Performance Evaluation of Sliding Mode Control-Based DC-DC Buck Converter

Mohammedamin Haji Bilisa

A Thesis Submitted to the Department of Electrical Power and Control Engineering

College of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electrical Power and Control Engineering (Control Engineering)

Office of Graduate Studies

Adama Science and Technology University

June, 2025

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DECELERATION

I declare that this thesis entitled "Performance Evaluation of Sliding Mode Control-Based DC-DC Buck Converter'' is my own work and has not been submitted to any university for similar purpose. The references used in this thesis are duly recognized by proper citations.

Mohammedamin Haji Bilisa	____________________	____________________
Name of Student	Signature	Date

RECOMMENDATION OF ADVISORS

I, the major advisor of this research, hereby certify that I have closely advised/supervised the student while developing this thesis and read the draft thesis entitled "Performance Evaluation of Sliding Mode Control-Based DC-DC Buck Converter" prepared under my guidance by Mohammedamin Haji Bilisa. Therefore, I recommend the submission of the thesis to the department for further review and evaluation.

Prof. Gang Gyoo Jin	______________________	04/06/2025
Major Advisor/Supervisor	Signature	Date
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Co-advisor/Co-supervisor	Signature	Date

BOARD OF REVIEWERS APPROVAL PAGE

I hereby certify that the recommendation and suggestion given by the thesis review committee are appropriately incorporated into the final thesis entitled "Performance Evaluation of Sliding Mode Control-Based DC-DC Buck Converter" by Mohammedamin Haji Bilisa.

Prof. Gang Gyoo Jin		04/06/2025
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Adisu Safo (MSc)		
Co-advisor/Co-supervisor	Signature	Date

We, the undersigned, members of the Board of Reviewers of the thesis open defense by Mohammedamin Haji Bilisa have read and evaluated the thesis entitled "Performance Evaluation of Sliding Mode Control-Based DC-DC Buck Converter" and assessed the understanding of the candidate about the proposed research. This is, therefore, to certify that the thesis is accepted and we recommend the implementation of the proposal.

Chairperson	Signature	Date
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Final approval and acceptance of the thesis is contingent upon submission of its final copy to the office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and College Graduate Committee (CGC).

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LIST OF ACRONYMS AND ABBREVIATIONS

CCM----------------------------------- Continuous Conduction Mode

DC-------------------------------------- Direct Current

DCM----------------------------------- Discontinuous Conduction Mode

ESR------------------------------------ Equivalent Series Resistor

GTO------------------------------------ Gate Turn off Thyistor

IGBT------------------------------------ Insulated Gate Bipolar Transistor

IAEU------------------------------------ Integral of Absolute Error of the Control Input

I/O--------------------------------------- Input-Output

MOSFET------------------------------- Metal-Oxide Semiconductor Field-Effect Transistor

PID-------------------------------------- Proportional-integral-deferential

PV--------------------------------------- Photovoltaic

PWM----------------------------------- Pulse Width Modulation

RSE-------------------------------------- Renewable Source of Energy

SCR-------------------------------------- Silicon Controlled Rectifier

SMC------------------------------------ sliding mode control

SMPS----------------------------------- Switching Mode Power Supply

VSS-------------------------------------- Variable Stricture System

ABSTRACT

Robust voltage control in DC-DC buck converters is important in application of modern power electronics such power supply system, where systems are commonly open to parameter uncertainties and disturbances. Buck converter are used in applications were step-down voltage is needed. This converter alone typically produces an output voltage that is unstable, oscillates, has an enormous overshoot, and exhibit long time convergence. Several converters are needed to solve this issue and achieve a steady output voltage with quick fast response. PID controllers are typically used with converters to achieve nominal output voltage due to their ease of usage. PID controllers however are not reliable when used with nonlinear systems. To overcome these limitations, this thesis presents performance evaluation of SMC methods for buck converter. Its state-space average is modeled using continuous conduction mode (CCM) and linearized around operating point. The linearized model is expanded to include uncertainties in parameter and load change. SMC controller is built by defining appropriate sliding surface including proportional-integral action, with tuned parameter using particle swarm optimization (PSO) to improve transient response and minimize control chattering. System stability is analyzed using Lyapunov theory. Proposed control method is insured using simulations MATLAB/Simulink and compared with PID controller. Results show that SMC improves the rise time by 6.27% and the settling time by 7.19%, while eliminating desired voltage overshoot that remains with PID control (reduced to 3.65%). The improved SMC presented minimal chattering, with control input energy comparable to PID controller. Controller also maintains performance under 58% increases in load resistance and variations in inductance values. Overall, simulation results confirm SMC strategy greatly exceeds PID control methods, bringing better performance with efficient control, making it reliable and robust solution for high-performance buck converters.

Key words: *DC-DC Buck Converter, Sliding Mode Controller, PID controller.*

CHAPTER ONE

1. INTRODUCTION

1.1 Thesis Background

An electrical circuit known as a DC-DC converter changes a DC source from given voltage level to another nominal voltage. In power electronics, these circuits are the most often utilized. These days, they are present in practically all electronic devices, since all DC sources provide the power for semiconductor components. They are essentially applied in every circumstance where a certain DC voltage needs to be stabilized to a specified (Baharudin N, Mansur T, 2018).

In switch-mode power supplies, it can be employed commonly in DC-DC converters. The switching-mode DC-DC converters are interested in variety of fields. Their many applications include powering personal computers and office supplies and controlling applications automobiles, aircraft, DC motor drives, and telecommunication equipment (S Bhat, 2015).

They are various types of DC-DC converters. The most commonly used typically includes, buck, buck-boost, and boost converter. The buck converter is utilized as reduction voltage. The buck-boost converter utilized as either step-up or step-down, while, the boost converter is utilized as step-up voltage. In buck converters techniques such as Pulse width modulators (PWM) are widely used to help stabilize output voltage (Samosir A et al., 2023). Efficient controller is needed to control the MOSFET switching signal and generate the appropriate duty cycle, ensuring a stable output with a rapid response.

DC-DC converters power semiconductor components serve as control switches. The function of the switching devices, such as the buck converter, are inherently nonlinear (Dinesh M, 2015). The buck converters output voltage is generally unstable in alone. Usually, this converter is utilized with linear controllers to generate a constant, stable output voltage because they are basic and cannot provide the best results when used to nonlinear systems.

Nonlinear control techniques that provide optimal performance in all circumstances are therefore constantly in demand. The sliding mode controller used in this thesis was created for buck converters in order to provide quick response times and a steady, steady output voltage. In this work SMC proposed to regulate buck converter output voltage. It offers a promising solution to the robustness and performance advantage of PID.

1.2 Statement of Problem

DC-DC buck converters are commonly used in today's power supply systems like small electronic devices, electric cars, solar systems, and control units. They help change high input voltage into a lower, steady voltage that key parts need to work safely. However, nonlinearity occurs by semiconductor switches during the switching period, resulting to a nonlinear desired voltage function. In addition, change in temperature, manufacturing issues, and environmental conditions cause source voltage and load resistance to change over time. As a result, converter suffers a disturbance that causes output voltage to fluctuate from its reference value. It's important to use effective voltage control in these types of devices. For voltage regulation, regular PID controllers are used because of their simple design. Even so, they tend to perform poorly in the presence of system variation and parameter changes. Strong robustness is provided by SMC. It has been suggested as reliable control technique for this system because of its great ability to model uncertainty and disturbance. However, there are number of drawbacks to existing SMC, such as chattering, late transient response, and poor steady-state error. For real-world power converter applications, these problems lower controller performance and reliability. This study aims to design and evaluate sliding mode controller-based for buck converters to enhance their dynamic performance and voltage regulation in power supply application. The study will include performance comparisons with PID, a comprehensive stability analysis using Lyapunov theory, and MATLAB/SIMULINK simulations.

1.3 Objective

1.3.1 Main objective

This study aims to design and evaluate sliding mode controller for buck converters to enhance their dynamic performance and voltage regulation.

1.3.2 Specific objective

- ✓ Obtain mathematical model of buck converter circuit.

- ✓ Design SMC law based on the model with uncertainties and external disturbances.
- ✓ Reduce chattering and steady-state errors in comparison to traditional SMC.
- ✓ Optimize the controller parameters using PSO.
- ✓ Using MATLAB/Simulink, realize the designed controller and buck converter model.
- ✓ Simulate responses of proposed method then analyze robustness in comparison to the PID controller under various load conditions.

1.4 Significant of the Thesis

SMC keeps output voltage of buck converters constant. It gives insight into design of SMC law of buck converter. Furthermore, controller provides insight into a buck converter produces regulated voltage under different conditions. When compared to PID controllers, it confirms the significance of sliding mode controllers.

1.5 Scope of Thesis

The current finding is centered on designing, modeling, and stability assessment of a buck converter managed through PWM. A key objective is to formulate a control approach that maintains a steady and precise output voltage, despite external disturbances. In simulation methods the entire models are applied using MATLAB/Simulink simulation. The impact of sliding mode controller compare to conventional PID controller is explored in context of maximum overshoot, rise time and settling time from desired value with varying parameter and sudden load change.

1.6 Thesis Limitation

Depending on SMC of buck converter, the controller performance is robust and very fast, but this work focused only on simulation software, not real-world application. Chattering is also the main cause of sudden changes in the control design signal. Additionally, SMC depends on approximation system parameter values, which can depend on manufacturing variation factors.

1.7 Thesis Layout

The current study pass through six chapters, each offering a distinct and crucial contribution to the research.

Chapter 1: Introduction –Overview on DC-DC buck converters can be found in this chapter. It explains the specific objectives and research problems. The limitations and scopes are explained as well as the thesis framework.

Chapter 2: Literature Review –This section reviews knowledge about buck converters and control systems. It examines the fundamentals of sliding mode control, highlighting both its benefits and drawbacks. Additionally, it looks at the strengths and weakness of past research on SMC applications for buck converters.

Chapter 3: Methodology –This chapter examines mathematical based buck converters for controllers. Small-signal research and state-space equations are used to describe stability and dynamic behavior. This foundation enables the control design in the next chapter.

Chapter 4: Controller Design –This section uses previously maintained mathematical model to build the control system. The SMC controller method is designed for utilization. Ensuring system continues function well even when circumstances change, a sliding surface is added. To help sliding surface to target quickly, unique control rule is applied. Lyapunov theory is utilized to demonstrate that the system remains stable. The chapter also discusses how to minimize chattering and select appropriate control parameters.

Chapter 5: Results and Interpretation- The outcome of the simulations are displayed and explained in this chapter. It talks on the significance of the findings and their implications. The ISMC controller's performance is contrasted with that of other controller types. The SMC methods advantages are examined and recommendations are offered for how this work can be expanded up on in the future.

Chapter 6: Conclusion and Recommendations – This section generalize the overall development of research, reaffirming the achieved objectives. It presents conclusions on outcome offers and recommendations for future research.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Basic Theories and Overview

A common component of switching- mode power systems is the DC-DC converter. Due to their various uses, these switch mode converters drawn interest from several sectors. Analysis, regulation, and stability of switching converters are hence the primary elements should be taken into account. This switching mode converter is controlled using a variety of control methods. High performing operations constantly require a simple and reasonably priced controller system. There is advantage and disadvantage of controller that make suitable for particular set of situation when compared to other control systems. In any situation, the control approach that yields the optimum outcomes is required (Alazrag & L. Sbita, 2023).

Several control systems, including PID and SMC, are examined in current research. SMC has become well-known among these due to its ability to manage system uncertainties. However, when faced with disturbances that above their intended tolerance levels, most SMC implementations show only a limited amount of robustness. While mismatched load changes frequently occur in real-world systems like buck converters, standard SMC designs focus primarily on matched disturbances. The gaps between theoretical assumptions and real-world operating conditions led to the formation of modified SMC. Through combining switching method and control operations, this new technique greatly enhances the ability to reject disturbances (R. I. Jabbar, 2023).

Differences between the input power supply and the load requirements can lead to significant energy loss in electrical systems. To keep the voltage stable and improve energy efficiency, DC-DC converters are used as important control tools. One type of DC-DC converter, which works by changing the frequency PWM adjusting the desired output (K, 2021). A buck converter that is controlled by the SMC technique is used to boost energy efficiency. The converter continuously modifies the duty cycle to modify its nominal voltage with changes in load conditions.

2.2 DC-DC Converters

In power electronics DC-DC converters are most efficient circuits, which used to convert DC source voltage from one level to other output levels. This circuit typically stores input voltage using an inductor and capacitor, and then releases it at a different voltage level. It is widely used in SMPS. These converters have become singly common in many modern applications.

The structure block diagram of SMPS is shown as Figure 2.1. In semiconductor power circuit High frequency switching converters are there at a rate much higher than the change in input and output curves. Low-pass filters can be used to remove undesired switching frequency components because of the significant disparity between the switching frequencies of external waveforms. The main function of these converters is to serve as connection between DC-DC systems that run at various voltage levels. Often called DC-DC converters with high frequency, they are frequently used in many supply devices.

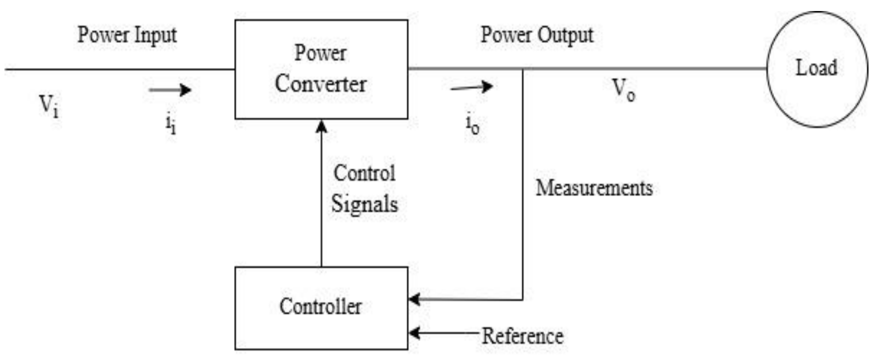


Figure 2.1 : Switch mode power supply structure (Posdzi et al., 2020).

2.3 Operating Principle of the Buck Converter

The term “buck” in “buck converter “likely refers to the fact that it “bucks” or lowers the frequency of source voltage to generate lower output value. It is also known as, step-down converter, is simple and cost-effective method of non-isolated, switching mode DC-DC conversion. In simple buck converter, as shown in Figure 2.2, an internal power MOSFET’s switching controls PWM by using DC input. The controlled DC desired voltage is obtained by using diode, inductor, and capacitor.

buck converter average desired voltage, occasionally known as decreasing converters, is lower than the source voltage (M. Gupta, 2014).

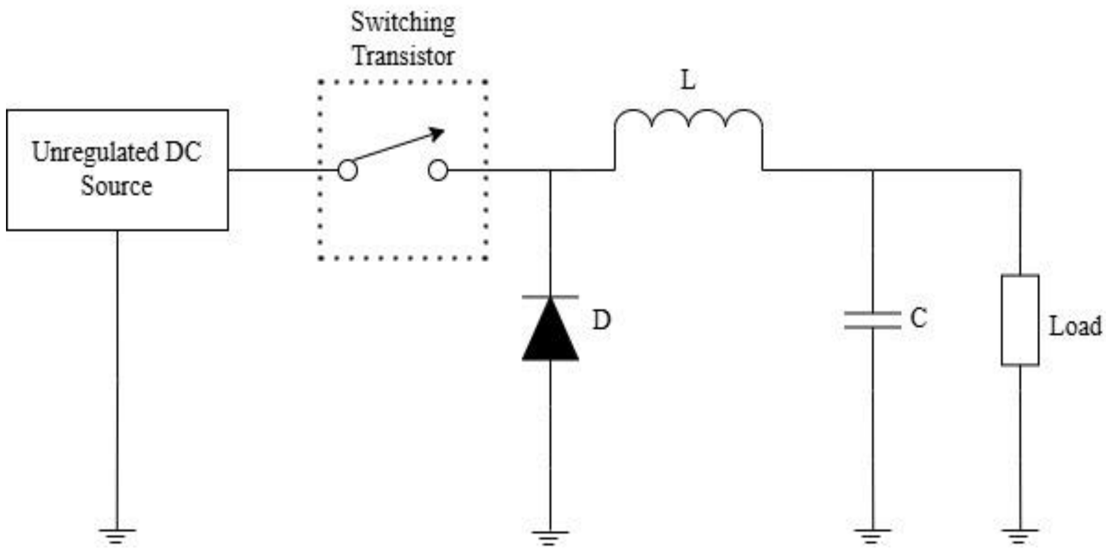


Figure 2.2: Topology of a switching regulator (Laghrouche S, Plestan F, 2007).

2.4 Buck Converter Component Functions

As discussed in the previously, every SMPS consists of five key components:

- ✓ Pulse-width Modulation (PWM)
- ✓ Mosfet switch
- ✓ Inductor
- ✓ Capacitor
- ✓ Free-wheeling Diode

This component selection criteria and operational details of each of these components are followed.

2.4.1 Switch and operating frequency

The most basic type of switch is transistor that control between ground and source voltage. In this case, the switching power source that selects transistor need to manage the surge voltage generated by inductor and has fast switching response. Most of the common switch control includes SCR, GTO, IGBT, and MOSFET. MOSFETs are the most important parts of switching power systems, including high frequency supply power (Peter E Perkins, 2017). MOSFETs are used in application of high frequency but lower voltages.

Performance, compactness, and efficiency are all impacted by the switching frequency. Higher frequencies impact efficiency by reducing component sizes while increasing inductor magnetic and switching losses. So that a suitable frequency is needed for buck converters that aim to balance efficiency (Posdzi et al., 2020).

2.4.2 Inductor

Inductor is used to limit the current rate of change, through the power switch is rice while the circuit is turned on. It is impossible for the inductor's current to fluctuate abruptly. The main goal of inductor maintains current flowing through it starts to drop by serving as a point of origin. The inductor's ability to store energy when utilized to lower voltage is its main benefit. Additionally, the inductor chooses whether converter is in CCM and regulates the eddy percentage. A small inductor causes fast response more eddy, which in turn increases conduction losses in component. Output voltage ripples decrease, large filter capacitor required.

2.4.3 Capacitor

By giving the distorted current a route far from load, capacitor performs filtering function. To minimize losses of converters nominal voltage ripple and overshoot response a step-down converter's output, output capacitance is necessary. This capacitance is sufficiently when switch is OFF, it has no discernible change in voltage.

2.4.4 Freewheeling diode

When the switch is OFF (open), the inductor current must path current that cannot change abruptly. The freewheeling diode, often known as the catch diode, provides this way. This diode's function is to guide flow of circuit current that guarantee and guarantee always current flow into the inductor, not to rectify. Additionally, this diode must be shut off really quickly. Thus, this diode allows the inductor converter to transfer stored energy to the load. We now more operate efficiently in DC-DC converters than in linear regulators because of this. A linear increase in current occurs as the control closed. The diode makes a linear decrease in current as the control opens.

2.4.5 Feedback

To control energy transfer and guarantee a steady output under typical working conditions, feedback and control circuitry are meticulously incorporated into these circuits. PWM need to maintain accurate desired control. Control switches, which control amount of power supplied to the load, are at the heart of switched power supplies. Chapter 3 will go into greater detail on the subject.

2.4.6 Comparator

Negative feedback is used by switching power supply to control output voltages. A differential amplifier creates an error signal that modifies the power supply to maintain the desired output by comparing the actual output value to a reference voltage.

As shown in Figure 2.3, a control voltage ($V_{control}$) is compared with a periodic wave form to produce a constant frequency PWM signal.

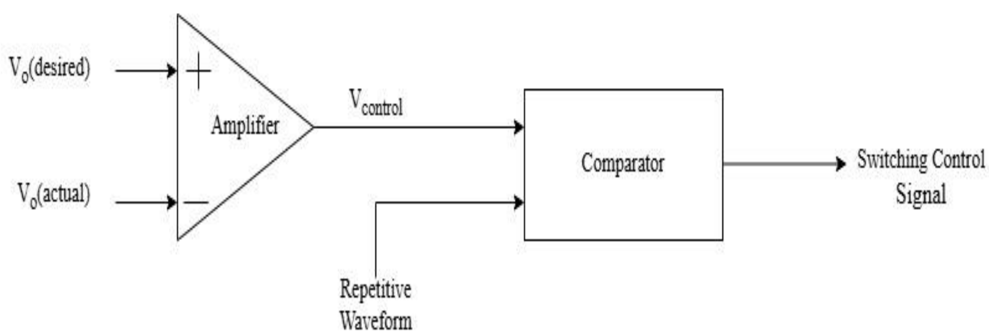


Figure 2.3: Voltage reference comparator (Mohan et al., 2002)

As shown in Figure 2.3, a control voltage ($V_{control}$) is compared with a periodic wave form to produce a constant frequency PWM signal.

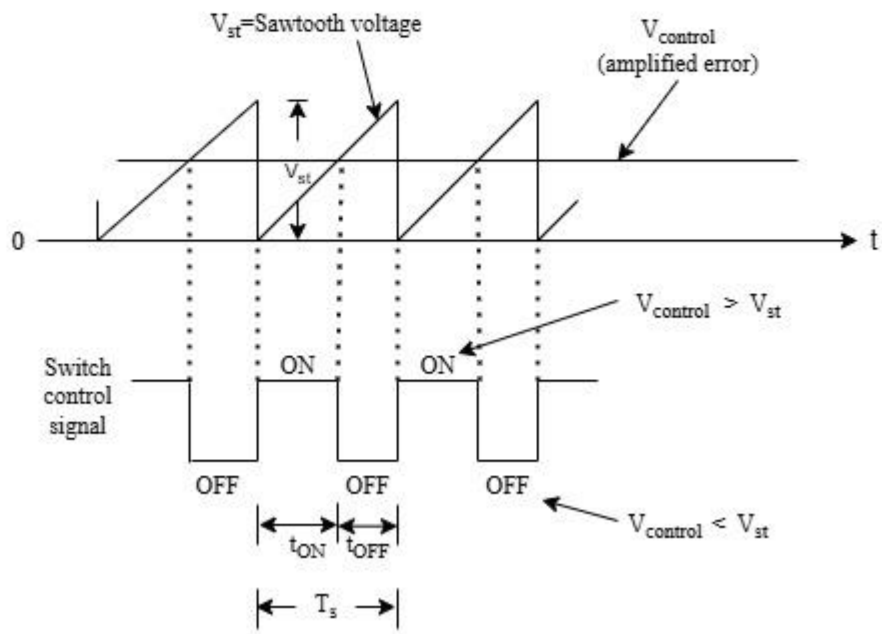


Figure 2.4: PWM comparator signals (Mohan et al., 2002).

The switching frequency is determined by frequency of sawtooth-shaped repeated signal shape top constant. This frequency is selected in range of a few hundred kilohertz and is maintained constant under a PWM control. The switch turns ON when amplified error signal, changes extremely delayed above time relation with switching time, exceeds the sawtooth signal and high with the switch control signal. Control switch is OFF otherwise. As a result, comparator threshold changes when the circuit output voltage along with the control voltage. As a result, the output pulse width varies as well.

The control loop is subsequently completed when this duty cycle shift lowers the output voltage to zero, reducing the error signal. The switch duty ratio in Figure (2.4) can be written as follows using $V_{control}$ and sawtooth waveform peak (V_{st}).

$$D = \frac{t_{ON}}{T_s} = \frac{V_{control}}{V_s}$$

2.5 Literature Review on Previous Works

SMC has appeared to be reliable technique of control power electronics converters, contributing advantage such as fixed determination to disturbance and uncertainty. (Utkin & Vadim, 1977) was the first to propose the idea of SMC by providing an extensive structure for its study and examination. The use of SMC in DC-DC buck converters has been carefully studied. (He & Luo, 2004) showed the usefulness of employing SMC to regulate buck converters, focusing how resistant it is to change in parameters. (Fadil & Giri, 2008) addressed at chattering a major weakness in traditional SMC, offering ways to reduce its effects.

For buck converter, (Bentalhik & Fadil, 2022) successfully tested a nonlinear SMC technique involving integral action. Under varied and uncertain load conditions, the recommended controller showed the ability of effectively controlling the inductor current while maintaining asymptotic stability. However, it gives little attention to transient matrices like overshoot, and settling time and lacks parameter optimization methods for controllers tuning.

In a most recent study, (Tatar & Chudzik, 2023) proposed a novel SMC technique for buck converters that significantly reduces voltage and current oscillations, improving overall system stability and electromagnetic compatibility. A composite control scheme consisting of recursive backstepping and integral terminal (SMC) verify convergence and improves the durability of DC-DC buck converters. Whereas experiments and simulations are used to check performance, Lyapunov theory is applied to show stability (Alam et al., 2023). But the proposed controller required an accurate model and has considerable computational complexity. There is possibility of improvement in handling uncertainties since its validation is restricted to a specific comparison.

An improved ISMC method to control load uncertainty of buck converters affected by mismatched has been put proposed by (Pandey et al., 2020). In this study, they propose disturbance observer which doesn't require the measurement for inductor current. In order to manage nominal voltage in deferent load and track, this observer is paired with ISMC while the proposed observer-based ISMC enhances adaptability, its accuracy is observer-dependent, may cause errors under sudden load changes, and its applicability to different buck converter situations is still unsolved. For a buck converter that works in case of both matched and mismatched disturbances (Ramezani-al et al., 2022) developed a new SMC based on an extended state observer (ESO).

(Rasheed, 2020) has investigated and contrasted the effective use of ASMC with modified SMC and classical SMC of regulating DC output voltage in buck converter. Sliding mode controllers were chosen because of maintain system stability in case of external disturbances and parameter unpredictability, given the systems nonlinear and time-varying properties. By minimizing settling, chattering and steady-state error, ASMC outperformed CSMC and MSMC, based up on simulation results gained with MATLAB/Simulink utilizing a flexible SMC. However, it did not contain organize tuning sliding parameters and did not employ optimization methods like PSO, (Attia, 2022) indicated a high-performance buck converter for distributed generation of sustainable energy.

In accordance with (Shareen et al., 2019) SMC may improve DC-DC converter performance by obtaining about linear PID controllers problems of controlling nonlinearity and modifying operating conditions. (Cham et al., 2024) found that the parallel application of ASMC and PSO significantly improves dynamic responsiveness of half-bridge bidirectional converter. (Huerta-Moro et al., 2023) proposed a buck converter of battery voltage regulation using SMC with a unique sliding surface. Lyapunov stability showed that the outcomes excelled those of earlier methods. Using only the input-output model, (Elhajji et al., 2018) claim a unique discrete-time SMC obtaining effective voltage control in buck converters.

Despite meaningful improvement being made in controlling buck converters methods such as PID and conventional SMC, key challenges remain in optimizing transient behavior, disturbance handling, and steady-state accuracy. PID controllers are often limited when dealing with nonlinear dynamics and sudden load changes, while traditional SMC techniques are delayed by the issue of chattering. Furthermore, most current SMC approaches highlight system stability, often missing the optimization of transient response characteristics such as settling time overshoot. Also most existing SMC focus on desired voltage behavior while, not focused on quality and behavior of controller input. As a result, issue such as losing control action and stress on component may arise. Importantly, many SMC designs depend on manually selected parameter tuning, missing use of systematic optimization methods to improve controller performance. Ensuring rapid dynamic response minimal steady-state error and reduced chattering under conditions of disturbance and uncertainty. This research aims to address these limitations by applying performance evaluation of SMC-based control scheme in MATLAB, focusing on examining its potential to enhance overall converter performance.

Previous studies on DC-DC buck converters have examined a range of control techniques, including PID and standard SMC, each offering specific trade-offs in performance. However, these controllers frequently fall short of delivering fast transient response, minimal overshoot, and low steady state error in the presence of disturbance and uncertainty. While a new SMC has been introduced as a robust alternative, most existing work emphasizes its stability properties rather than assessing its capacity to improve transient and steady-state behavior or suppress chattering. To bridge this gap, the present study employs MATLAB/SIMULINK simulations to evaluate SMC's performance in switching mode buck converters to close this gap. This study compares SMC and standard PID control side by side, focusing on theoretical stability.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Methodology

The methodology of this thesis starts with problem identification and continuous review of relevant literature, including books, research articles, and online resources. This step identifies key challenges in controlling DC-DC buck converters, especially their nonlinear dynamics, sensitivity to load variations, and susceptibility to uncertainties. A major problem is achieving accurate and robust voltage regulation, which conventional sliding mode control (SMC) struggle with due to chattering and steady state error. To address this limitation, this research aims to design and simulate optimized SMC method of buck converter. Using averaging techniques, a buck converter mathematical modeling is first derived, providing basis for design of controller. Next, with an emphasis on minimizing chattering, proportional-integral sliding surface and combination with control law are constructed. MATLAB/Simulink simulations are used to analyze the effective optimized SMC approach under different conditions. Finally, a comparison of SMC with PID control shows superior reliability and tracking.

3.2 Materials Used

Software like Mocrosoft Office 2007, Math Type 7.0 equation editor, and MATLAB/2016a are used in this study project. Simulink and technical toolboxes are components of the computer program MATLAB. The documentation for this work is written using Microsoft Office. Writing mathematical equations and formulas Microsoft Office Word and Power Point tools requires Mathtype 7.0. Finally, Mendely Reference Manageris used for managing citations and references.

3.3 Methods Used

Figure 3.1 shows technique used in this study, which directs the research toward its goals. In order to determine the research problem, this procedure starts with a review on the body of existing literature. The components of the system are then represented mathematically. The suggested controllers are created using these concepts as a basis. Simulation and data analysis are part of the fourth step. The study came to an end after the results were documented

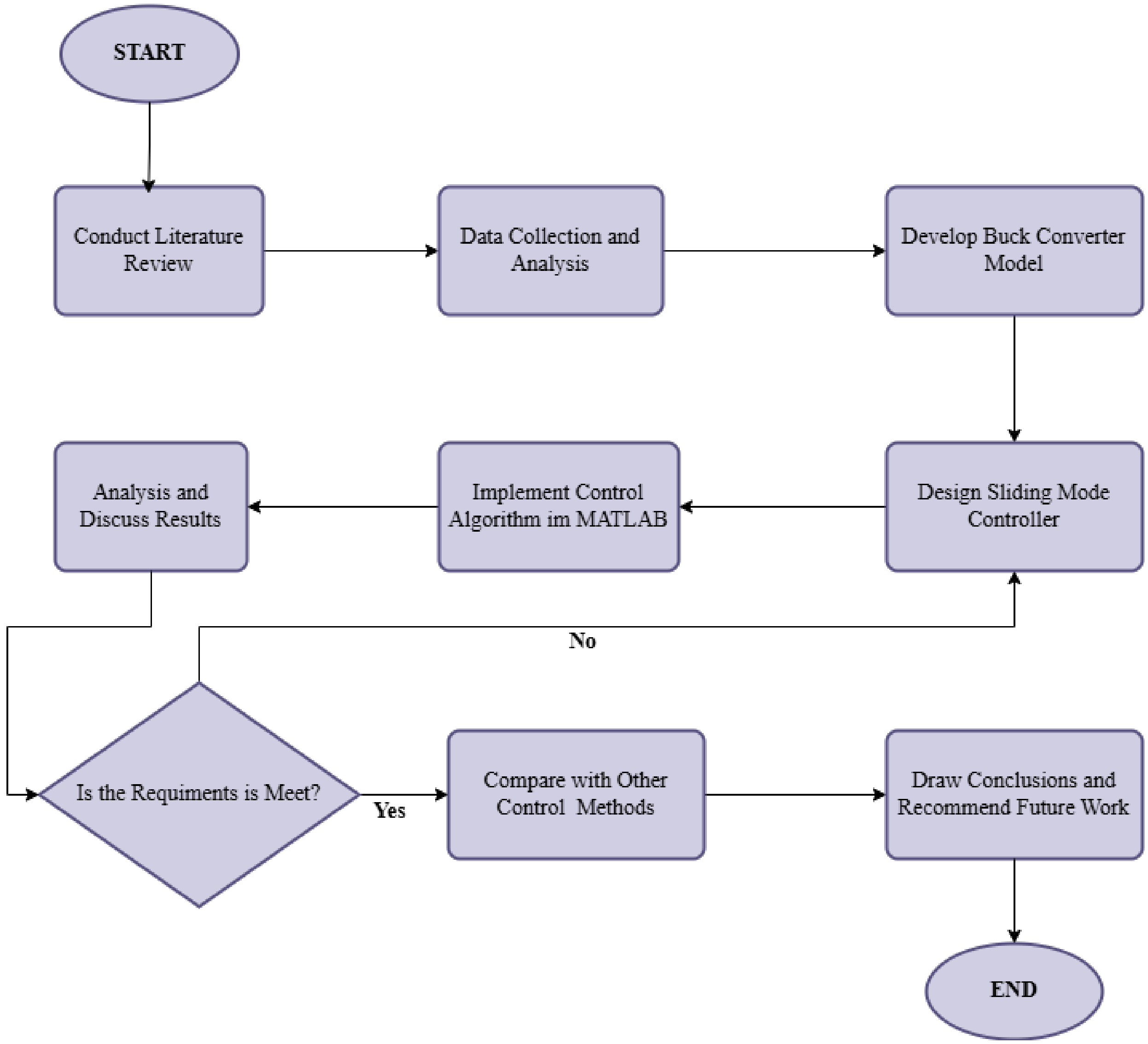


Figure 3.1: Flow chart of methods

3.4 Block Diagram of Proposed Work

Based on understanding of the components and overall operation of the buck converter, this section focuses on simulation of general structure of the SMC and buck converter, incorporating their individual components.

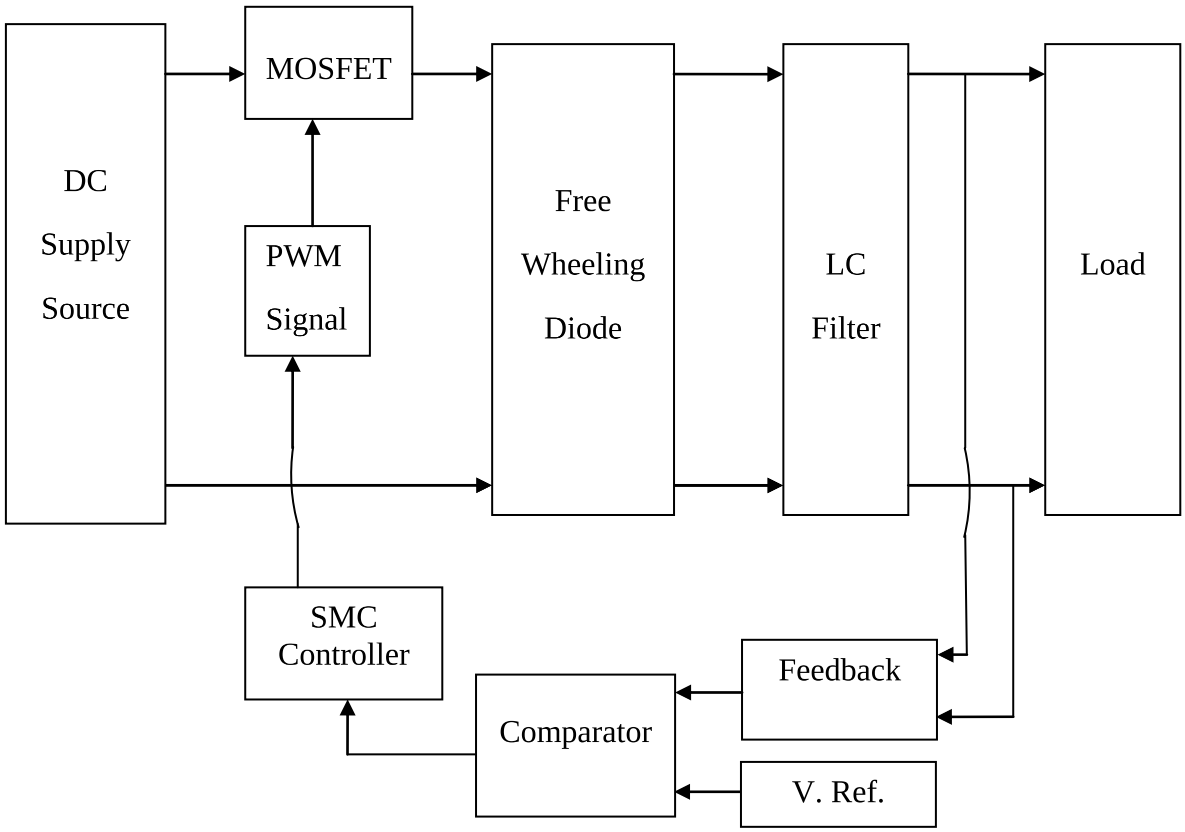


Figure 3.2: Block diagram of proposed SMC

An SMC used to regulate buck converter desired voltage with precise and steady voltage with varying conditions. Depending on the application of the buck converter effectively decreases source voltage to controlled limited desired voltage is needed. A PWM control signal produced by the SMC governs the high-frequency switching of a MOSFET to make this regulation. To provide steady power delivery, the power stage consists of inductor, capacitor, and diode. Varying supplied SMC compare the desired voltage is continually measured to reference voltage (V_{ref}).

Depending upon voltage error and its total value, SMC controller has a sliding surface that has a proportional-integral term, and it calculates the control action. This guarantees strong rejection of disturbances, quick dynamic reaction, and steady state error removal. The control signal is that is calculated to control a PWM signal for control purposes, and then it modifies the duty cycle of the MOSFETs. The SMC is suitable for conversion applications because of its closed loop system, and also improves accuracy, resilience, and flexibility to changes in disturbance and load conditions (Souvik Dasa & Swarnkarc, 2018).

3.5 Modeling of Buck Converter

Buck converter is type of type of DC converter that reduced source voltage to desired level (Noronha et al., 2019). A simple buck converter circuit contains diode, capacitor, inductor, and switch. The diode makes current track on one direction, capacitor energy store, and inductor flat current flow, and switch controls current flow.

Figure (3.3) illustrates buck converter topology.

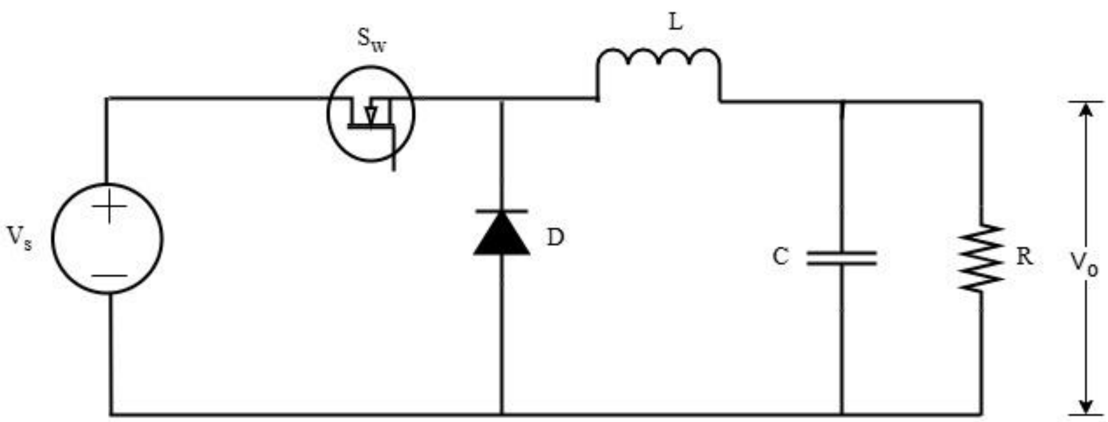


Figure 3.3: Buck converter circuit diagram (Baharudin N, Mansur T, 2018)

When switching, MOSFETs are chosen over IGBTs in low voltage applications because of their greater frequency switching capability. When the transistor is at t=0s, current flow from input source to the inductor, charging it. In the second mode at t= t_1 , when the transistor turned off, inductor generate a back EMF. This back EMF, combined with the source voltage and a small diode voltage drop, powers load charges the output capacitor. The switching period of converter illustrated in figure 3.4.

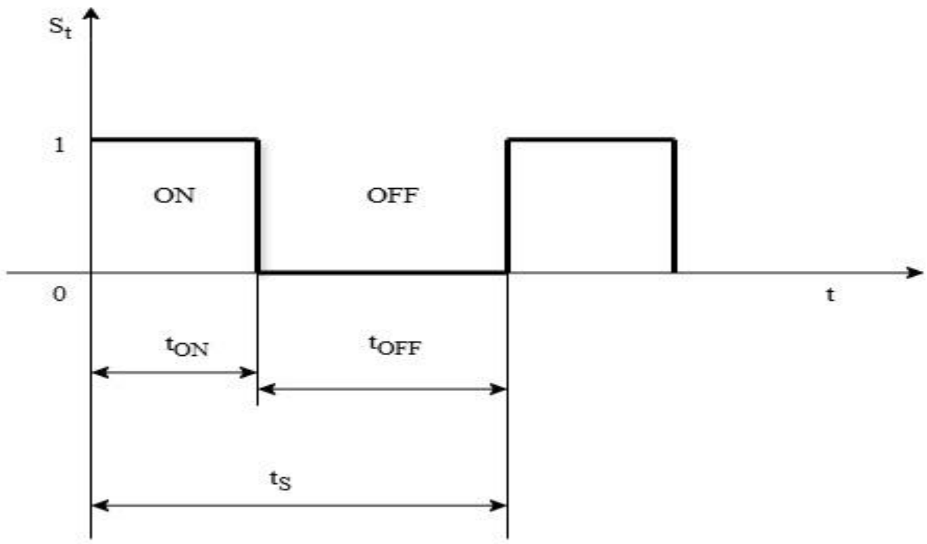


Figure 3.4: Buck converter switching period (M. Gupta, 2014).

3.5.1 ON-state mode

When the MOSFET is closed, current through the load and the capacitor charge gradually increase. This occurs because energy is simultaneously being stored in the inductor.

Buck converters related circuit models during the modes of the switch ON are depicted in Figure 3.5.

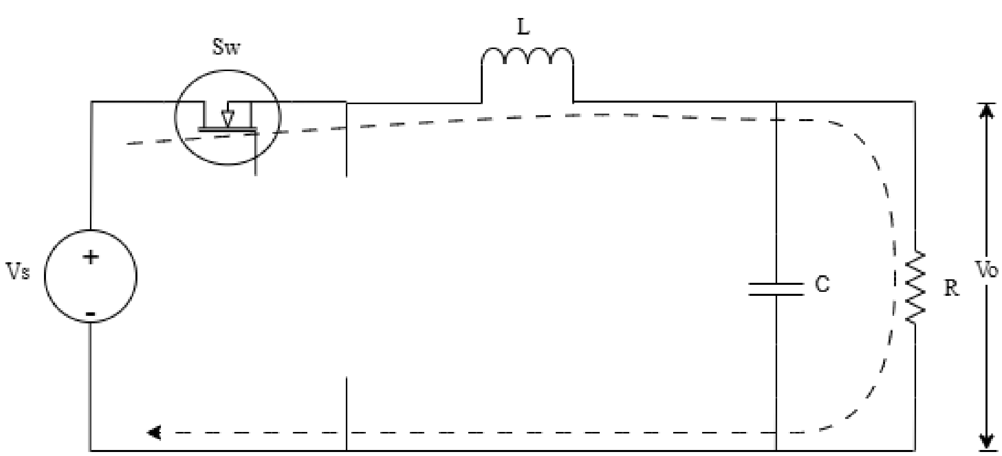


Figure 3.5: ON state circuit diagram (Samosir et al., 2022)

Buck converter model is derived from Kirchhoff's laws (KCL and KVL).

$$\frac{di_L}{dt} = \frac{V_s}{L} - \frac{V_o}{L} \tag{3.1a}$$

$$\frac{dV_o}{dt} = \frac{i_L}{C} - \frac{i_o}{C} \tag{3.1b}$$

In terms of impedance loading, Equation (3.1) becomes:

$$\frac{di_L}{dt} = \frac{V_s}{L} - \frac{V_o}{L} \tag{3.2a}$$

$$\frac{dV_o}{dt} = \frac{i_L}{C} - \frac{V_o}{RC} \tag{3.2b}$$

The timing parameters of a transistor can be determined by:

$$t_{ON} = D * t_S \tag{3.3}$$

The generated voltage inductor (L) is determined as:

$$L\frac{di_L}{dt} = V_s - V_o \tag{3.4}$$

Equation (3.3) when substituted into Equation (3.4)

$$L\frac{\Delta i}{D * t_S} = V_s - V_o \tag{3.5}$$

The ripple current Δi can be determined by:

$$\Delta i_{ON} = \frac{(V_s - V_o)(D * t_S)}{L} \tag{3.6}$$

3.5.2 OFF-state mode

Upon opening the switch, the direction of the inductor voltage reverses. The diode flows current forward biased in the same direction. The capacitor becomes the circuit’s main source of current until the switch turned on again after inductor has fully discharged.

The related buck converter circuit models during the modes of the switch OFF are followed as figure 3.6.

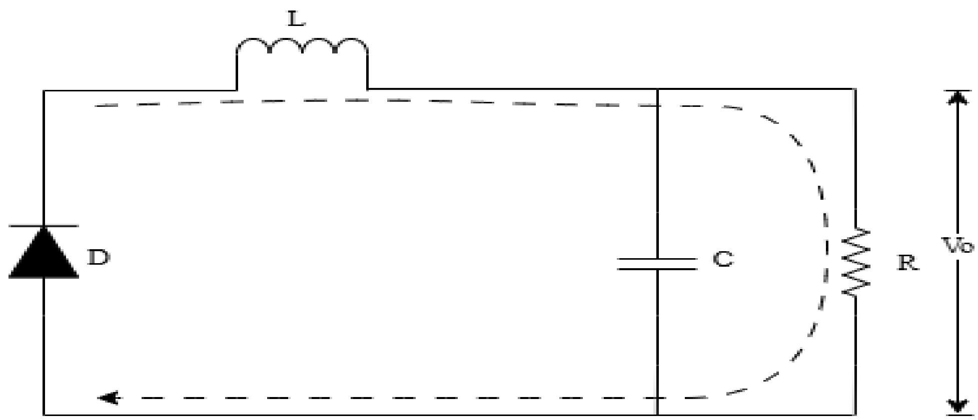


Figure 3.6: buck converter circuit during OFF state (Samosir et al., 2022)

$$\frac{di_L}{dt} = -\frac{V_o}{L} \tag{3.7a}$$

$$\frac{dV_o}{dt} = \frac{i_L}{C} - \frac{i_o}{C} \tag{3.7b}$$

In terms of impedance loading, Equation (3.7b) becomes:

$$\frac{di_L}{dt} = -\frac{V_o}{L} \tag{3.8a}$$

$$\frac{dV_o}{dt} = \frac{i_L}{C} - \frac{V_o}{RC} \tag{3.8b}$$

The timing parameters of a transistor can be determined by:

$$t_{OFF} = (1-D)t_S \tag{3.9}$$

The voltage induced across the inductor (L):

$$L\frac{di_L}{dt} = -V_o \tag{3.10}$$

Putting Equation (3.9) into Equation (3.10):

$$L\frac{\Delta i}{(1-D)t_S} = -V_o \tag{3.11}$$

The ripple current Δi, is taken as follow:

$$\Delta i_{OFF} = -\frac{V_o(1-D)t_S}{L} \tag{3.12}$$

3.5.3 Average model of buck converter

By equating the ripple current expressions derived for ON-state mode and OFF-state mode:

$$\Delta i_L = \Delta i_{ON} + \Delta i_{OFF} = 0 \tag{3.13a}$$

$$D(V_s - V_o) - (1-D)V_o = 0 \tag{3.13b}$$

$$V_s D = V_o + DV_o - DV_o \tag{3.13c}$$

$$D = \frac{V_o}{V_s} \tag{3.13d}$$

where V_s is source voltage, V_o is output voltage, t_{ON} is MOSFET ON(sec), $t_{OFF}$is MOSFET OFF (sec), t_S is switching period (sec), D is duty cycle, and Δi is ripple current.

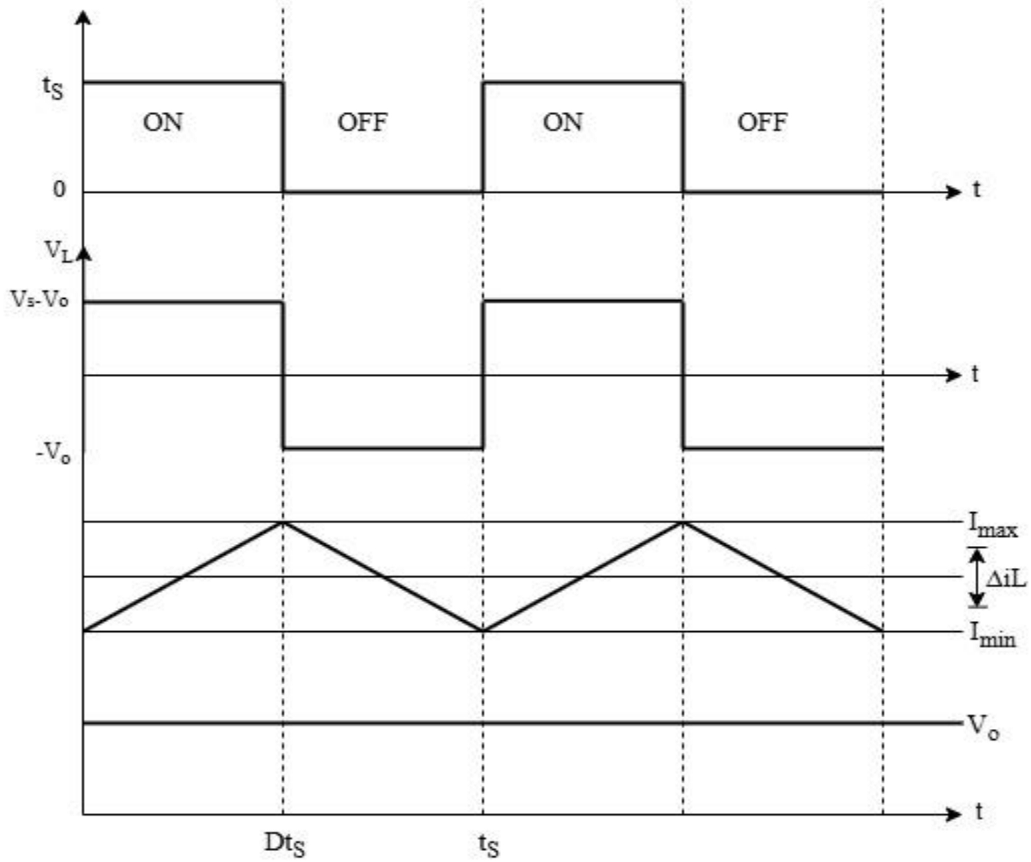


Figure 3.7: Buck converter output wave form (Høyerby M, 2006).

Average terminal voltage is less than source voltage, since 0<D<1.

Applying averaging to Equations (3.2) and (3.8), it can be expressed as the average dynamic model below:

$$\begin{aligned}\frac{di_L}{dt} &= \left(\frac{V_s}{L} - \frac{V_o}{L}\right) D - \frac{V_o}{L}(1-D) \\ &= -\frac{V_o}{L} + \frac{V_s}{L} D\end{aligned} \tag{3.14a}$$

$$\begin{aligned}\frac{dV_o}{dt} &= \left(\frac{i_L}{C} - \frac{V_o}{RC}\right) D + \left(\frac{i_L}{C} - \frac{V_o}{RC}\right)(1-D) \\ &= \frac{i_L}{C} - \frac{V_O}{RC}\end{aligned} \tag{3.14b}$$

Defining state variables as inductor current $i_L = x_1$, capacitor voltage $V_0 = x_2$ and duty cycle $D = u$ gives the state space model:

$$\dot{x}_1 = -\frac{1}{L}x_2 + \frac{V_s}{L}u \quad (3.15a)$$

$$\dot{x}_2 = \frac{1}{C}x_1 - \frac{1}{RC}x_2 \quad (3.15b)$$

$$y = x_2 \quad (3.15c)$$

The matrix-vector form of the above equations may be written as:

$$\dot{x} = \mathbf{A}x + \mathbf{B}u \quad (3.16a)$$

$$y = \mathbf{C}x \quad (3.16b)$$

where state vector $\boldsymbol{x}$ and system matrices are defined as follows:

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (3.17a)$$

$$\mathbf{A} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} \frac{V_s}{L} \\ 0 \end{bmatrix}, \mathbf{C} = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad (3.17b)$$

3.5.4 Steady-state analysis

The steady state stability of buck converter is defined as the ability to obtain constant desired voltage under constant source voltage and load condition, without having oscillations after the initial transient period has passed. In a stable steady state, the output voltage will have small, predictable ripple at the switching frequency, but its average value will remain constant at the desired level.

From Equations (3.15a) and (3.15b), in the steady-state, the following relationships are satisfied:

$$x_{20} = V_{ref} \tag{3.18a}$$

$$x_{10} = \frac{1}{R} x_{20} = \frac{1}{R} V_{ref} \tag{3.18b}$$

$$u_0 = \frac{1}{V_s} x_{20} = \frac{1}{V_s} V_{ref} \tag{3.18c}$$

3.5.5 State equation with disturbance

There are some factors that affect performance and accuracy of the model of the buck converter. Some common disturbances include source voltage fluctuations and sudden load change. Variations in supply voltage can affect buck converter function. Changes in load connected alter terminal voltage and current. As parameter variations, inductor, capacitor and resistor value can slightly deviate from nominal values.

The presence of external disturbance and parameter change, state space equation of buck converter can cause deviations from the expected behavior of the converter and affect in their operation. Therefore, equation (3.15) can be written as follow, which is closer to the actual model.

$$\dot{x}_1 = -\frac{1}{L} x_2 + \frac{V_s}{L} u + \xi_1 d(\boldsymbol{x}, t) \tag{3.19a}$$

$$\dot{x}_2 = \frac{1}{C} x_1 - \frac{1}{RC} x_2 + \xi_2 d(\boldsymbol{x}, t) \tag{3.19b}$$

$$y = x_2 \tag{3.19c}$$

where $d(\boldsymbol{x},t)$ represent uncertainties, that is, load variations, input voltage fluctuations and parameter variations, which is known upper bound $|d(x,t)| = d_{max}$.

The state space with disturbance can be written as:

$$\dot{x} = \boldsymbol{A}x + \boldsymbol{B}u + \boldsymbol{\xi} d(\boldsymbol{x}, t) \tag{3.20a}$$

$$y = \mathbf{C}x \tag{3.20b}$$

where $\boldsymbol{\xi}$ is defined as follow:

$$\boldsymbol{\xi} = \begin{bmatrix} \xi_1 & \xi_2 \end{bmatrix}^T \tag{3.21}$$

3.6 Discontinuous and Continuous Conduction Mode

The average of inductor current is equal to average of minimum and maximum inductor current. Therefore, the maximum inductor current can be determined through equation (3.22),

$$I_{L,\max} = I_L + \frac{\Delta i_L}{2} \tag{3.22}$$

By the amp-second balance principle average inductor current equals average output current.

$$I_L = I_{out} = \frac{V_o}{R} \tag{3.23}$$

Substituting equations (3.11) into (3.22) and simplifying yields:

$$I_{L,\max} = V_o * \left(\frac{1}{R} + \frac{(1-D}{2*L*f} \right) \tag{3.24}$$

The minimum inductor current same manner as maximum inductor current:

$$I_{L,\min} = I_L - \frac{\Delta i_L}{2} \tag{3.25}$$

Substituting equations (3.17) into (3.25) and simplifying yields:

$$I_{L,\min} = V_o * \left(\frac{1}{R} - \frac{(1-D)}{2*L*f} \right) \tag{3.26}$$

Two distinct modes of buck converters are CCM and DCM. Every switching cycle in CCM maintains a positive inductor current. DCM inductor current decreases to zero before switching cycle’s finished. Equation (3.26) determines that the inductance (L) must fulfill the condition L > L_{min} in order to guarantee continuous conduction mode operating in a buck converter.

$$L_{\min} = \frac{(1-D)*R}{2*f} \tag{3.27}$$

The minimal capacitance needed to sustain the desired ripple voltage can be determined once the inductor value has been determined. This entails examining the amount of charge the capacitor delivers when the switch is in the ON and OFF positions.

Change in charge can be determined to calculate triangular area of current waveform during switch state. Height of triangle is equal to half of change in current and base.

$$\Delta Q = \frac{1}{2}*\left(\frac{\Delta i_L}{2}\right)*\frac{T}{2} \tag{3.28}$$

Calculating change in charge (ΔQ) when considering change in current during switch open.

Substituting equation (3.17) into (3.23) and simplifying gives:

$$\Delta Q = V_o * \frac{(1-D)}{8*L*f^2} \tag{3.29a}$$

$$C = \frac{\Delta Q}{\Delta V_o} \tag{3.29b}$$

Substituting equation (3.29a) to (3.29b) we get minimum capacitor.

$$C_{\min} = \frac{(1-D)}{8*L*f^2}*\frac{V_o}{\Delta V_o} \tag{3.30}$$

In this context C_{min} is minimum capacitance, R is load resistance, and f_s is switching frequency.

3.7 Buck Converter Design

Factors that are considered when selecting controlled desired voltage include

- ✓ The source voltage.
- ✓ Magnitude of output voltage.
- ✓ Permissible desired voltage ripple.

- ✓ Required transient response.
- ✓ The switching frequency.

Design implementation requires careful consideration of key parameters. These priorities could be optimizing performance

The standard parameter for buck converter is as follows:

Table 3-1: Standard parameter specification of buck converter (Weewooday, 2020)

Specification	Value
Source Voltage	12V
Load Power	15W
Desired Voltage	5V
Ripple Voltage in Percentage	1%
Current ripple	0.6A

These specifications apply to automotive power supply, particularly in devices such as driving recorders, GPS navigation systems, and car audio equipment, where the trend is toward progressively lower operating voltages.

3.8 Design Equations

A 15W load requires a 1.67Ω resistance. For reliable operation, the inductor must be at least 20% larger than minimum value, and the output voltage ripple voltage limited to 1%. The 100 kHz switching frequency was selected to satisfy the specifications listed in Table 3.1. Using the above Discontinuous and continuous conduction mode the component calculation were in Appendix A, its values were calculated as follows.

Table 3-2: Component specification of buck converter

Component	Symbol	Value
Capacitor	C	28μF
Inductor	L	39μH
Load resistor	R	1.67Ω
Switching frequency	f_{sw}	100kHz

CHAPTER FOUR

4. CONTROLLER DESIGN

4.1 Sliding Mode Control System Design

SMC is an effective control approach because DC-DC converters inherent nonlinearities and substantial uncertainty. This robust control technique provides outstanding performance in regulating buck converter circuits while managing uncertainties with effectiveness. Sliding mode control is also used in this study to design DC-DC circuits of the buck type.

In SMC, sliding surface is formed by crossing of hyper surfaces within the system. This command referred to as the switching plane. The reaching phase limits of standard methods are solved by sliding mode control. The SMC surface equations order, which defines the systems state space dimension, guarantees robustness from the very beginning of the systems reaction (Pandey et al., 2020).

SMC incorporate three control parameters, which includes, load voltage error, integral of the voltage error and inductor current error (Haris Sheh Zad et al., 2024). The converters behavior with these three control parameters can be described by its state space representation.

Let define new variables as:

$$e_1 = x_2 - x_{20} \tag{4.1a}$$

$$e_2 = \int e_1 dt \tag{4.1b}$$

$$e_3 = x_1 - x_{10} \tag{4.1c}$$

where x_{10} and x_{20} are the steady-state values of x_1 and x_2 defined in Equations (3.18a) and (3.18b).

Substituting the steady-state values in Equation (3.18) to Equation (4.1) gives:

$$e_1 = x_2 - V_{ref} \tag{4.2a}$$

$$e_2 = \int e_1 dt \tag{4.2b}$$

$$e_3 = x_1 - x_{10} = x_1 - \frac{1}{R} V_{ref} \tag{4.2c}$$

Differentiating both sides of Equation (4.2) and applying Equation (3.15) yields

$$\dot{e}_1 = \dot{x}_2 - \dot{V}_{ref} = \frac{1}{C} x_1 - \frac{1}{RC} x_2 + \xi_2 d(\boldsymbol{x}, t) \tag{4.3a}$$

$$\dot{e}_2 = \int e_1 dt = x_2 - V_{ref} \tag{4.3b}$$

$$\dot{e}_3 = \dot{x}_1 - \frac{1}{R} \dot{V}_{ref} = -\frac{1}{L} x_2 + \frac{V_s}{L} u + \xi_1 d(\boldsymbol{x}, t) \tag{4.3c}$$

4.2.1 Sliding surface

By adding a hyper-plane called the sliding surface, SM works, to produce path of the systems states to quickly converge onto then slide along this surface. It is crucial to choose the right sliding surface. To improve converters transient and steady-state performance, PI-type sliding surface was used in SMC design. It increases converter stability and improves desired voltage. PI sliding surface also helps in reducing chattering, when paired with smooth switching technique.

The pi-sliding surface of SMC is defined as,

$$s = \lambda_1 e_1 + \lambda_2 e_2 + e_3 \tag{4.4}$$

where λ_1, λ_2 are positive constants. The differentiation sliding surface can be defined as

$$\dot{s} = \lambda_1 \dot{e}_1 + \lambda_2 \dot{e}_2 + \dot{e}_3 \tag{4.5a}$$

$$= \lambda_1 [\frac{1}{C} x_1 - \frac{1}{RC} x_2 + \xi_2 d(\boldsymbol{x}, t)] + \lambda_2 (x_2 - V_{ref}) - \frac{1}{L} x_2 + \frac{1}{L} V_s u + \xi_1 d(\boldsymbol{x}, t) \tag{4.5b}$$

$$= \frac{\lambda_1}{C} x_1 + \left(\lambda_2 - \frac{\lambda_1}{RC} - \frac{1}{L} \right) x_2 - \lambda_2 V_{ref} + \frac{V_s}{L} u + \left(\lambda_1 \xi_2 + \xi_1 \right) d(\boldsymbol{x}, t) \tag{4.5c}$$

Since control input u exists in the sliding surface first derivative, It increases control accuracy by using a sliding mode controller.

4.1.3 Control law design

Once sliding manifold reach the path, the corresponding control is in charge of keeping the system inside it. It stands for the smooth control input that ensures the desired motion along the sliding surface by counteracting system dynamics.

By solving the equation $\dot{s} = 0$, we choose the equivalent control law, which is given Equation (4.5c).

$$u_n = \frac{L}{V_s}[-\frac{\lambda_1}{C}x_1 - (\lambda_2 - \frac{\lambda_1}{RC} - \frac{1}{L})x_2 + \lambda_2 V_{ref}] \tag{4.6}$$

Robustness is assessed solely within the sliding phase, which can be modeled as a composed of two different waveforms according to in Figure (4.1), high frequency component oscillating through zigzag pattern around the sliding surface and low frequency component moving through the surface (Haris Sheh Zad et al., 2024).

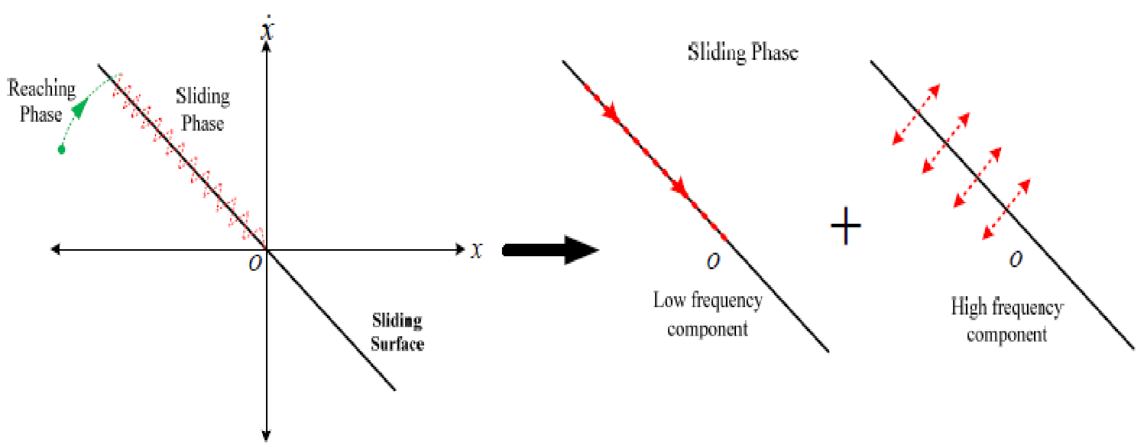


Figure 4.1: Equivalent control principle (Souvik Dasa & Swarnkarc, 2018).

In closed loop controlled buck converter utilizing PWM, the duty ratio (D) is the ratio of the control signal $V_{control}$ to amplitude of carrier waveform $V_{saw-tooth}$. Expressing equivalent control action with duty ratio rearranging Equation (4.7), obtain:

$$0 < D = \frac{V_{control}}{V_{saw-tooth}} = \frac{u_n}{V_s} < 1 \tag{4.7}$$

The discontinuous control or switch control (u_d) manages $d(x,t)$ as

$$u_d = \frac{L}{V_s}[-ks - \eta sgn(s)] \tag{4.8}$$

where k is defined positive constant. To derive overall control law that integrates both the equivalent and discontinuous components, we substitute Equations (4.6) and (4.8), resulting in the following expression.

$$u = u_n + u_d \tag{4.9a}$$

$$= \frac{L}{V_s}[-\frac{\lambda_1}{C}x_1 - (\lambda_2 - \frac{\lambda_1}{RC} - \frac{1}{L})x_2 + \lambda_2 V_{ref} - ks - \eta sgn(s)] \tag{4.9b}$$

Due to its discontinuous nature, the *sgn* function causes high-frequency oscillations in the control signal, leading to undesirable vibrations in actuator systems and increasing energy consumption. To address these challenges, we use the tanh function. Then the proposed control law becomes

$$u = \frac{L}{V_s}[-\frac{\lambda_1}{C}x_1 - (\lambda_2 - \frac{\lambda_1}{RC} - \frac{1}{L})x_2 + \lambda_2 V_{ref} - ks - \eta \tanh(\frac{s}{\varepsilon})] \tag{4.10}$$

where ε is a small positive constant. In this study, ε is set to 0.001.

$$\tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \tag{4.11}$$

Figure 4.2 shows graph of tanh(x).

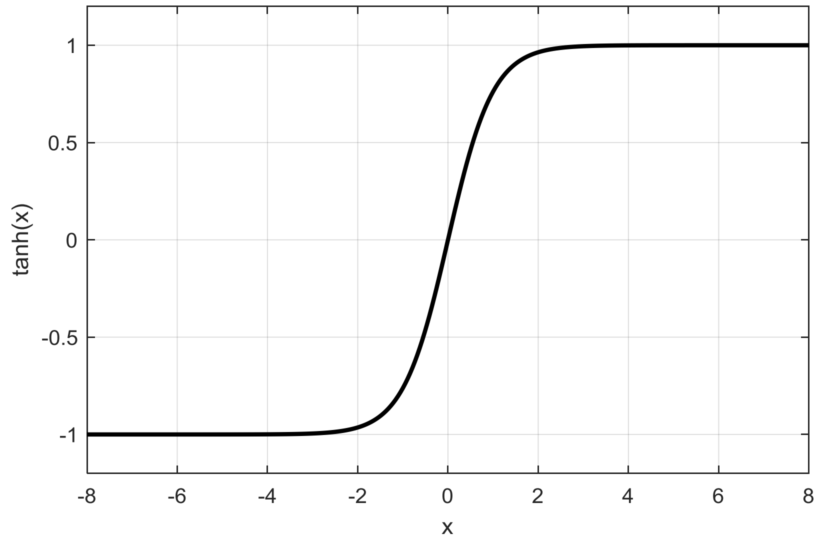


Figure 4.2 Graph of tanh(x)

4.2.3 Stability analysis using the lyapunov direct method

The Lyapunov function of SMC system is as follows:

$$V = \frac{1}{2} s^2 \tag{4.12}$$

Its time derivative is:

$$\dot{V} = s\dot{s} \tag{4.13}$$

In order to guarantee the existence of SM, the following inequality holds:

$$s\dot{s} < 0 \tag{4.14}$$

This means the system phase directed toward sliding surface $s = 0$, which is a necessary condition of sliding mode for the existence.

$$s\dot{s} = s[\frac{\lambda_1}{C} x_1 + (\lambda_2 - \frac{\lambda_1}{RC} - \frac{1}{L}) x_2 - \lambda_2 V_{ref} + \frac{V_s}{L} u + (\lambda_1 \xi_2 + \xi_1) d(\boldsymbol{x}, t)] \tag{4.15}$$

Substituting Equations (4.10) into (4.15) gives

$$s\dot{s} = s[-ks - \eta \tanh(\frac{s}{\varepsilon}) + (\lambda_1\xi_2 + \xi_1)d(\boldsymbol{x},t)] \tag{4.16}$$

$$\dot{V} = s\dot{s} = s[-ks - \eta \tanh(\frac{s}{\varepsilon}) + \left(\lambda_1\xi_2 + \xi_1\right)d(\boldsymbol{x},t)] \tag{4.17}$$

As shown in Figure 4.2, if $s > 0$, then $\tanh(s/\varepsilon) > 0$, implying $s\cdot\tanh(s/\varepsilon) > 0$. If $s < 0$, then $\tanh(s/\varepsilon) < 0$, implying $s\cdot\tanh(s/\varepsilon) > 0$. Therefore, $s\cdot\tanh(s/\varepsilon)$ is positive for all values of s (except at $s= 0$, where it is zero). Thus

$$s\cdot\tanh(s/\varepsilon) = |s| \tag{4.18}$$

Substituting Equation (4.18) to Equation (4.17) yields

$$\begin{aligned}\dot{V} &= -ks^2 - \eta s \cdot \tanh(\frac{s}{\varepsilon}) + s\left(\lambda_1\xi_2 + \xi_1\right)d(\boldsymbol{x},t) \\ &\le -ks^2 - \eta\,|s| + s\left(\lambda_1\xi_2 + \xi_1\right)d(\boldsymbol{x},t) \\ &\le -ks^2 - \eta\,|s| + |s|\cdot|\lambda_1\xi_2 + \xi_1|\cdot|d(\boldsymbol{x},t)|\end{aligned} \tag{4.19}$$

Grouping |s| on the right side, we have

$$\dot{V} \le -ks^2 - |s|(\eta - |\lambda_1\xi_2 + \xi_1|\cdot|d(\boldsymbol{x},t)|) \tag{4.20}$$

From the fact of $|d(\boldsymbol{x},t)|= d_{max}$,

$$\dot{V} \le -ks^2 - |s|(\eta - |\lambda_1\xi_2 + \xi_1|\,d_{\max}) \tag{4.21}$$

It's necessary to choose η so that it dominates disturbance term in order to guarantee robust stability. This ensure that $\eta > d_{max}(|\lambda_1\,\xi_2| + |\xi_1|)$ such that $\dot{V}$<0 is guaranteed for any bounded disturbances.

From Equation (4.21), if we choose η as

$$\eta = |\lambda_1\xi_2 + \xi_1|\,d_{\max} + \rho \tag{4.22}$$

where ρ is a small positive constant, we have

$$\dot{V} \leq -(ks^2 + \rho |s|) < 0 \tag{4.23}$$

Thus the control law in Equation (4.23) ensures global stability and guarantees that the framework reaches the sliding in finite time.

4.3 PSO-based SMC Controller Parameters Design

Inspired by nature, particle swarm optimization (PSO) is based on the two-directional group movement of bird flocks. It employs swarm of particles, each of which signifies potential solution that travels search space, to get of best result. During this process, each particle seeks the best global solution, known best. PSO enables particles to learn from one another by considering best-found solution (bBest) and best solution found by swarm (gBest). All current location updates its particle position, velocity, and distance to these best solutions. The mathematical formulation of PSO is given in (Radosavljević J, Jevtić M, 2016).

$$v_i^d(t+1) = s(t)v_i^d(t) + C_1 r_1 (bBest_i^d(t) - k_i^d(t)) + C_2 r_2 (gBest_i^d(t) - k_i^d(t)) \tag{4.24a}$$

$$k_i^d(t+1) = k_i^d(t) + v_i^d(t+1) \tag{4.24b}$$

$$s(t) = \frac{(t_{MAX} - t)(w_{MAX} - w_{MIN})}{(t_{MAX} - 1) + w_{MIN}} \tag{4.24c}$$

were, s(t) represents inertia weighting factor, while r_1 and r_2 are random values between 0 and 1. The parameters C_1 and C_2 serve as acceleration factors. The position of the d^{th} and i^{th} variable at time t, is denoted by k_i^d whereas v_i^d represents its velocity at iteration t.

In this study, which designs an SMC, the controller performance is affected by the four parameters k, λ_1, λ_2 and η. Since η depends on a priori known magnitude of uncertainties, only three parameters k, λ_1, and λ_2 are tuned. The Integral Absolute Error of the Control Input (IAEU) is primarily used to minimize small errors, as it operates on the absolute value of the error (Mei JKirtley J, 2018). In this study, we use the integral of the absolute error and absolute control deviation. The PSO algorithm aims to minimize the following objective function:

$$IAEU = \int_0^{\infty} (|e(t)| + w|u - u_0|)dt \tag{4.25}$$

where e is error deference between reference value and the actual measured value, u_0 is steady-state value of u, and w is weighting factor. Mathematically, this optimization problem written as follows:

Objective function:

$$\min \int_0^{\infty} (|e(t)| + w|u - u_0|)dt \tag{4.26}$$

Subject to:

$$\begin{aligned} K_t^{MIN} \le K_t \le K_t^{MAX} \\ K_i^{MAX} \le K_t \le K_i^{MAX} \end{aligned} \tag{4.27}$$

To optimize the SMC controller for buck converter control λ_1, λ_2 and K parameters were constrained within specific ranges. Specifically, λ_1 was limited to the interval (0, 10), λ_2 to (0, 10), and K to (0, 10). Through a tuning process, the optimal values were determined to be λ_1=0.8720, λ_2=1.4395, and K =9.2825. These tuned parameters along with those optimized for buck converter, is detailed in Table (4.1).

Table 4-1: Parameter specification of SMC

Parameter	Value	Lower Bound	Upper Bound
λ_1	0.8720	0	10
λ_2	1.4395	0	10
k	9.2825	0	10

4.4 PID Control System Design

To compare performance of proposed method in this study with other methods, the PID controller is employed. The PID controller contains three control actions: proportional control action, Integral action, and derivative action. The time-domain equation of PID controller is described by

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \tag{4.28}$$

where K_p, K_i and $K_{d.}$ are proportional gain, integral and derivative gains, respectively. They insure faster correction since proportional term produces an answer precisely corresponding to current error. The error is steady increased by integral term to reduce steady state error. The four key variables of overshoot, steady state error, rising time, and time to setup are used to determine a DC-DC converter controllers performance. These parameters define how well the controller can keep the output voltage within its desired range.

To enhance its performance, these parameters must be appropriately tuned. The process of determining the optimal values for these parameters is known as tuning. The mathematical expressions for the PID control algorithm are given in Equation (4.28).

To make a fair and meaningful comparison between proposed SMC and conventional PID controller, both approaches are evaluated using the same performance measure. Chosen performance index is IAEU, as given in Equation (4.25). The PID controller is also tuned using the IAEU criterion so that its settings aim for the same objectives to reduce both the control effort and the tracking error. By relying on this shared performance measure, we make sure that any difference in results truly reflects how each control strategy performs, not just how it was tuned.

Figure 4.3 illustrates the closed-loop PID controller block diagram of buck converter.

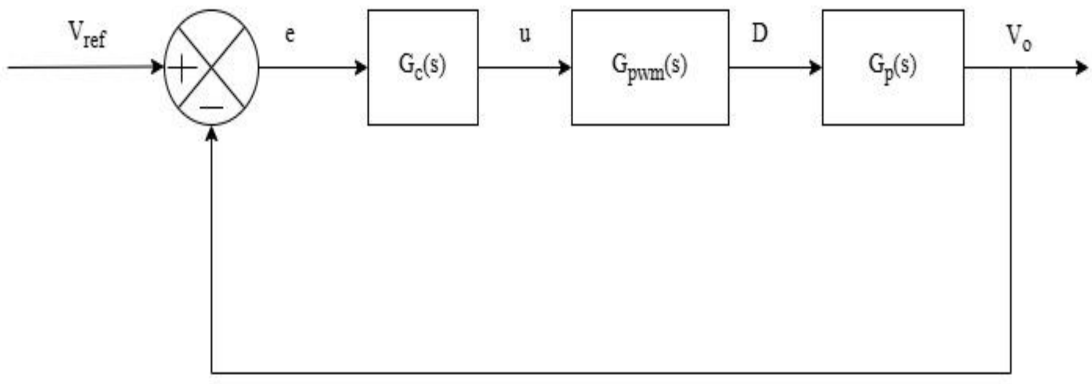


Figure 4.3: Closed loop control of PID buck-converter

where e is error between reference and desired voltage, u is control signal generated, D is duty cycle, $G_c(s)$ is transfer function of PID controller, $G_{pwm}(s)$ is gain of PWM, and $G_p(s)$ is transfer function of the buck converter.

CHAPTER FIVE

5. SIMULATION AND RESULTS DISCUSSIONS

5.1 Parameter Settings of the Buck Converter and Controllers

5.1.1 Parameter settings of the buck converter

In this chapter the performance of open-loop buck converter was examined and validated using a MATLAB/Simulink model. The parameters utilized in simulation are detailed in Table 5.1.

Table 5-1: Component specification for simulation

Description	Parameter	Value	Unit
Source voltage	V_s	12	V
Required desired voltage	V_o	5	V
Inductance	L	39	μH
Capacitance	C	28	μF
Load resistance	R	1.67	Ω
Switching frequency	f	100	kHz
Duty cycle	D	0.42	−

5.1.2 Parameter settings of the controllers

Both the PID and SMC were adjusted using the integral of absolute error of the control input (IAEU), an indicator of performance stated in Equation (4.25), to ensure an equitable and consistent comparison. This criterion was selected to reduce the tracking accuracy and control effort.

The SMC controller design needed choosing suitable values for the switching control term and sliding surface gains. Fast dynamic response, little chattering, and great robustness under parameter variation and disturbance were the goals of improving these parameter. Table (5.2) provides an overview of the chosen SMC parameters.

Table 5-2: Parameter of SMC

Parameter	Value	Lower Bound	Upper Bound
λ_1	0.8720	0	10
λ_2	1.4395	0	10
k	9.2825	0	10

To compare PID controller with SMCs performance goals, the same IAEU-based optimization method was used. It was ensure by this tuning process that the PID controller was configured to reduce the same performance index. The optimal controller parameters were obtained using (PSO) algorithm. In this approach, a swarm of candidate solutions was initialized based on a pole-placement method, and the lower and upper boundaries for each controller gain (K_p, K_i, K_d). The determined PID parameters are shown in Table (5.3).

Table 5-3: Parameter for PID controller

Controller Parameter	Symbol	Value
Proportional	K_p	23
Integral	K_i	50
Derivative	K_d	0.00035

This parameter values were used to evaluate controller performance in all succeeding simulations. It is guaranteed that the observed performance variances are due to the control methods and not to variations in the tuning procedure by applying the optimization criterion uniformly to both controllers.

5.2 Open-Loop Response of Buck Converter

To understand a clear essential behavior of buck converter, open loop response was analyzed first using a constant duty ratio of 0.42, before development of any control strategies. This initial simulation provides to display performance characteristics of system operated without control feedback. The purpose of this step is to observe voltage response to change in source voltage and load in the absence of any controller. It shows major problems such as poor voltage control, delayed time response, and variation to external disturbances. Observing this response helps comparison point for examining usefulness of next control method. This work confirm that converter cannot maintain stable output by itself, as a result pointing out the requirement of robust control system to show better dynamic response, robustness, and stable operation under varying conditions.

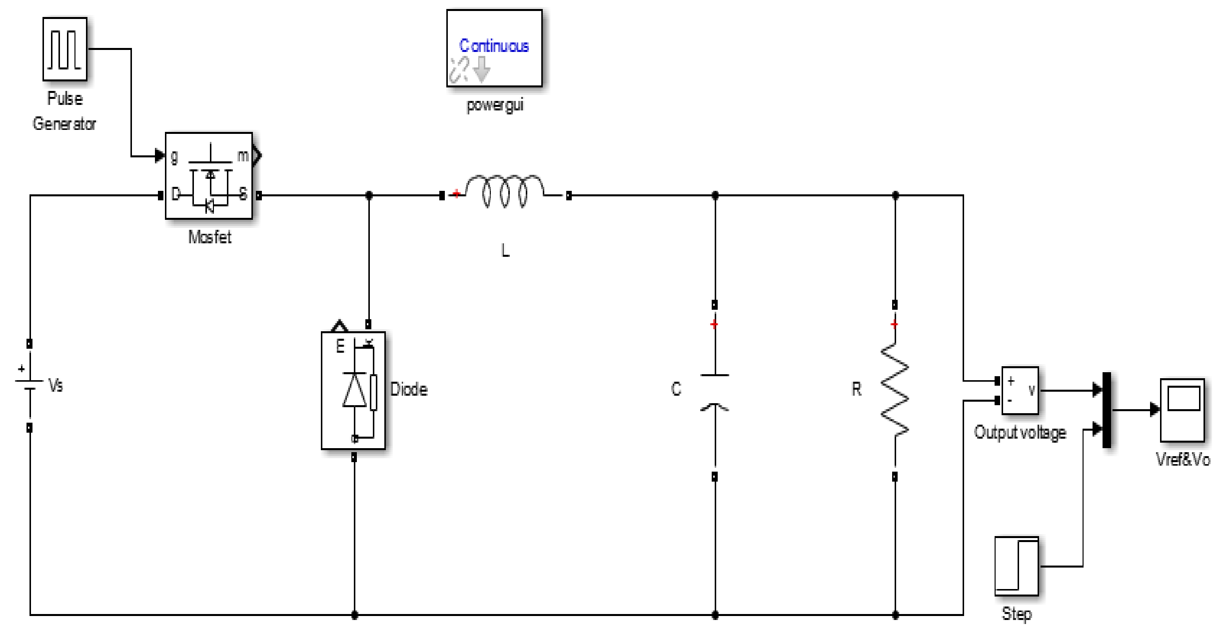


Figure 5.1: Simulink system structure of open-loop buck converter

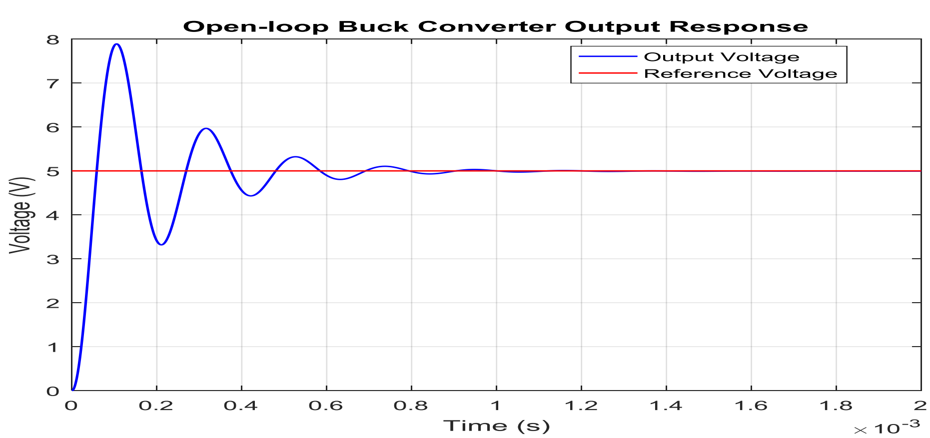


Figure 5.2: Desired voltage of the open-loop system.

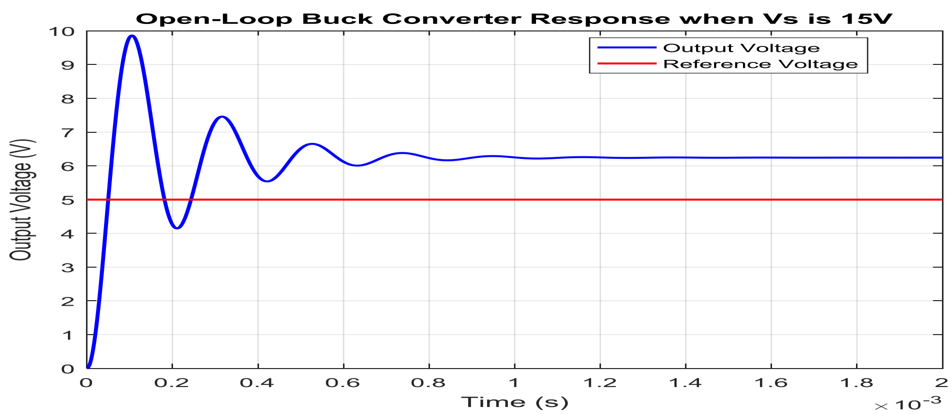
Figure (5.2) displays the response of output voltage obtained from the MATLAB/Simulink simulation. The analysis shows a significant overshoot of 58%, a rise time 0.038749 milliseconds, and a settling time 0.75146 milliseconds. Such a high overshoot in the output voltage is considered undesirable for the intended application.

Table 5-4: Response of open loop buck converter

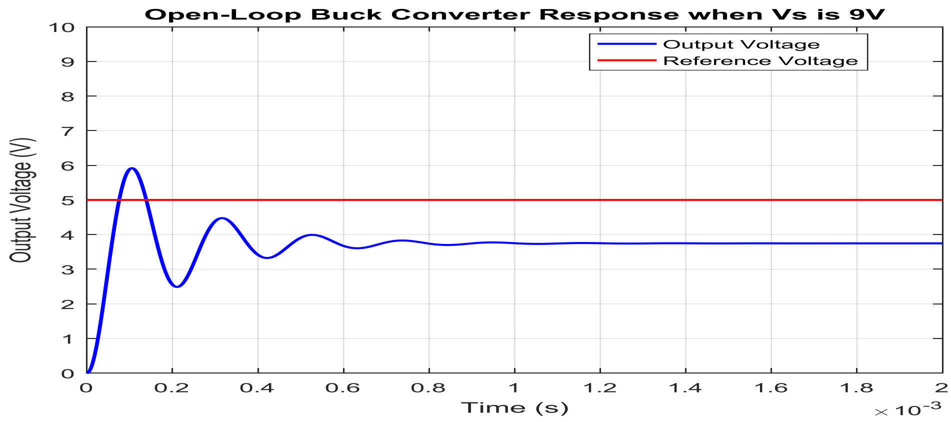
Buck Converter	Performance		
	Rise time (sec)	Settling time (sec)	Overshoot (%)
Open-loop system	0.03875	0.75146	58

5.2.1 Open loop response of buck converter under varying source voltage

To examine DC-DC buck converters open loop performance under different situations, Simulations has executed. The result of these tests is depicted as follow:



(a)



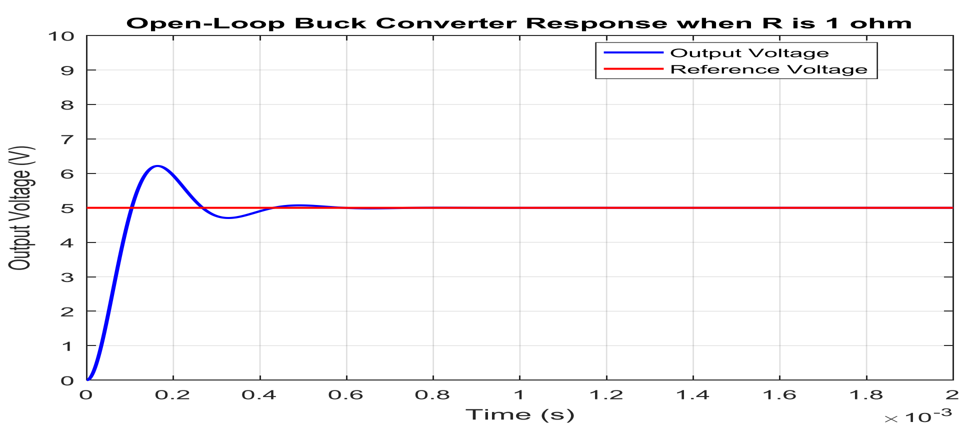
(b)

Figure 5.3 : Open-loop response subjected to varying source voltage

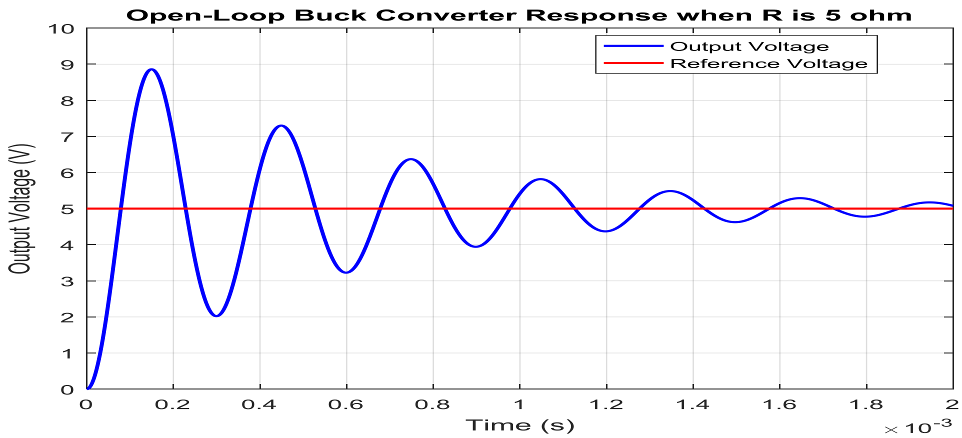
Figure (5.3a) and (5.3b) displays the simulated behavior of buck converter under condition of varying DC source voltage. It illustrates desired voltage response to changes in voltage from 12V to 15V first and then from 12V to 9V, respectively. Furthermore, variations in DC source voltage prevent the converter from achieving desired output voltage, within increase of source voltage causes grater overshoot.

5.2.2 Open-loop response of buck converter under varying load resistance

Also simulation have been carried out under variation of load resistance investigated by varying the load from 1.67Ω to 1Ω, and then to 5Ω. The results of these tests are shown below.



(a)



(b)

Figure 5.4: Open loop response subjected to varying load resistance

Figure (5.4a) and (5.4b) shows results of simulation under varying load resistance of buck converter. The decrease in load resistance does not negatively affect the ability to reach the desired output, an increase in load resistance leads to a larger overshoot. Consequently, to mitigate these issues and improve the dynamic response and regulation of buck converter, adoption of different control method is required.

5.3 SMC Response of Buck Converter

5.3.1 Setpoint tracking response

To demonstrate the effectiveness of SMC for buck converter, I utilized a MATLAB/Simulink model. The converters parameters as specified in Table 5.1, I used in this model, which is depicted as.

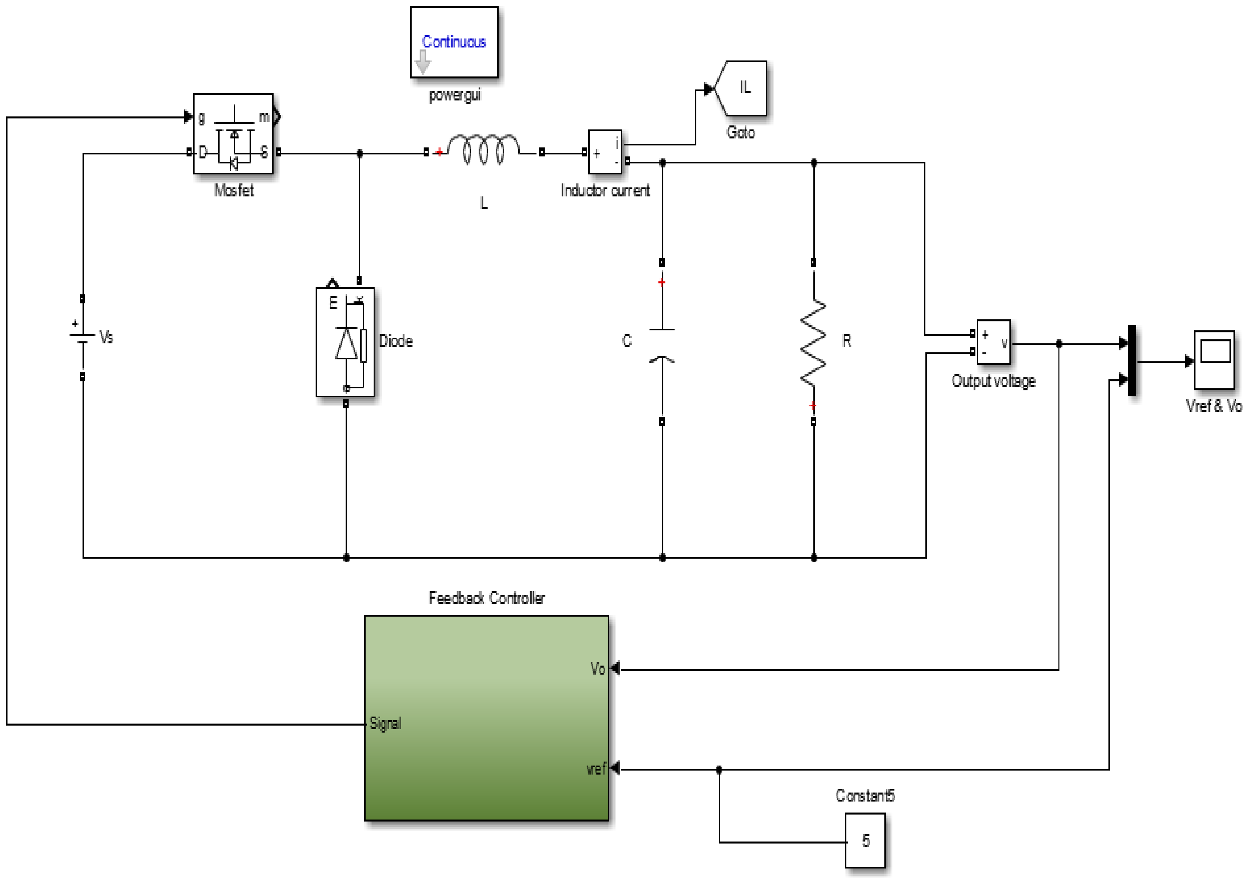
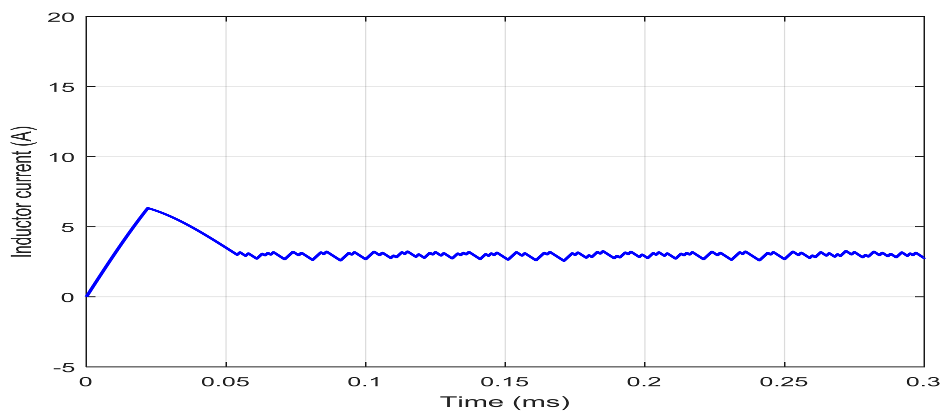
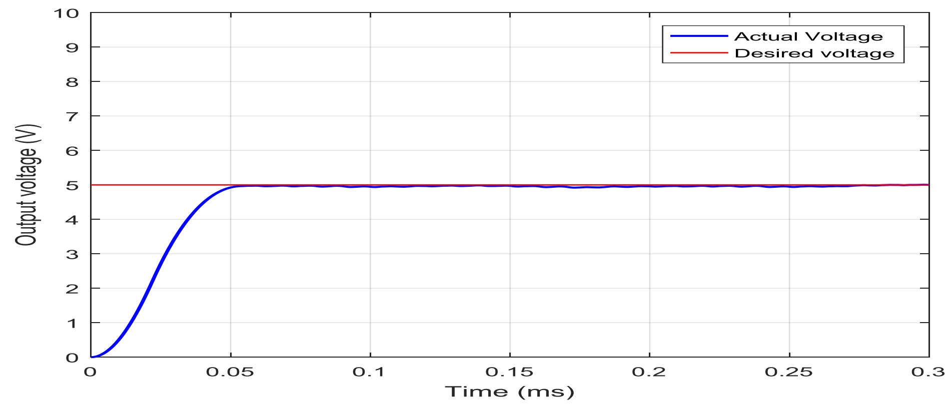


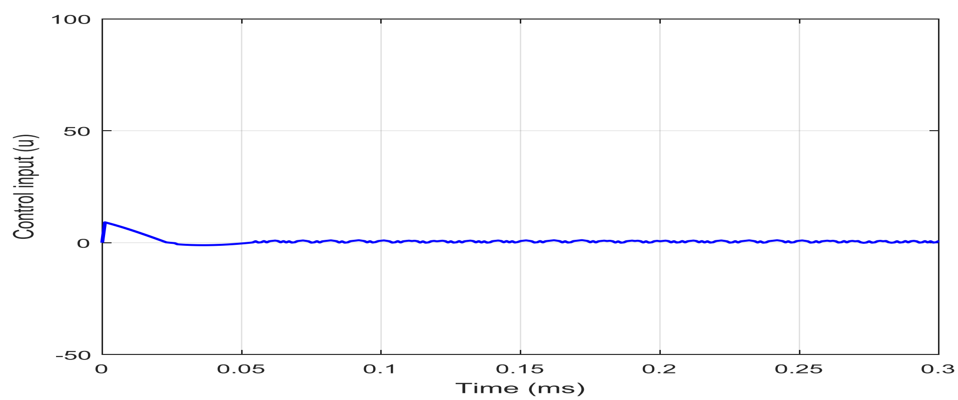
Figure 5.5: Simulink model of SMC



(a)



(b)



(c)

Figure 5.6: Response of buck converter using SMC controller

The results presented in Figure (5.6) shows, the sliding mode control controller exhibits rapid and stable dynamic performance, as evidenced by system response. Becouse of the high control effort as startup, the inductor current in Figure (5.6a) rises rapedly at first, peaking just above 6A. It then gradually settles, with minor oscillations around its steady-state value. Figure (5.6b) shows the output voltage steadily rising toward the reference value of 5V, with no noticeable oveshoot and quick settling time indicating effective voltage regulation. Meanwhile, the control input depected in Figure (5.6c) starts at a high level and then decreases to a moderate value, exhibiting slight oscillations as it stabilizes.

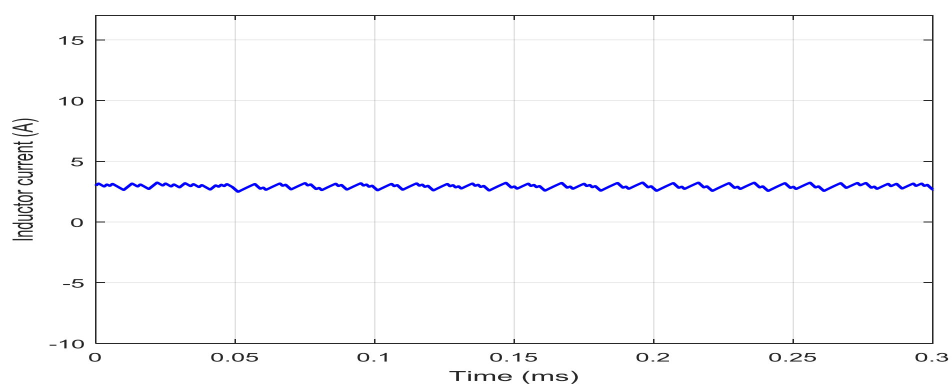
Table 5-5: Response of SMC

Controller	Performance		
	Rise time (msec)	Settling time(msec)	Overshoot (%)
SMC	0.0287	0.0417	0.2868

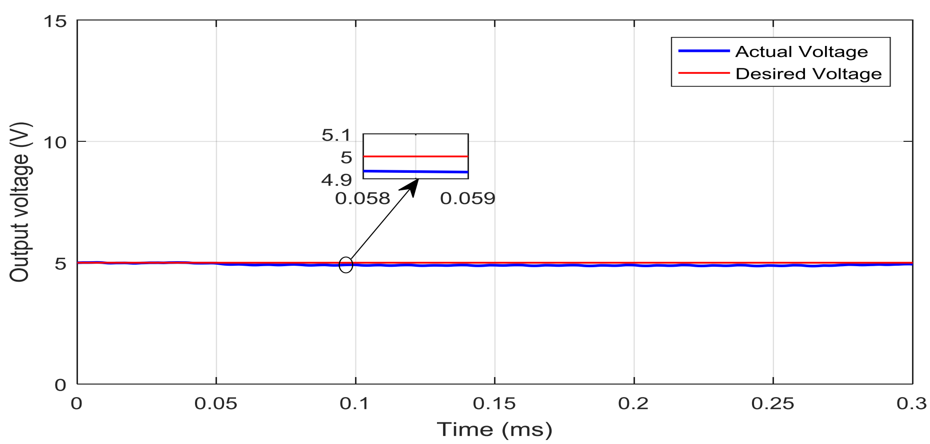
5.3.2 Disturbance rejection response

5.3.2.1 Inductor parameter variation

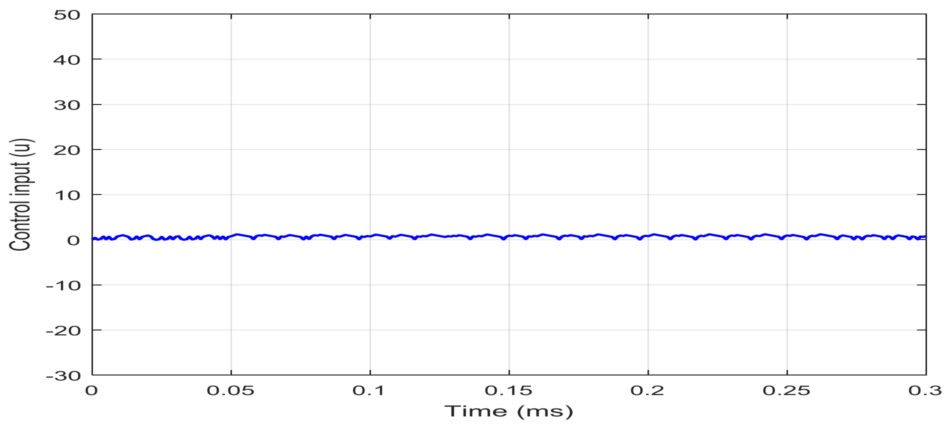
The MATLAB simulation was used to assess buck converters performance with SMC controller when internal parameter change was introduced. The results of these simulations is shown as



(a)



(b)



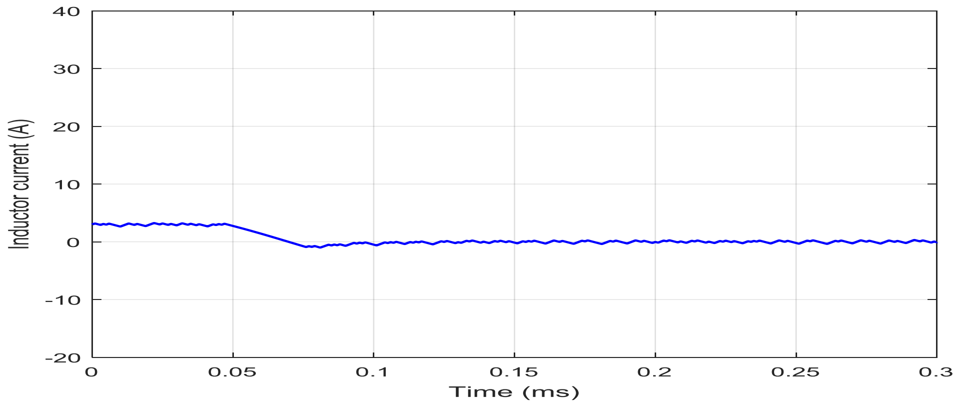
(c)

Figure 5.7: Response of SMC under inductor parameter variation

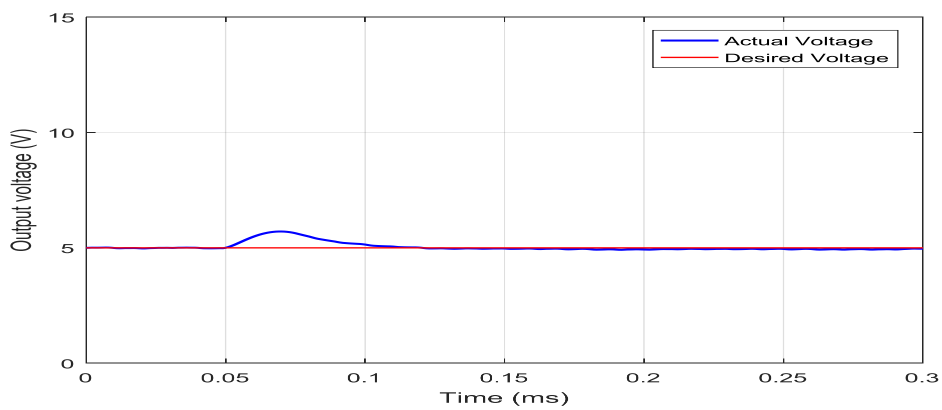
As shown in Figure (5.7a), the simulation confirms that SMC method regulates buck converter output effectively. It provides strong regulation of the current and responds quickly to changes. After an initial adjustment period, the current settles close to its steady-state values, with only slight and acceptable fluctuations. The output voltage tracking behavior is shown in Figure (5.7b), where these is little overshoot and a smooth convergence of the voltage to the reference value of 5V with very little steady-state error. This attests to the controller’s ability to regulate voltage under ideal circumstances. Lastly, the control input is displayed in Figure (5.7c). Despite the high switching frequency, it is bounded and displays little chattering.

5.3.2.2 Load resistance variation

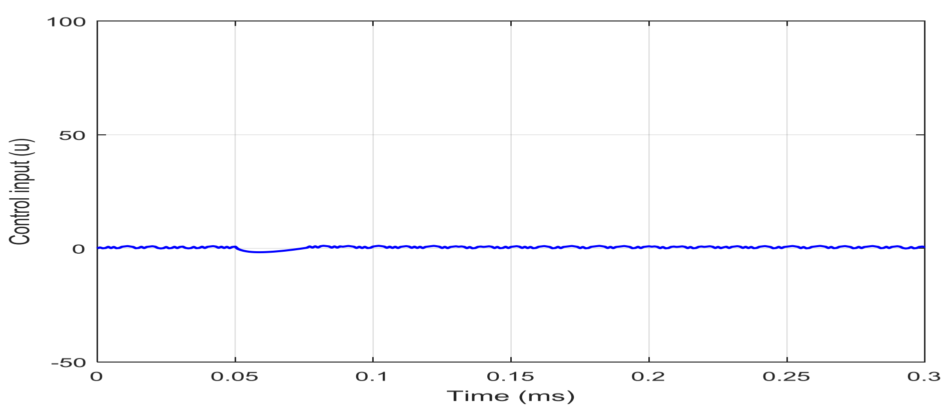
To evaluate buck converters performance using SMC under disturbance, load resistance was raised by 30%. The responses of these simulations are displayed as follows:



(a)



(b)



(c)

Figure 5.8: Performance of SMC under sudden change in load resistance

Figure 5.8 displays the simulation results illustrating response of buck converter responds to disturbance on load resistance under SMC. At approximately t=0.05 milliseconds, a sudden disturbance change in load causes a temporary deviation of inductor current as well as output voltage. With a fast return to stability, of its output voltage in Figure (5.8b) to the reference with only slight overshoot and a quick return to stability. The inductor current in Figure (5.8a) briefly drops and then smoothly toward nominal value. Also control input in Figure (5.8c) declines briefly before rising slowly and staying within reasonable limits.

The PWM signal and sliding surface s(t) were designed to be displayed to test control performance of SMC based buck converter using the MATLAB simulation.

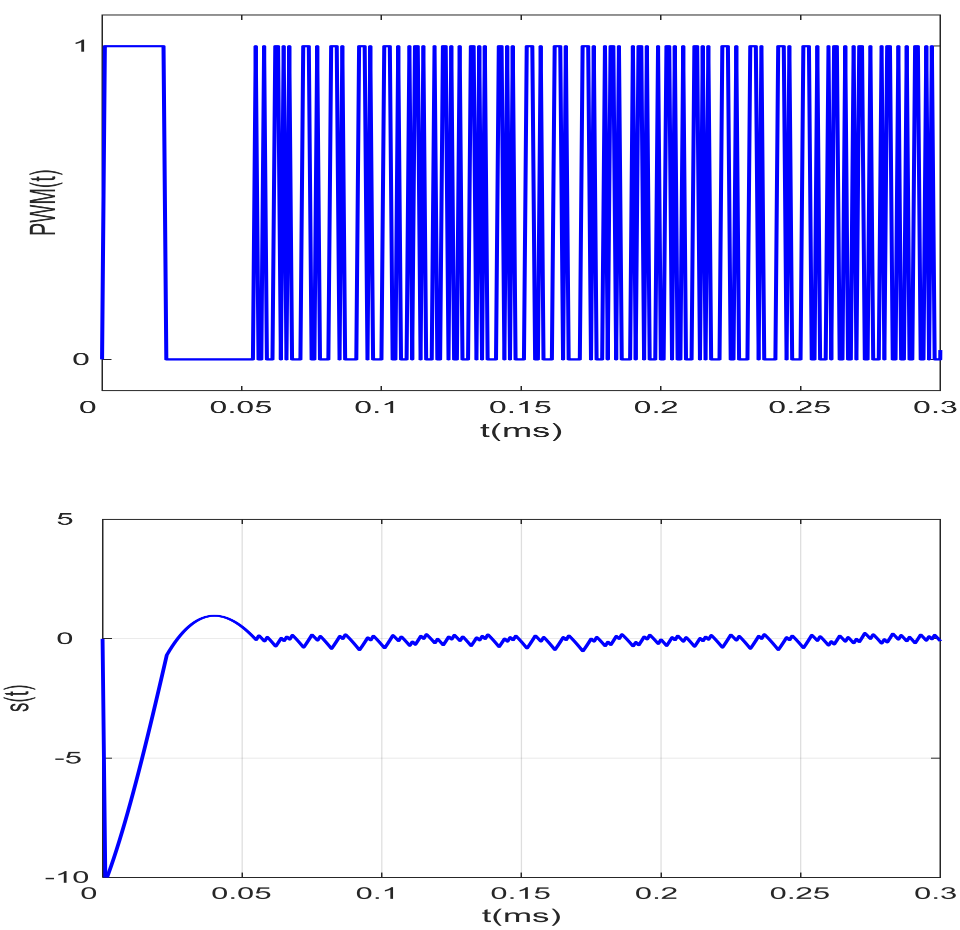


Figure 5.9: Response of PWM and surface control

The rapid decrease of s(t) toward zero with minimal steady-state deviation demonstrates that SMC effectively forces the state variables to reach its sliding surface. Even though these are still some chattering in the switching action, the PWM signal's high frequency indicates constant control effort and robust resistance to disturbances.

5.4 Responses of the PID Controller

5.4.1 Setpoint tracking response

This section shows structure MATLAB/Simulink-implemented buck converter that is managed by a PID controller. The Simulink model structure is depicted as below:

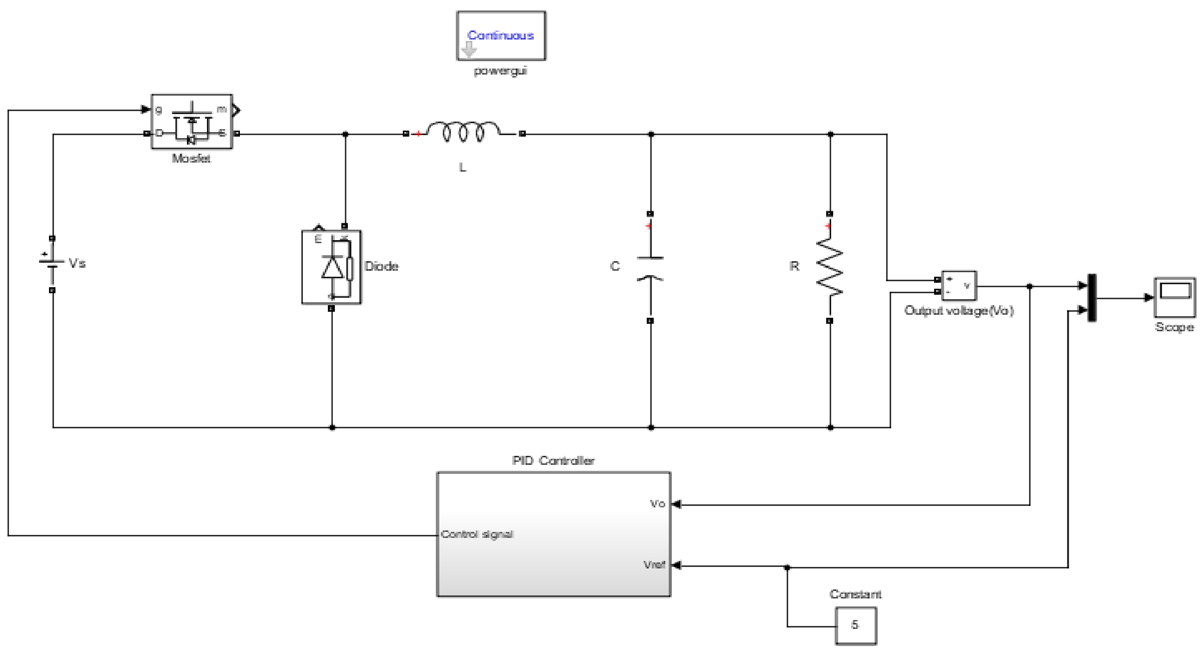
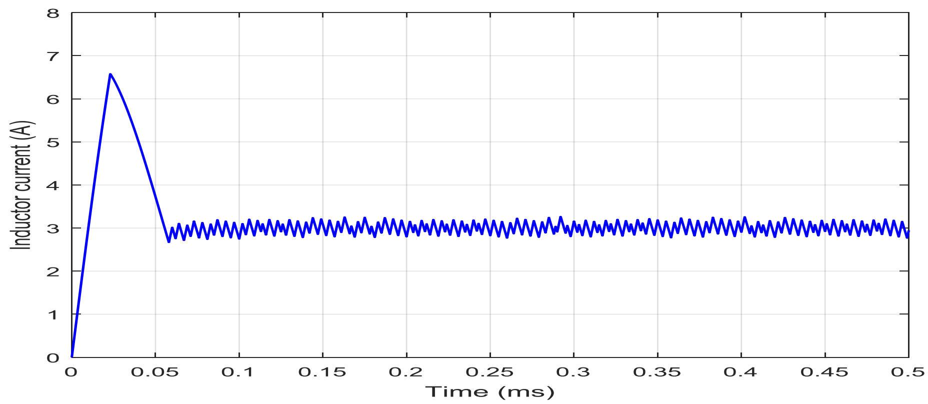
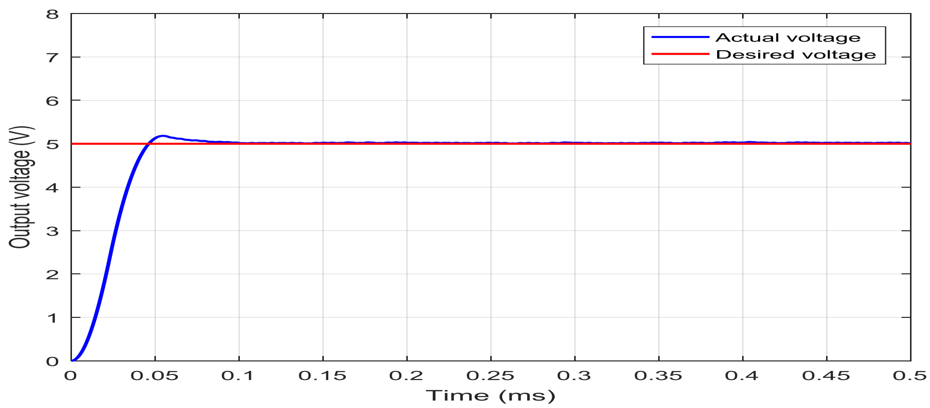


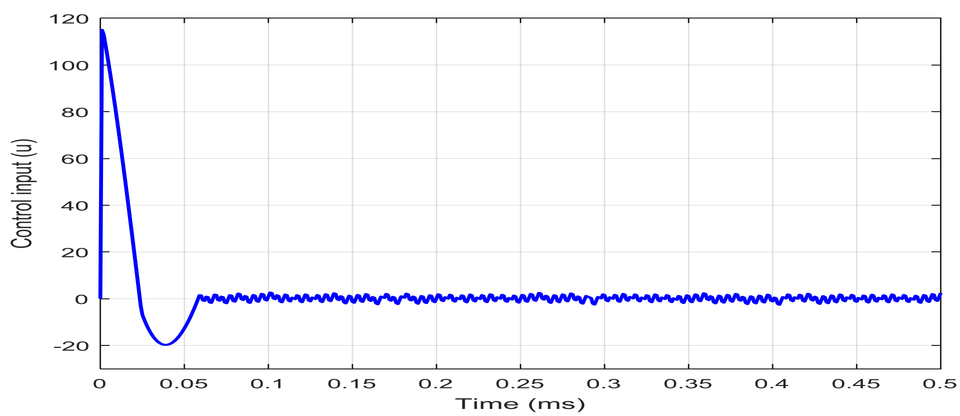
Figure 5.10: Simulink model of PID controller



(a)



(b)



(c)

Figure 5.11: Response of PID controller

As shown in the figure (5.11), the PID controller minimized overshoot from 58% to 3.6563% of buck converter. However, as we seen from a response settling and rising time becomes increased.

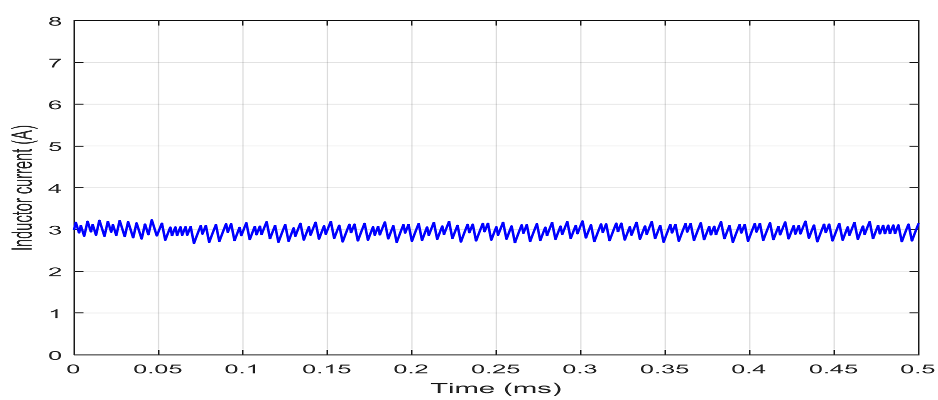
Table 5-6: Response of PID controller

Controller	Performance		
	Rise time (sec)	Settling time (sec)	Overshoot (%)
PID	0.0305	0.0447	3.65

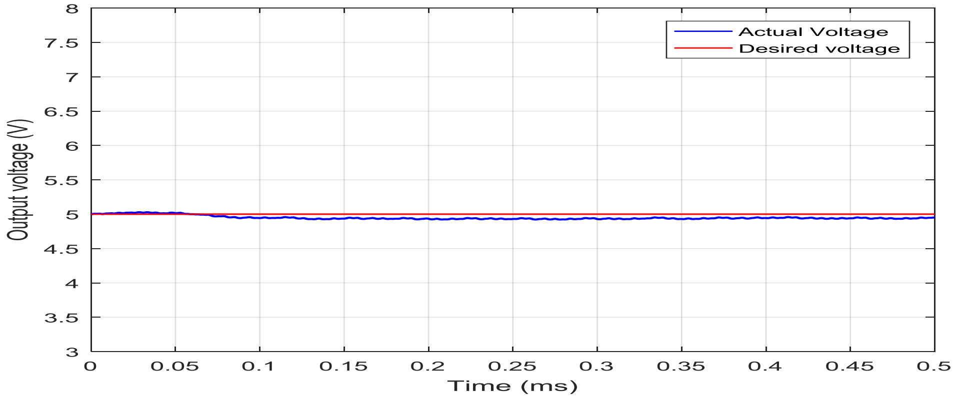
5.4.2 Disturbance rejection response

5.4.2.1 Inductor parameter variation

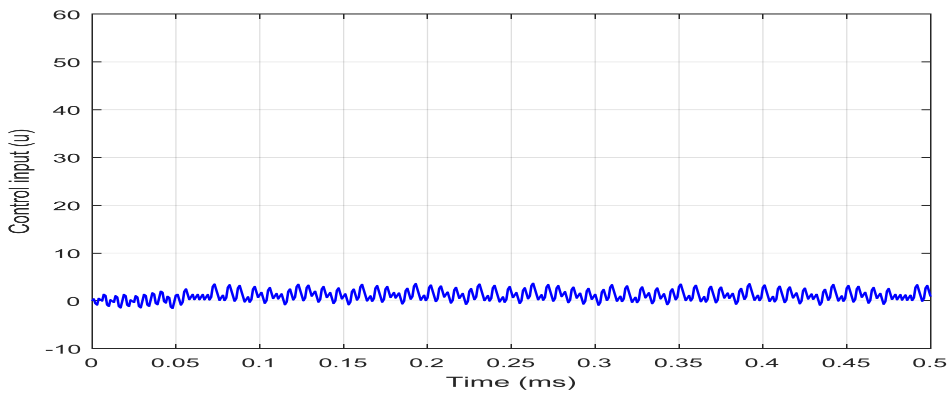
To examine the buck converters performance of PID controller under internal parameter variation introduced and the MATLAB simulation was conducted. The outcomes of these simulations are presented as:



(a)



(b)



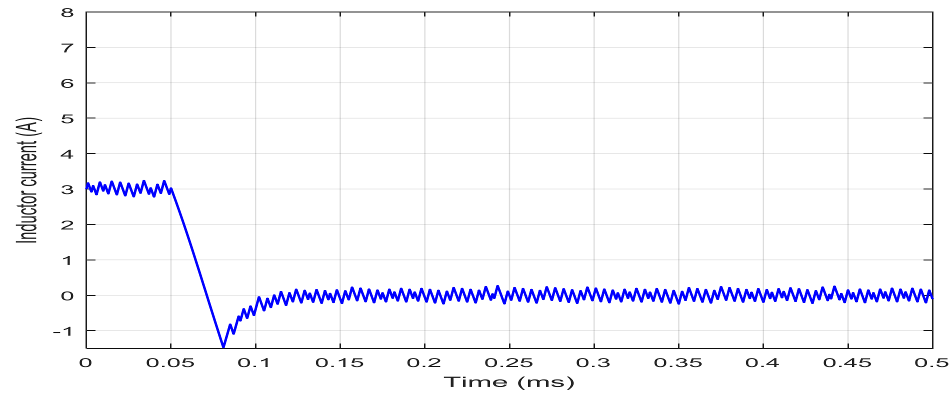
(c)

Figure 5.12: Response of PID under varying inductor parameter change

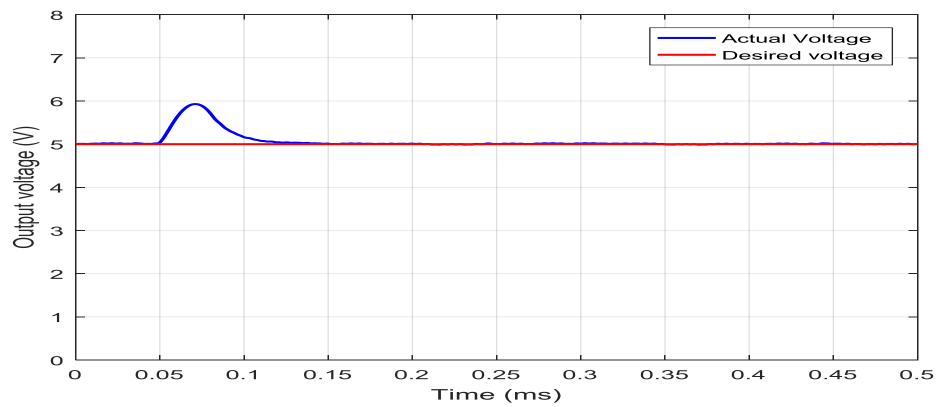
As we see the response in the Figure (5.12) when a small internal parameter changed is applied to the system during simulation. The buck converters PID controller tracks its voltage response. With a minor overshoot at 5.2V, the output voltage first closely matched the 5V reference. It then steadily stabilized at 4.9V, suggesting a minor steady-state inaccuracy. As the system settled, the control input gradually dropped while the inductor current steady with little ripple.

5.4.2.2 Load resistance variation

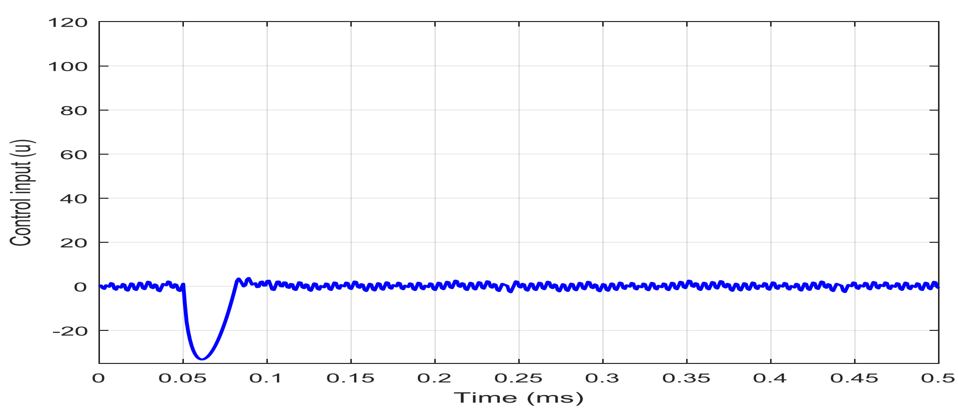
The load resistance was increased by 30% to assess buck converters response using a PID controller under sudden change in load resistances. The simulation result under this condition is as follows:



(a)



(b)



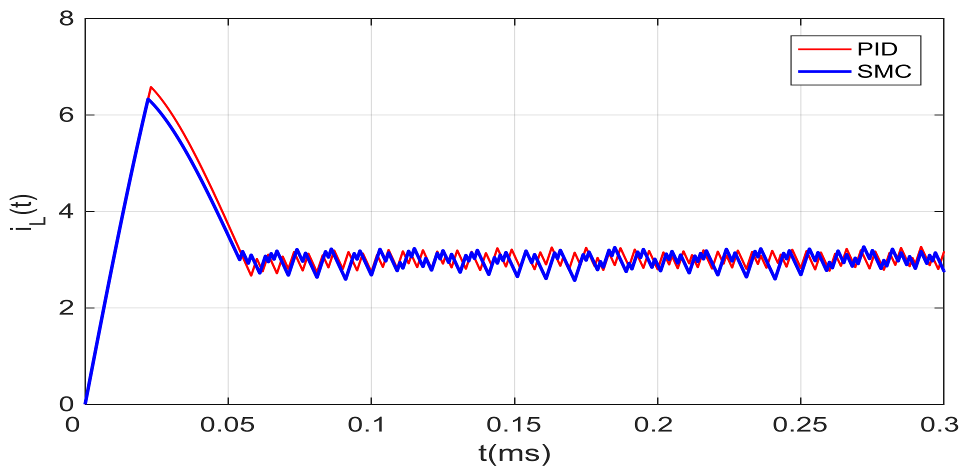
(c)

Figure 5.13: Response of PID controller under sudden change in load resistance

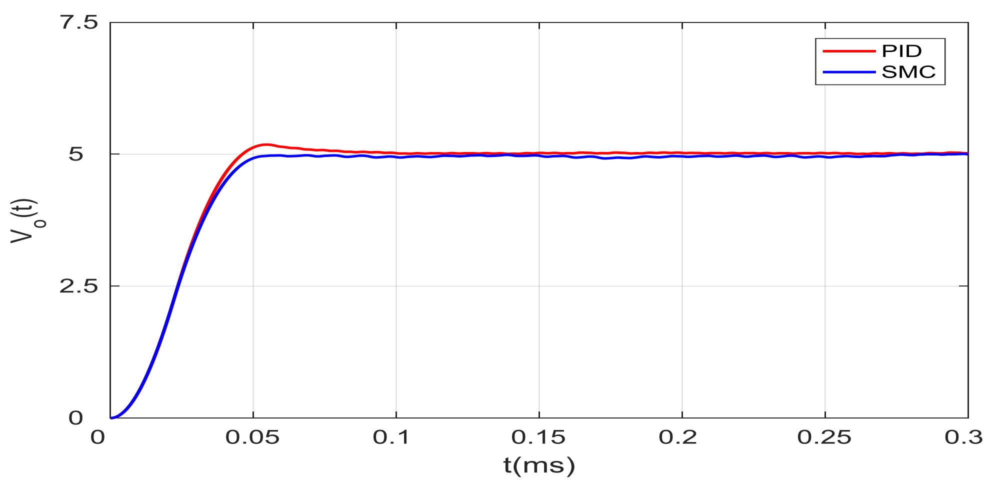
As we see from the response in Figure (5.13), that when sudden change in load resistance t=0.05 milliseconds. The PID controller output voltage overshoots and then maintains rapid settling, minimal overshoot, and accuracy, even with fluctuating load conditions, as shown by the systems transient followed by constant working.

5.5 Performance Comparison of SMC and PID for Buck Converter

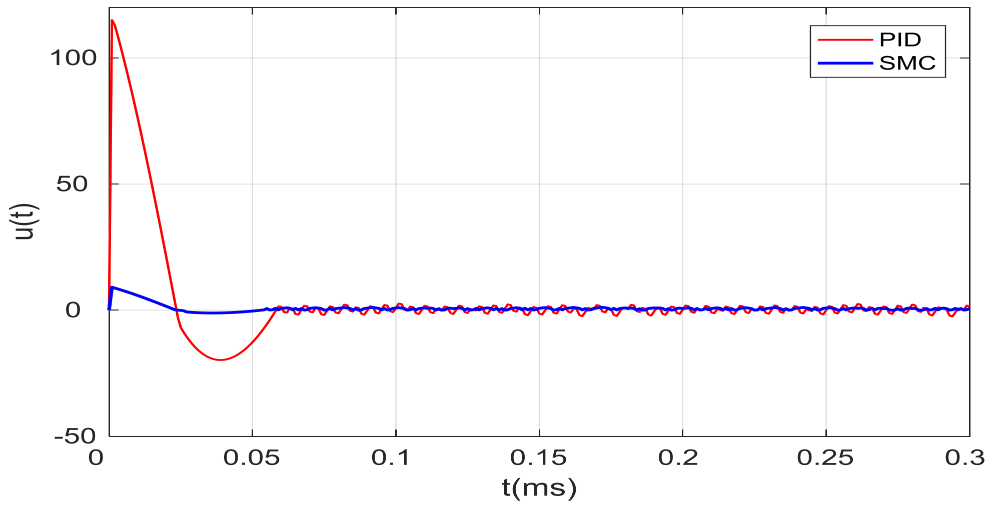
I used a simulation model to show how well the sliding mode and PID controller operate for buck converter structure. Figure 5.14 shows the comparison of performance.



(a)



(b)



(c)

Figure 5.14: Performance comparison of SMC and PID controller

Figure 5.14 displays three subplots that compare the dynamic responses of a PID controller and an SMC. In the first Figure (5.14a), the output voltage rises noticeably for both controller's suggesting a less rising time for SMC and faster stabilization. Figure 5.14b shows the inductor current, SMC exhibits less overshoot and settles closer to 8A, whereas PID shows a oscillatory tends. The control signal (u) in Figure (5.14c) illustrates how SMC employs better to achieve stability as compared to PID control effort.

Table 5-7: Performance comparison of SMC and PID controller

Controller type	Performance			
	Overshoot (%)	Settling time (sec)	Rising time(sec)	IAEU
SMC	0.2868	0.0417	0.0287	0.1605
PID	3.65	0.0447	0.0305	0.427

Performance comparison response in flow chart.

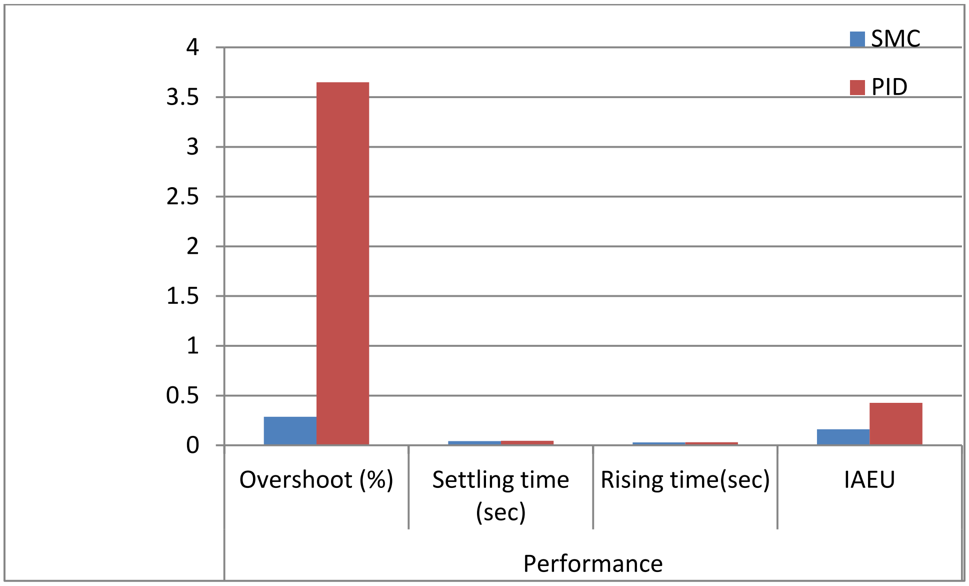
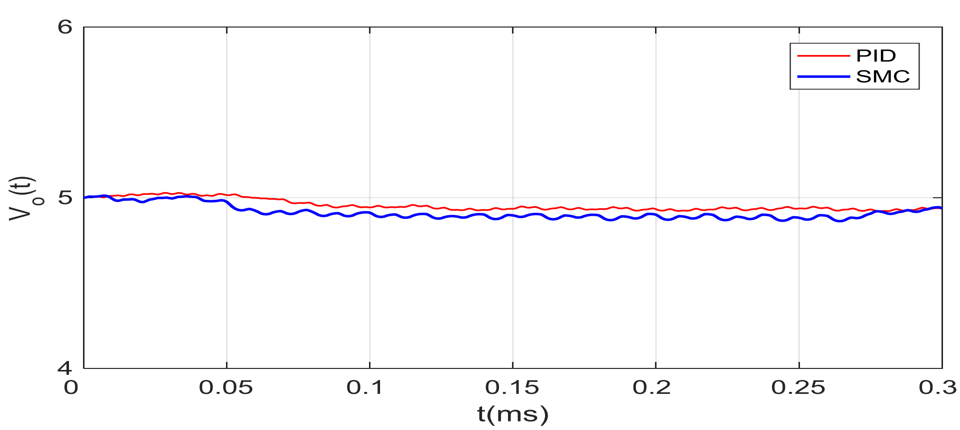


Figure 5.15: Response of SMC and PID controller

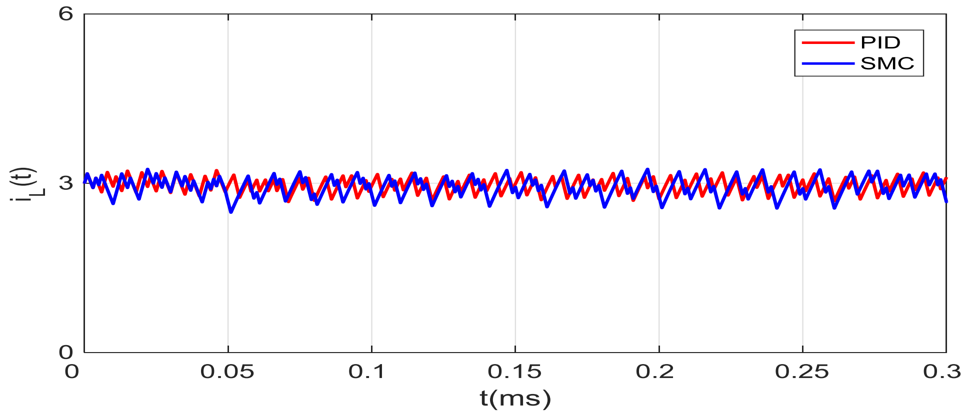
5.5.1 Performance comparison under disturbance rejection response

5.5.1.1 Inductor Parameter Variation

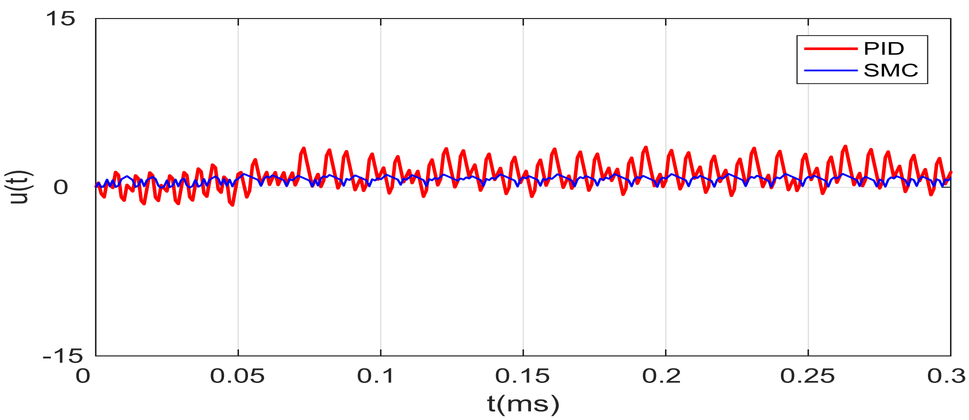
The performance comparison of PID and SMC of buck converters under the effect of internal inductor parameter change was evaluated using the MATLAB simulation. The outcomes of these simulations are displayed as follows:



(a)



(b)



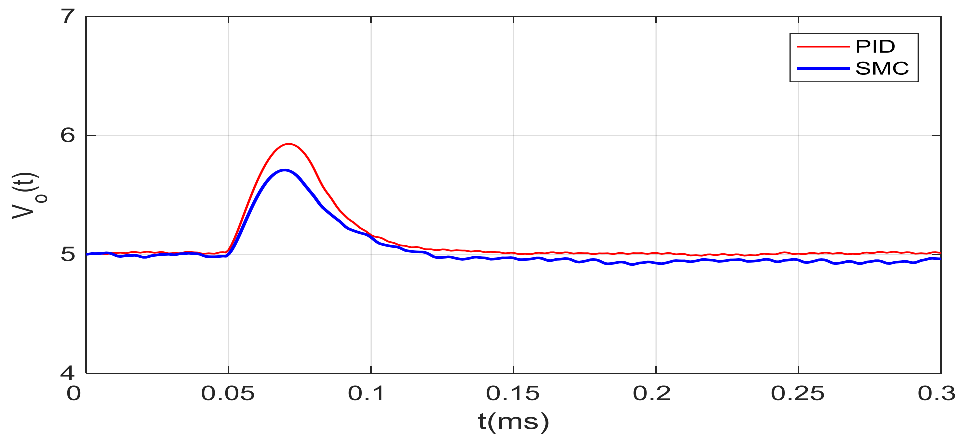
(c)

Figure 5.16: Performance comparison of SMC and PID under varying inductor

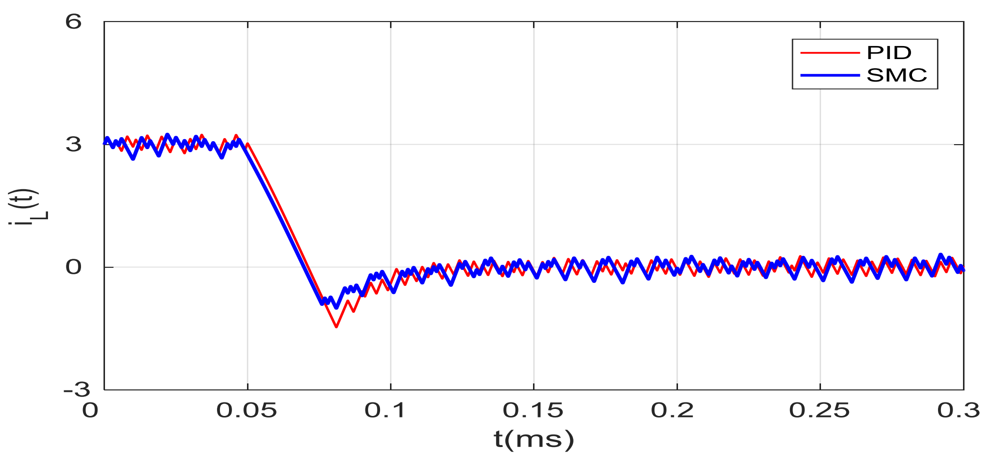
Figure 5.16 compares response of PID and SMC controllers changing in three system parameters that are applied internally. The SMC controller shows more stable tracking with fewer oscillations than the PID controller, which shows a slight overshoot before settling. Both controllers settle near nominal output. To compare the PID, which displays minor fluctuations, SMC offers a more constant response with less overshoot when it comes to current regulation. The control signal (u) indicates the more active to SMC's control method.

5.5.1.2 Load resistance variation

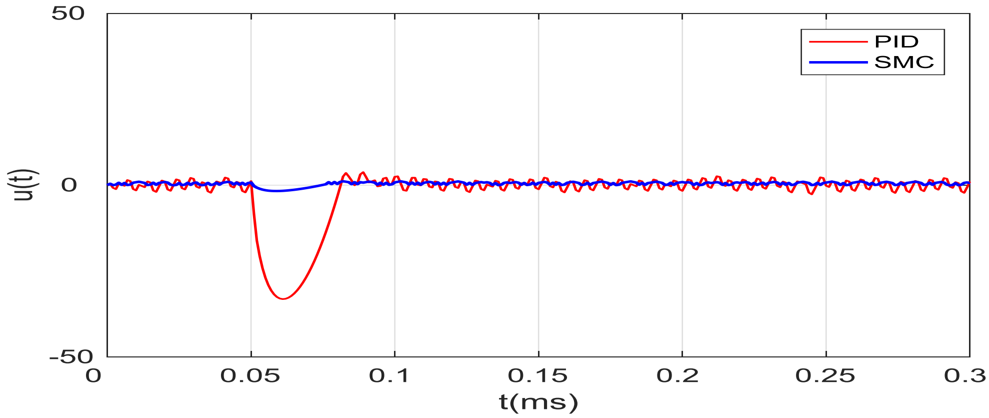
The load resistance was increased by 30% in order to evaluate how well DC-DC buck converters with PID and SMC controller operated under various load resistances. The simulation result is depicted as follows.



(a)



(b)



(c)

Figure 5.17: Response of SMC and PID under sudden change in load resistance

Figure 5.17 shows the buck converter's response to SMC and PID control. Faster settling and fewer overshoot are achieved by the SMC, whereas the PID controller shows more overshoot and a slower response. Better inductor current ripple reduction and quicker recovery are provided by SMC. Under SMC, the smoother and constant control signal indicates lower switching stress. In both steady-state and transient situations, SMC improves PID overall.

CHAPTER SIX

6. CONCLUSION AND RECOMMENDATION

6.1 Conclusion

This thesis investigates two different control techniques for buck converter voltage controls are presented. SMC controller is the first control method, and PID provides the basis for the second controller methodology. It is specifically determined that SMC is based on the specified convergence algorithm. Both controllers performance in the transient zone, during load variation, and under parameter change was evaluated using MATLAB/Simulink. PID control results in a longer settling and rise times and lower overshoot, from 58% to 3.6563%. However, the settling and rise times are very short (0.0447 msec and 0.0305 msec, respectively). Overshoot is completely eliminated when using sliding mode control. The SMC showed faster settling and less overshoot when the load resistance varied, while the PID controller responded more slowly and with more overshoot. An SMC overcome effects of increasing parameter variation and sudden changes of load resistance to provide the desired output voltage more quickly than a PID controller, which is unable to do so due to variations in the inductor parameter. The SMC is nonlinear control systems that compensate nonlinearity of converter's, which indicates a bright future for its employment in DC-DC buck converters. Additionally, the complexity of nonlinear mathematical analysis is comparatively low, and designing a converter with SMC is simpler than PID control in terms of choosing the control specifications and putting into practice in MATLAB/Simulink.

6.2 Recommendation

Although computer simulations have confirmed the theoretical use of SMC for buck converter voltage regulation, it would be beneficial to look into its actual application. Testing a different sliding mode control algorithm than the one that is currently recommended is another research concern. A performance comparison of SMC controllers created with different algorithms may provide new insight.

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APPENDIXES

A.1 Specification for Buck Converter Parameters

The converter is intended for high switching frequency and low power applications. Thus, the following is the value of the converter parameter used for MATLAB/Simulink:

- ✓ The switching frequency is 100 kHz.
- ✓ The input voltage is 12V.
- ✓ The desired output voltage is 5V.
- ✓ The load resistance is 1.67Ω.
- ✓ Assume that the output voltage is 1% of the ripple voltage of the capacitor

These parameters allow for the calculation of the minimum capacitor to limit ripple voltage below a specific value and to avoid overshoot, as well as the minimum inductor that establishes the boundary between continuous and discontinuous conduction modes. With the use above value the duty cycle is displayed as follows:

$$D = \frac{V_o}{V_s} = \frac{5}{12} = 0.42$$

The minimum inductor is given as,

$$L_{\min} = \frac{(1-D)}{2f}R = \frac{(1-0.42)}{2*10^5}*1.67 = 4.84\mu H$$

The inductor value should be higher than the minimal value because the converter is only intended to operate in continuous conduction mode. Therefore to assure continuous conduction mode of operation let the value of inductor eight times the minimum inductor, so that $L=39\mu H$.

The minimum required of capacitors needed is provided by:

$$C_{\min} = \frac{(1-D)}{8\Delta VLf^2}V_o = \frac{(1-0.42)}{8*0.05*39*10^{-6}(10^5)^2}*5 = 18.6\mu F$$

In order to avoid voltage overshoot and limit the peak-to-peak ripple voltage value should be higher than the minimum value. Let's boost the capacitor's value this reason by 50% of its minimum value, that is $C=28\mu F$.

A.2 MATLAB Code

(a) Open-loop response

```
clc;
clear;
close all;

% Measured / transfer function:
num =3.8159e+08;
den=[1,1.036e+04,9.1675e+08];

Gp=tf(num,den);    % Create transfer function

% --- Time and Input Setup ---
t=0:1e-6:0.002;          % Time vector (2 ms total, 1 µs step)
u=Vs*ones(size(t));  % Step input of 12V

% --- Simulate Output Response using lsim ---
[y,t_out]=lsim(Gp,u,t);

% --- Normalize output for stepinfo (to treat as unit step response) ---
y_normalized=y/Vs;

% --- Analyze Step Response Characteristics ---
stepinfo_data=stepinfo(y_normalized,t_out);

Overshoot=stepinfo_data.Overshoot;
RiseTime = stepinfo_data.RiseTime;
PeakTime = stepinfo_data.PeakTime;
SettlingTime = stepinfo_data.SettlingTime;

% --- Display Results ---
disp('--- Open-Loop Step Response Analysis ---');
disp(['Overshoot: ', num2str(Overshoot), ' %']);
disp(['Rise Time: ', num2str(RiseTime), ' s']);
disp(['Peak Time: ', num2str(PeakTime), ' s']);
disp(['Settling Time: ', num2str(SettlingTime), ' s']);

%---Plot Output Response ---
figure;
plot(t_out,y,'b','LineWidth',1.5);
hold on;
plot(t_out,Vo*ones(size(t_out)),'r-','LineWidth',1.5); % Reference voltage
grid on;
xlabel('Time (s)');
ylabel('Output Voltage (V)');
title('Open-Loop Buck Converter voltage Response');
legend('Output Voltage', 'Reference Voltage', 'Location', 'Best');
ylim([0 10]);
```

(b) SMC controller

```
%% ISMC of a DC-DC buck converter
    global L C R Vs

    % ISMC parameters
     k= 0.8720; lam1= 1.4395; lam2= 9.2825; % Tuned by a GA
     eta= 0.21; % Manual setting based on disturbances

    % Converter parameters
    L= 39e-6; C= 28e-6; R= 1.67; Vs= 12;
    fPWM= 100e3; Vref= 5; dVref= 0;

    % Simulation parameters
    t= 0; x= [0;0]; h= 1e-6; loop= 500; z2= 0;

    % Storage for results
    buf= [t x' 0 0 0];

    for i= 1:loop
        z1= x(2)-Vref;
        z2= z2+h*z1;
        z3= x(1)-Vref/R;
        s= lam1*z1+lam2*z2+z3; % Sliding surface

        % Nominal control
        un1= -lam1/C*x(1)+(1/L+lam1/(R*C)-lam2)*x(2);
        un2= lam2*Vref+(lam1+1/R)*dVref;
        un= L/Vs*(un1+un2);

        % Discontinuous control
        ud= -k*s-eta*tanh(s/0.001);

        % Total control
        u= un+ud;

        % Clamp duty cycle and generate the PWM signal
        duty_cycle= min(max(u,0),1);
        pwm= My_PWM(fPWM,t,duty_cycle);

        % Integrate the converter model
        x= RK4(@fun,t,x,pwm,h);

    t= t+h;
    buf= [buf;t x' u pwm s];
    end

    %save 'ISMC_SP' 'buf'

    % System performances
    t= buf(:,1);
    iL= buf(:,2);
```

```
    Vo= buf(:,3);
    u= buf(:,4);

    % System performances
    u0= Vref/Vs; w= 0.1;
    ae= abs(Vref-buf(:,3))+w*abs(buf(:,4)-u0);
    IAEU= 0.5*h*(ae(1)+2*sum(ae(2:end-1))+ae(end))

    subplot 311
    plot(t*1000,iL,'k','linewidth',1);
    xlabel('Time (ms)');
    ylabel('Inductor current (A)');
    axis([0 0.3 0 8])
    subplot 312
    plot(t*1000,Vo,'k','linewidth',1);
    xlabel('Time (ms)');
    ylabel('Output voltage (V)');
    axis([0 0.3 0 10])

    subplot 313
    plot(t*1000,u,'k','linewidth',1);
    xlabel('Time (ms)');
    ylabel('Control input (u)');
    axis([0 0.3 -5 15])
    grid on
end

function xdot= fun(t,x,u)
    global L C R Vs
    xdot=zeros(2,1);
    xdot(1) = -x(2)/L+Vs*u/L;  % Inductor current
    xdot(2) = x(1)/C-x(2)/(R*C); % Output voltage
end
```

(c) PID controller

```
%% Tracking response of the PID controller for a buck converter
function Sim_PID_SP
    global L C R Vs
    % Converter parameters
    L= 39e-6; C= 28e-6; R= 1.67; Vs= 12;
    fPWM=100e+3; Vref= 5;

    % PID parameters
    Kp= 23; Ki= 50; Kd= 0.00035;

    % Simulation parameters
    t= 0; x= [0;0]; h= 1e-6; loop= 500;
    z= 0; ee=Vref-x(2);

    buf=[t x' 0];

    for i= 1:loop
```

```
        e= Vref-x(2);
        z= z+0.5*h*(e+ee);
        ce= (e-ee)/h;
        ee= e;

        % PID control
        u= Kp*e+Ki*z+Kd*ce;

        % Clamp duty cycle and generate the PWM signal
        dutycycle= Saturation(u,[0 1]);
        pwm= My_PWM(fPWM,t,dutycycle);

        % Integrate the converter model
        x= RK4(@fun,t,x,pwm,h);
        t= t+h;
        buf= [buf; t x' u]; % x(2) represents output voltage
    end

%     save 'PID_SP' 'buf'

    % System performances
    t= buf(:,1);
    iL= buf(:,2);
    Vo= buf(:,3);
    u= buf(:,4);
    stepinfo(Vo,t,Vref)

    % System performances
    e= Vref-Vo;
    ae= abs(e);
    IAE= 0.5*h*(ae(1)+2*sum(ae(2:end-1))+ae(end))

    subplot 311
    plot(t*1000,iL,'k','linewidth',1);
    xlabel('Time (ms)');
    ylabel('Inductor current (A)');
    axis([0 0.5 0 8])
    grid on

    subplot 312
    plot(t*1000,Vo,'k','linewidth',1.5);
    xlabel('Time (ms)');
    ylabel('Output voltage (V)');
    axis([0 0.5 0 8])

    subplot 313
    plot(t*1000,u,'b','linewidth',1.5);
    xlabel('Time (ms)');
    ylabel('Control input (u)');
    axis([0 0.5 -30 120])
    grid on
end
```

```
%% Implements a buck converter model
function xdot= fun(t,x,u,d)
    global L C R Vs
    xdot=zeros(2,1);
    xdot(1) = -x(2)/L+Vs*u/L;  % Inductor current
    xdot(2) = x(1)/C-x(2)/(R*C); % Output voltage
end
```