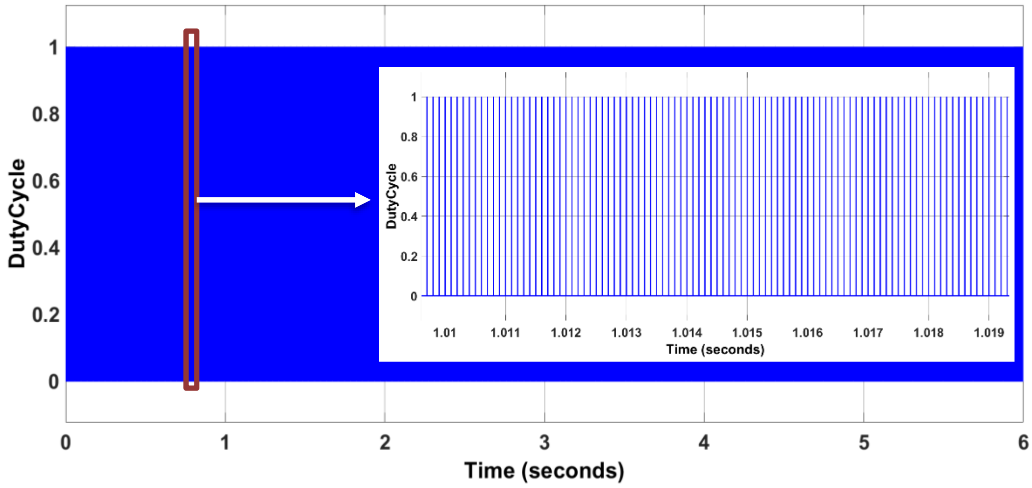

Figure 4.3 PWM signal for PID buck-boost converter

In this study, we applied many scenarios to test the performance of PID controller. In first case the reference voltage change from 100v to 150 v as a boost converter testing for two second and then in 4 second the reference voltage changed from 150 to 50v to test the buck converter mode based PID converter as shown in Figure 4.4.

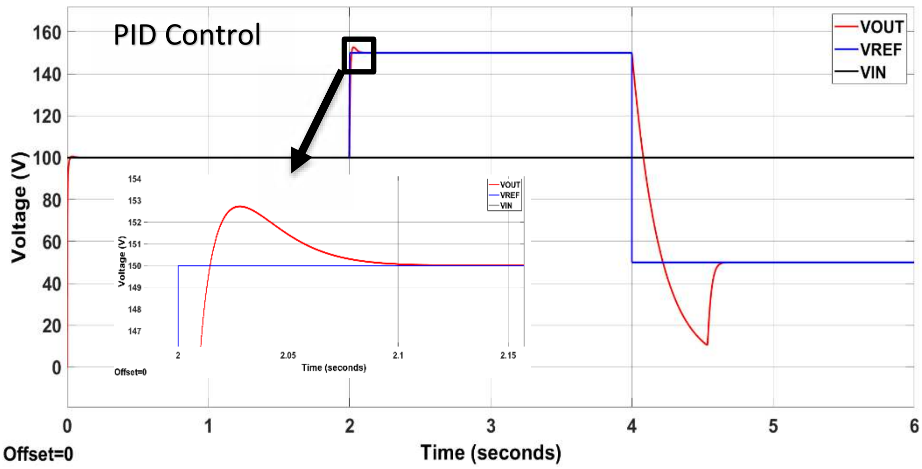

Figure 4.4 Transient of PID under reference voltage variations

From Figure 4.4, we obtained overshoot near to 2v for 0.1 mill second when the converter works in boost mode at 150 v. also when the reference voltage changed from 150-50 v. in buck mode notice there are so high drop voltage and the PID control spent 0.4 mill second to get stable.

Figure 4.5 demonstrates that the buck boost converter's output voltage remains stable under varying input voltage values. However, there is a noticeable voltage drop close to 4v at the 4th second, followed by the converter stabilizing in less than 0.1 seconds, according to the reference voltage. Additionally, at the 6.2th second, the alterations in the input voltage (Vin) did not influence the output voltage (Vout), which achieved stability within 0.14 seconds.

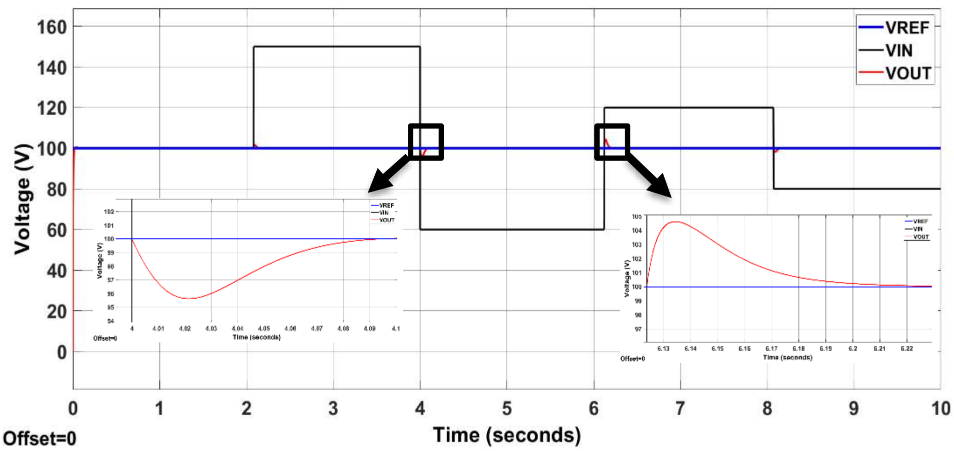

Figure 4.5 Dynamic PID under input voltage variations

In addition to the earlier tests, a dynamic PID control test was conducted under various voltage and load conditions, as depicted in Figure 4.6. This assessment was designed to understand how the PID controller would perform under varying load conditions, which is essential for many real-world applications where load can change frequently and unexpectedly.

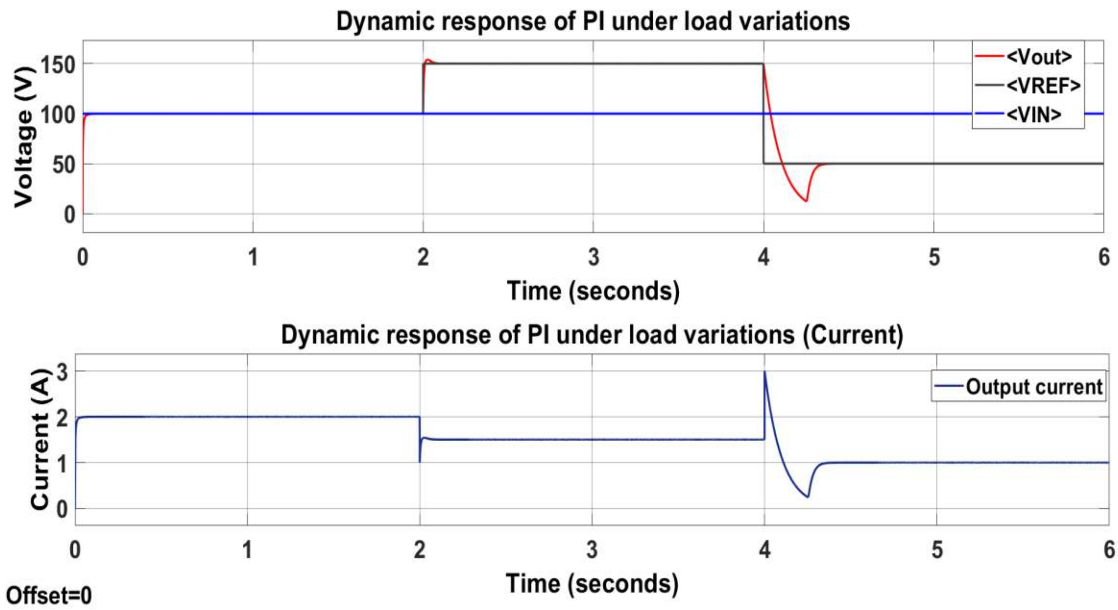

Figure 4.6 Dynamic PID under different voltage with load variations

In the PID controller, when the load was switched from 100 ohms to 200 ohms, the output voltage and current adjusted accordingly. Notably, a drop in current was observed at the 2nd second, a phenomenon caused by the initiation of the second load. Similarly, at the 4th second, when the load was changed again, there was a significant drop in both current and voltage. This behavior highlights the impact of load variation on the system and the potential strain that could be induced on the converter by sudden load changes.

In another scenario, this time with the reference voltage held constant at 100V, overshoots near to 2 volts were observed at the 2nd and drop at 4th seconds. After these overshoots, the PID controller stabilized the voltage after approximately 0.15 milliseconds, as shown in Figure 4.7.

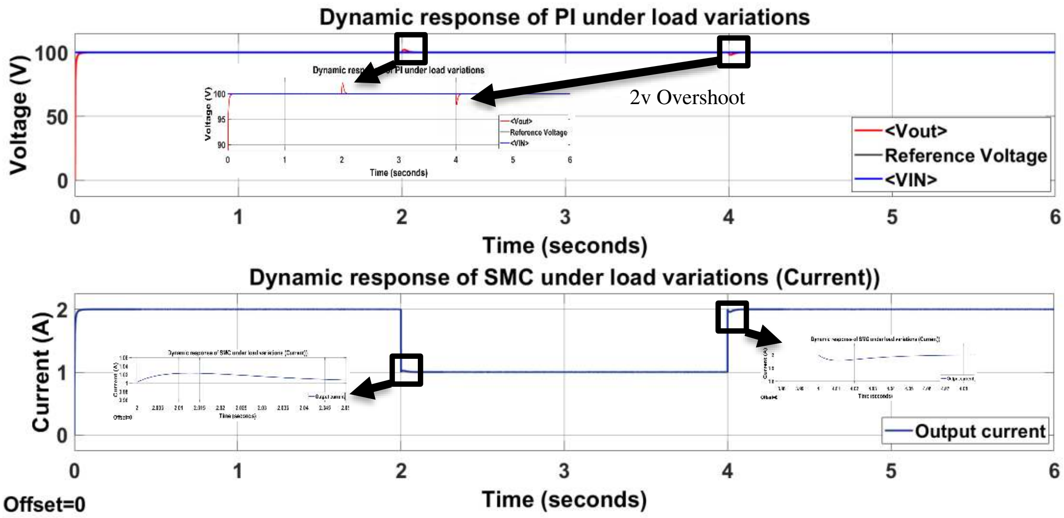

Figure 4.7 Dynamic PID under constant voltage with load variations

4.2 Buck-Boost Converter Based Slide Mode Control

Figure 4.8 shows the final Buck-Boost converter circuit diagram using the dc input power supply with SMC.

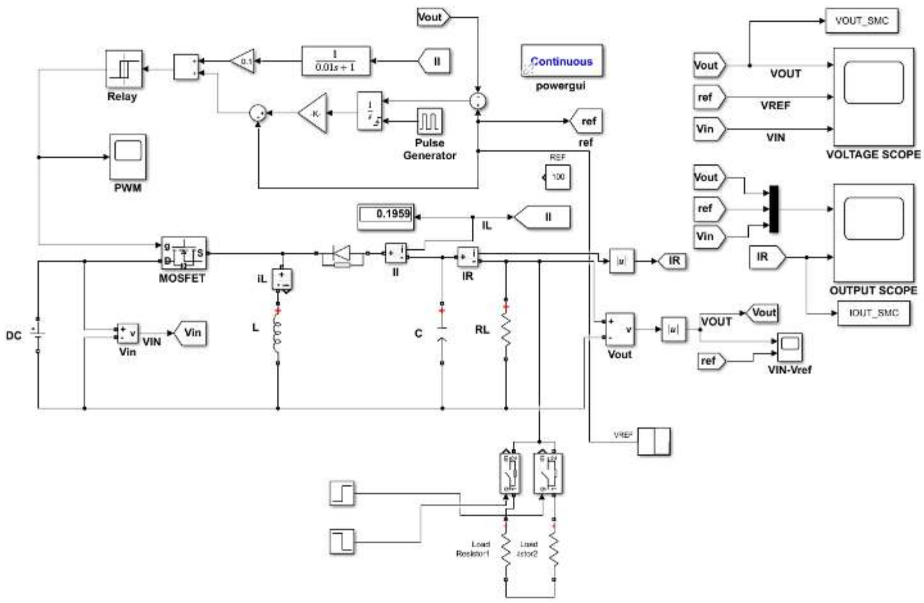

Figure 4.8 SMC module and Buck-Boost converter circuit diagram

The PWM signals when the reference is 100 are shown in Figure 4.9.

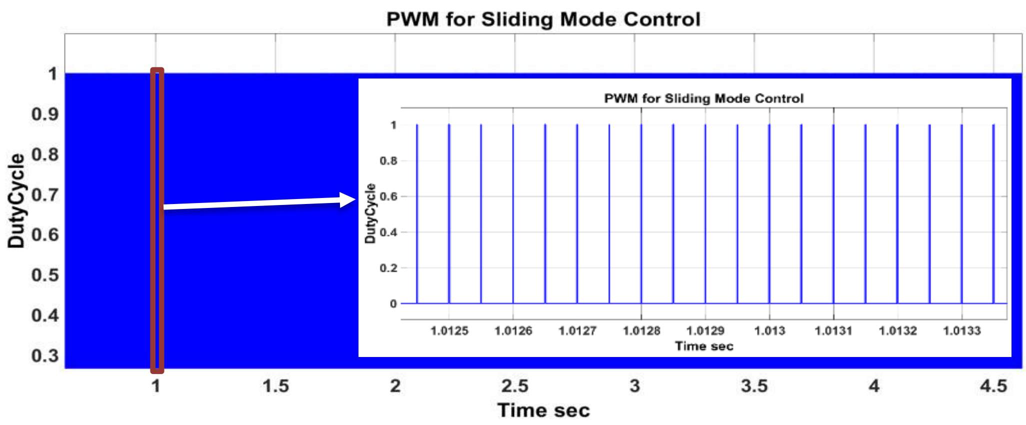

Figure 4.9 PWM signal for SMC

In sliding mode control, many difference scenarios were applied to test the performance of control during voltage transient and load variations.

In Figure 4.7, we simulated the system by altering the reference voltage to test two converter modes: one as a boost converter and the other as a buck converter. The reference voltage changes from 100V to 150V at the 2 second (Boosting), and the output signal exhibits a high-level response time with no overshoot or damping when compared to the PID controller. Furthermore, when the reference voltage changes from 150V to 50V at the 4 second (Bucking), the signal settles down within 0.1 seconds, without any overshoot or damping.

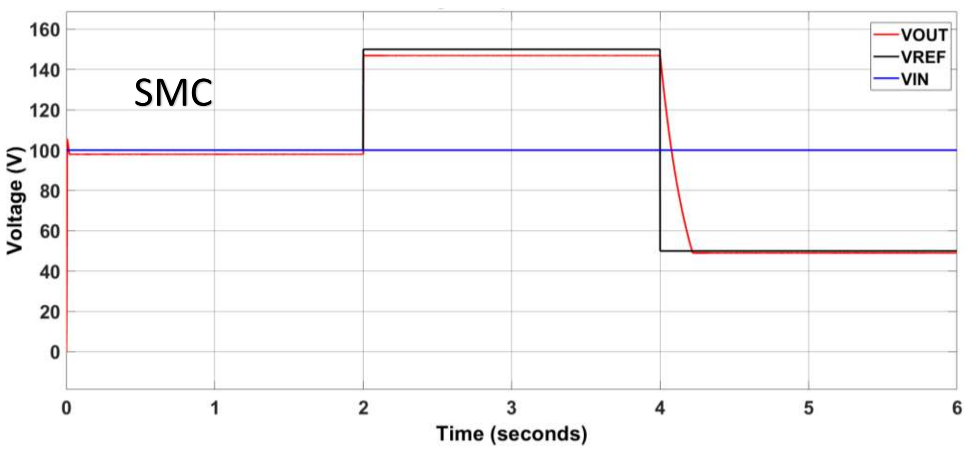

Figure 4.10 Transient of SMC under reference voltage variations

Also, when we altered the scenario by holding the reference voltage constant and testing the output voltage by changing the input voltage (Vin), we found that the system was unaffected by this change. The reference point of the SMC controlled the output signal without any discernible difference as shown in Figure 4.11.

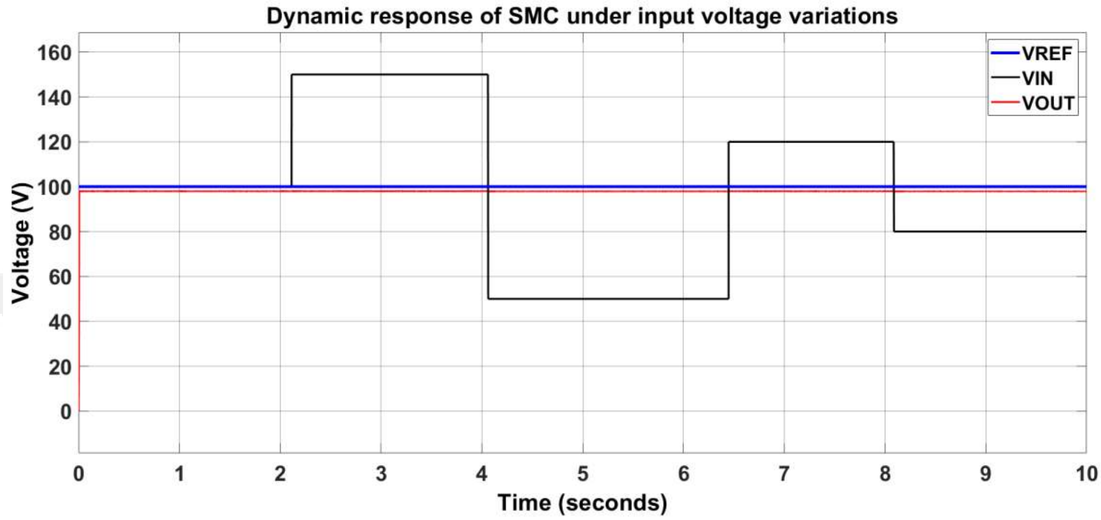

Figure 4.11 Dynamic SMC under input voltage variations

In Figure 4.12, the SMC is tested using dynamic load variations to examine the changes in output voltage and current. When the dynamic load is switched on, the current decreases according to Ohm's law. However, this decrease happens without a spark. The load changes from 100 to 200 ohms at the 2 second and is switched off at the 4 second. Dynamic load changes can pose a significant challenge in controlling electrical systems due to the rapi adjustments required to maintain stability. The SMC, operating without a spark, exhibits a smooth transition during the load change. This indicates the system's ability to handle abrupt changes without causing sudden voltage spikes or dips, which could lead to electrical arcing.

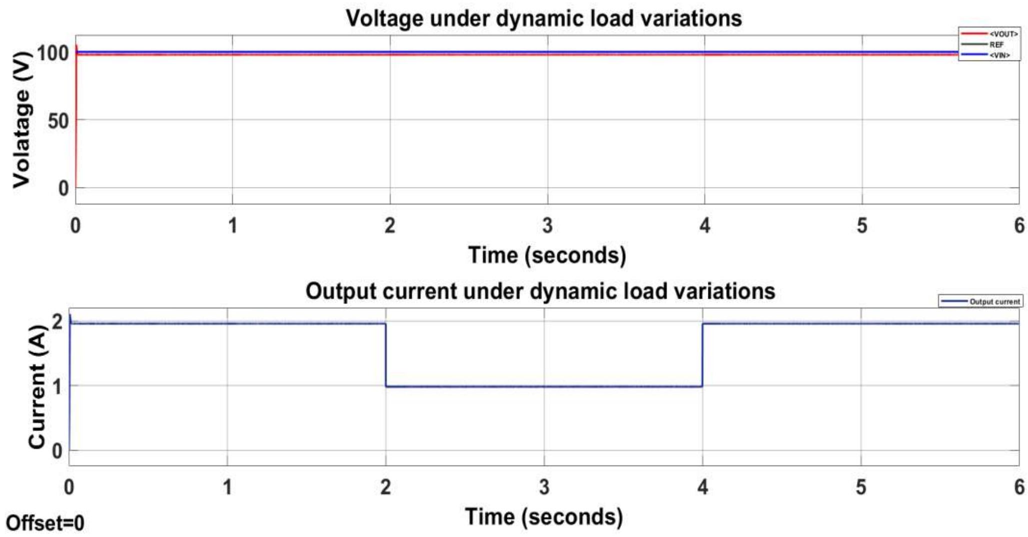

Figure 4.12 SMC under load variations

4.3 Comparison Based PID and SMC

In this section, we compare the PID and SMC under the same test conditions. Figure 4.13 illustrates the comparison of output voltage variations under changes in reference voltage for both the PID controller and the SMC. According to Figure 4.13, the SMC exhibits a high-level time response without any overshoot or damping. In contrast, the PID controller is affected by changes in the reference voltage. The PID controller also experiences overshoot when the reference voltage changes, as well as damping at the 4th second, with a slower settle-down time compared to the SMC.

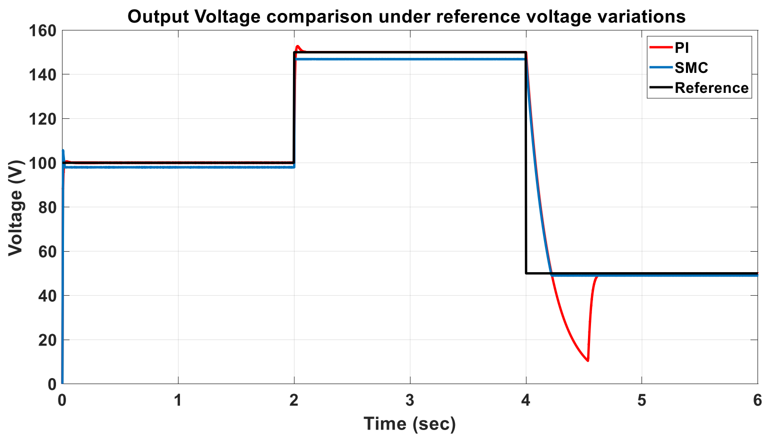

Figure 4.13 Output voltage comparison under reference voltage variations

Additionally, when comparing the PID and SMC based on output voltage variations under load changes, the SMC demonstrates superior results. Despite changes in dynamic load, the SMC maintains a constant value, whereas the PID controller responds with a minimum overshoot, close to 2 volts. Figure 4.14 shows the output voltage comparison under load variations for both the SMC and PID controller.

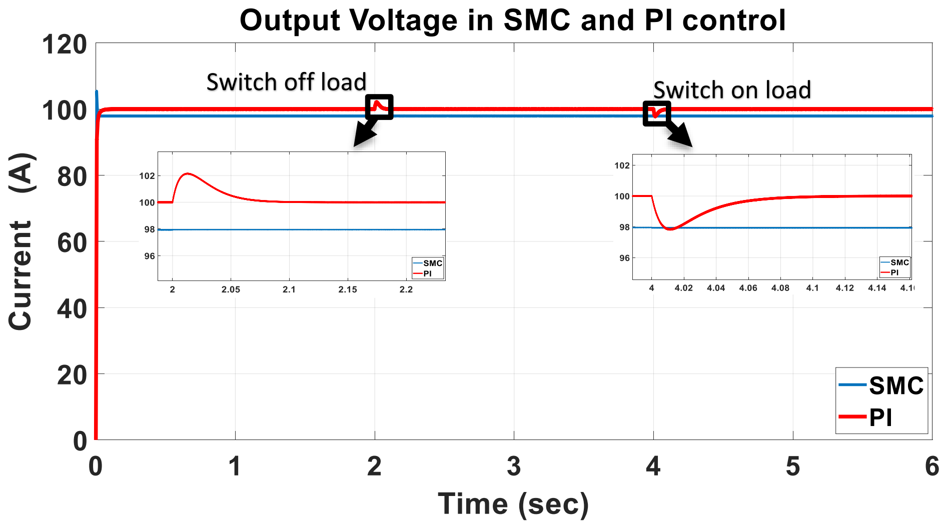

Figure 4.14 Output voltage comparison under load variations for SMC and PID control

Also, in the case of a robust test (involving changes in reference voltage and dynamic load variations) to compare the output current controlled by the SMC and the PID, Figure 4.15 demonstrates a superior response from the SMC compared to the PID controller.

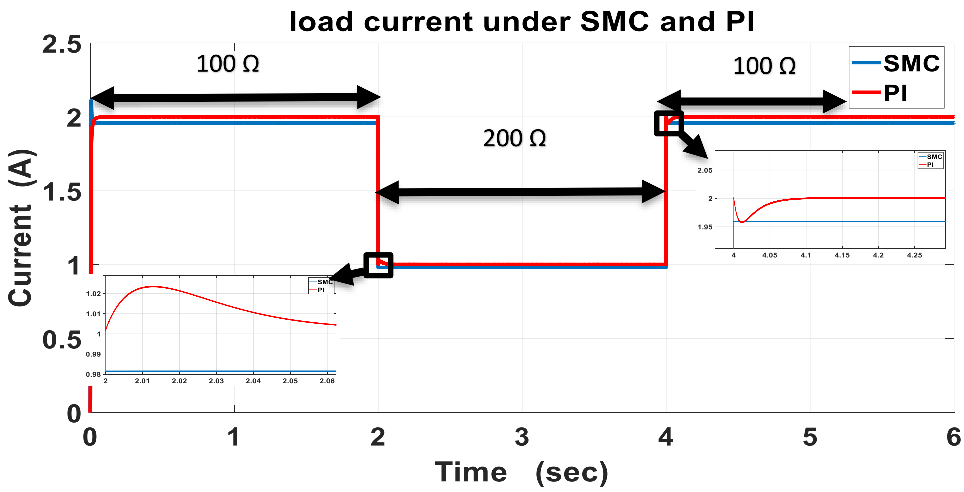

Figure 4.15 Output current comparison for more than parallel loads under SMC and PID control

So, this study evaluated the performance of a PID controller, specifically a PID controller, under different voltage and load conditions, as well as a SMC. In two different scenarios - a boost converter mode and a buck converter mode - the PID controller displayed stability, desPIDte a few minor inconsistencies. In dynamic PID control tests, sudden changes in load had a significant impact on current and voltage, reflecting potential strain on the converter. Comparatively, the SMC, tested under dynamic load variations, performed well without sparking during rapi load adjustments.

A comparative analysis between the PID controller and the SMC under the same conditions revealed that the SMC had superior response time and stability. While the PID controller was affected by changes in reference voltage, the SMC exhibited a high-level time response without overshoot or damping. Furthermore, under load changes, the SMC maintained a constant output value, demonstrating its superiority over the PID controller. The study concluded that the SMC outperformed the PID controller under various scenarios, offering valuable insights into the design and operation of PID controllers in real-world applications.

5. CONCLUSIONS AND RECOMMENDATIONS

The boost and buck converter, highlighted the controller's adaptability to varying input voltages, varying reference voltage and dynamic loads by using PID controller and SMC. Despite an occasional drop in voltage, the SMC promptly stabilized the voltage output, affirming its robustness. However, the PID controller exhibited sensitivity to load changes, causing significant drops in both current and voltage. This aspect underscores the necessity to consider sudden load variations in real-world applications as they may exert undue strain on the converter. SMC was also tested under similar conditions. The SMC proved adept in controlling voltage transients and load variations, managing to maintain consistent output even in the face of dynamic load changes. Notably, this occurred without any electrical disturbance such as chattering, demonstrating the SMC's superior performance in maintaining system stability. A comparative analysis of the PID controller and the SMC underscored the SMC's heightened time response and its robustness against reference voltage changes. The PID controller, while effective in certain scenarios, exhibited some overshoot during reference voltage alterations and a slower settling time compared to the SMC. Further, the SMC performed optimally under dynamic load changes, maintaining consistent output, unlike the PID controller, which exhibited a minor overshoot. The study underscores the effectiveness of the SMC over the PID controller in managing voltage and load changes, offering valuable insights into the design and operation of PID controllers. This understanding is crucial to optimizing their performance under varying conditions, thereby enhancing the efficiency and reliability of numerous real-world applications.

Based on the study's findings, it is recommended to opt for the SMC over the PID controller, particularly in systems experiencing frequent voltage and load changes due to its superior performance and adaptability. However, more research should be undertaken to further optimize the SMC, as there may be scenarios where it is not as efficient. It is equally crucial to customize the controller design to suit specific system requirements, given that diverse conditions may necessitate different controllers. The significant impact of load variations on controller performance, as demonstrated in this study, suggests the necessity to incorporate potential load variations into the system designs and to validate them under a variety of conditions for improved robustness. System optimization should be a constant pursuit regardless of the chosen controller type, as both the PID controller and SMC demonstrated potential for further improvement in response time and stability. By following these recommendations in future research and development efforts, the performance of control systems can be continually enhanced, facilitating more efficient and effective operation across a broad spectrum of conditions.

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