VOLTAGE CONTROL OF A DC-DC BUCK CONVERTER FOR ELECTROLYSIS USING FRACTIONAL ORDER SLIDING MODE CONTROL

MASTER OF SCIENCE IN CONTROL AND INSTRUMENTATION ENGINEERING

BY:

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EXAMINERS' APPROVAL SHEET

We, the undersigned members of the Board of Examiners of the final open defense by Demoz Lisanework, have read and evaluated his thesis entitled "VOLTAGE CONTROL OF DC-DC BUCK CONVERTER FOR ELECTROLYSIS USING FRACTIONAL ORDER SLIDING MODE CONTROL", and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree.

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DECLARATION

I hereby declare that this MSc thesis entitled “VOLTAGE CONTROL OF DC-DC BUCK CONVERTER FOR ELECTROLYSIS USING FRACTIONAL ORDER SLIDING MODE CONTROL” is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

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ABSTRACT

Switching DC-DC converters are non-linear and the most widely used circuits in power electronics. Generally, they are used in all conditions where there is need of stabilizing a given DC voltage to a desired value. DC-DC buck converters are used in voltage step-down applications. A DC solar energy is converted to the desired voltage level using the a buck converter, for hydrogen generation with electrolysis process have been investigated. The electrolysis load for hydrogen production especially needs low voltage and high currents. To have these conditions the converter must be designed and controlled sensitively. For this aim, the fractional order sliding mode (FOSM) controller is used as a solution in this paper.

Simulation results showed that, FOSM controller improved the rise time and settling time by 2% and 15.3% respectively compared the values using PID controller. Similarly, FOSM controller shows comparatively best performance improvement over SOSM in terms of high reduction of unwanted oscillation in addition to the rise time, settling time improvements. The overshoot is reduced from 46.3% to 5.208% using PID controller while it is totally removed when SOSM and FOSM controllers are applied. Both SOSM and FOSM controllers overcome the effect of electrolysis load variations. The actual output voltage is not deviated from desired value even for large input voltage variation using FOSM controller. Furthermore, the performance of controller was tested by increasing and decreasing 58.52% electrolysis load from operating point while desired output voltage is decreased by 50% and increased up to 20% from operating point. Generally, from the above analysis results it is evident enough that FOSM is better and preferable controller than the SOSM and PID controller.

Key words: *DC-DC Converter, Buck Converter, PID Control, SOSM Control, FOSM control, Photovoltaic energy.*

CONTENTS

LIST OF FIGURE

LIST OF TABLE

LIST OF SYMBOL

C ………………………..........................Capacitor

C_{min}………………………..……………....Minimum capacitor

D ……………………………………………Average duty cycle

d ………………..……………..………........Duty cycle

$\hat{d}$……………………..…………………..........Duty cycle variation

f ……………...……………………………Switching frequency

i_C ……………………………….………........Actual capacitor current

I_L …………………………………….........Average inductor current

i_L ……………………………………….……..Actual inductor current

$\hat{\imath}_L$……………………………………………Small signal variation of the inductor current

i_{Lmax} …………………………......................Maximum inductor current

i_{Lmin} ……………………...........................Minimum inductor current

I_o …………………………........................Average output current

i_o …………………………………..……......Actual output current

I_s ……………………………..... ….…………Average source current

i_s………………………….………. …………..Actual source current

$\hat{\imath}_s$ ………………………….…. …………Small signal variation of the source current

K_d ……..…………………….….……………Derivative gain

K_i ………………………………………….Integral gain

K_p ………………………...……………..Proportional gain

L ……………………….……. ………....Inductor

L_{min} ……………………….….……………Minimum inductor

R ………..………………….….……………Load resistor

S ……………………….…. …………....Switch

T ………………………. ………………..Switching period

t_P …………………………….. …………Peak time

t_s ………………………….…. …………Rise time

t_s …………………………….………….…settling time

u ……………………….……...………………Control signal

V_c……………………..….………………....Average capacitor voltage

v_c ………………………...…. ………….Actual capacitor voltage

$\hat{v}_c$ ……………………………........................Small signal variation of the capacitor voltage

V_{in}………………………...……………….....Average input voltage

v_{in}………………………………………..Actual input voltage

$\hat{v}_{in}$……………………..……………………Small signal variation of the input voltage

V_L………..…...…. …………………………Actual inductor voltage

V_o……………………..…………………..Average output voltage

v_o………………………………………...Actual output voltage

$\hat{v}_o$ ………………………………………Small signal variation of the output voltage

V_{ref} ………………………...…………....Reference voltage

V_s……………………………………………Average source voltage

w_n ………………………………………..Natural frequency

ξ ………………………………………………Damping ratio

ΔQ …………………………………….……Change of charge

Δi_L……………………………..…………….peak-to-peak inductor current

ΔVo …………………………… ………..Ripple output voltage

τ………………………………..…………....Sampling time

LIST OF ACRONYMS

CCM..……………..…… …………………….Continuous Conduction Mode

DC ………….……… …………………….Direct Current

DCM …………………..…………………..Discontinuous Conduction Mode

GTO ……………………..……………..………..Gate Turn off Thyristor

HOSM ………………….….………………Higher Order Sliding Mode

IGBT ……………………….......................Insulated Gate Bipolar Transistor

MOSFET…………………….....................Metal oxide Semiconductor Field Effect Transistor

PID …………..………….……………………Proportional Integral Derivative

PI …………..……….…….………………...Proportional Integral

SCR …………..………..……......................Silicon Controlled Rectifier

SMC …………..………..…..………………..Sliding Mode Control

SM …………..…………..…………………Sliding Mode

SOSMC ……………….….………………..Second Order Sliding Mode Control

FOSMC…………………………………….fractional Order Sliding Mode Control

SMPS ……………..……..…………………..Switch Mode Power Supply

1-SMC ……………………………………...First Order Sliding Mode Control

VSS…………..…………….……………….....Variable Structure System

CHAPTER ONE

INTRODUCTION

1.1Background

Now a day's, world population is increasing in an exponential pattern. This causes to a multi-dimensional power demand in areas of food production, transport facility, home appliance etc. These operations, especially in developing countries, are performed mainly in traditional way. To simplify these traditional operations, there is a day to day development in technological advancements which consume huge amount of power. Power electronic circuits are used in power transmission lines to enhance the utility and efficiency of energy sources like, wind, solar system, bio fuel and geothermal energy by saving excess power instead of wasting it. Power electronics makes efficient and accurate control of electrical power possible; since the DC voltage from renewable sources are unregulated in nature. A DC-DC buck converter is required to supply a fine and adjustable DC voltage to a variable load from such unregulated DC sources. The Buck converter is the simplest and the most useful to convert a high DC input to lower DC output voltage. The drawback of renewable and other advanced energy sources is the storage of energy for sustainability; it is possible to store energy in battery, but method of storing energy in the battery is more costly and limited. Therefore, scientists are proposed energy storage as hydrogen, as a new solution for future generations and also an appropriate energy transporter since it is environmental compatible for the 21st century [1, 2].

Because of fast technological improvement of energy conversion, a buck converter is become significant for power electronics application. In current years, water electrolysis is the most suggested solutions for hydrogen generation and storage by compression [4]. For electrolysis process approximately 2V DC Voltage is required to produce hydrogen gas. However, the solar scheme is calculated for high voltages for shared bus voltages 12 V or 24 V particularly for battery charging [5]. Consequently, buck converter is necessary to reduce voltage levels to desired value and to increase the current that is required for electrolysis process. This thesis work focuses on conversion of photovoltaic energy to reference value using buck converter for electrolysis application.

Investigation, control and balance of a buck converter with electrolysis load are issues which must be considered to obtain constant steady output voltage. Since linear controllers are simple controller mostly used to control a buck converter. Though, these conventional methods are incapable to perform adequately under uncertainty condition. Therefore, nonlinear controllers are the most suitable for controlling DC-DC buck converters. In recent years, the research's associated to fractional controller's application of in various field discipline and engineering are notable increasing. In fact, this is because of well understanding about calculus potentialities. Fractional order controllers which are the oversimplification of classical integer order controllers would lead to more exact and robust control performances for any system [8, 10]. Therefore, here is required to design a fractional order slide mode control to accommodate those non-linear behaviors and to enhance the performance of a switched mode buck converter.

1.2 Problem Statement

The PV energy is transformed to the desired level with buck converter to hydrogen production process. Electrolysis system desires energy for decomposition of water in to oxygen and hydrogen gases. The converter is designed for a 100 W commercial solar input. This PV panels can produce 12-24 V output for various loads and currents. Buck converter is used to regulate the voltage and the current to the desired level for electrolysis process. The current increment has direct relation to the amount of hydrogen produced. Analysis, control and stabilization of switching mode DC-DC buck converters are basic issues that must be considered for best performance applications. Control technique which gives best performances under any situations is always in demand. Therefore, in this thesis fractional order sliding mode controller is going to design for buck converter to improve the converter performance.

1.3 General objective

To design voltage control of a DC-DC buck converter with electrolysis load using fractional order sliding mode control.

1.3.1 Specific objectives

- To model and analyze the buck converter with electrolysis load and simulate using MATLAB/Simulink.

- To design fractional order sliding mode controller for voltage regulation of buck converter
- To design second order sliding mode controller for voltage regulation of buck converter.
- To examine the effectiveness of the proposed fractional order sliding mode controller as compared to second order sliding mode controller and conventional PID controller at operating point and under input voltage and load variations.

1.4 Significance of the Research

- It provides regulated output voltage for electrolysis process.
- It gives the knowledge how regulated voltage obtained from buck converter.
- It verifies the importance of FOSM controller compared to SOSM controller.

1.5 Methodology

To accomplish this thesis work the following methodologies have been used:

- Review of the buck converter control mechanism was done. Different literatures which are related to this thesis work and their control mechanism are studied
- Mathematical model of DC-DC buck converter for hydrogen production
- Design controller: designed FOSM controller to a buck converter
- Developed and analyze the system model using MATLAB/Simulink.
- Lastly conclusion is given from simulation result.

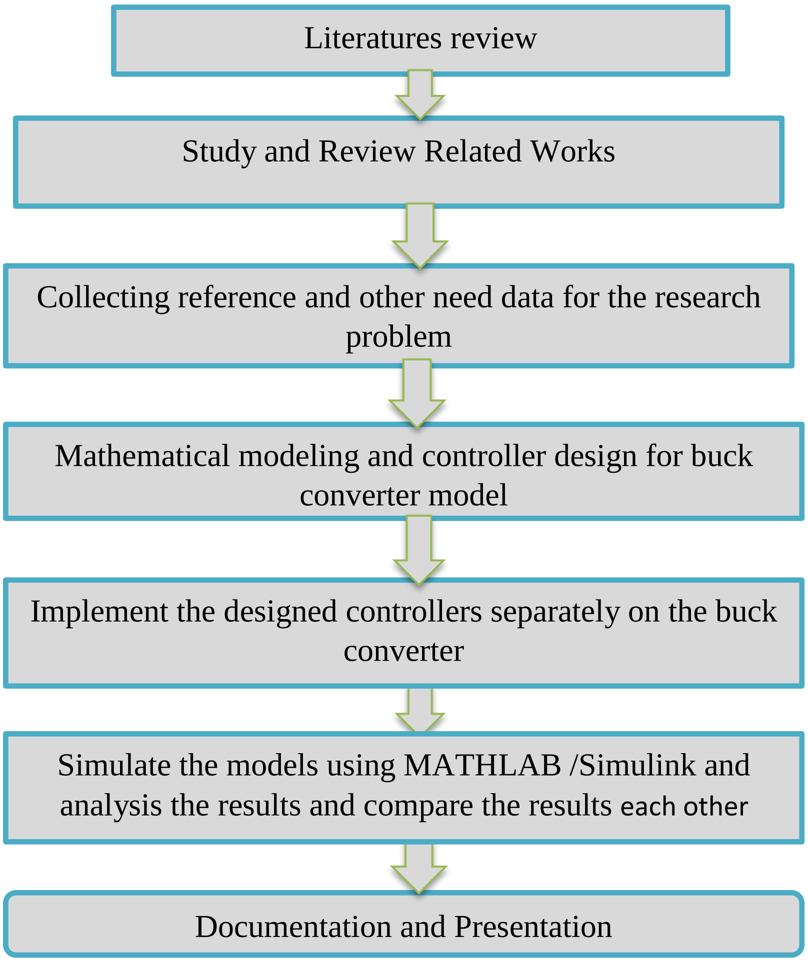


Figure 1.1flow diagram of the thesis methodology

1.6 Scope of Thesis

- Study the different a buck Converter operation mode.
- Carry out investigation of the buck converter only for CCM.
- Study the effectiveness among FOSM controller, SOSM controller and conventional (PID) controller in terms of rise time, overshoot, settling time and ripple voltage from desired value under input voltage and load variations.

1.7 Thesis Report Layout

Chapter 1 explains background, problem statement, thesis objective, importance of thesis work, thesis scope, and thesis report layout is presented.

Chapter 2 covers the literature review and general information about buck converter, Buck Converter Mode of Operation, Control Methods for DC-DC Buck Converter and, SOSM control system and FOSM control system.

Chapter 3 presents the general information about buck converter, methodology (mathematical modeling of buck converter)

Chapter 4 Presents controller design of PID controller, SOSM controller and FOSM controller are defined.

Chapter 5 Presents results obtained using the PID controller, SOSM controller and FOSM controller presented. Also, the performances of the controllers are compared.

Chapter 6 Conclusions and Recommendation.

CHAPTER TWO

LITRATURE REVIEW

2.1. Related Study

Direct current –direct current converters is extensively used in switch-mode power supplies. These switch mode DC-DC buck converter has received an increasing deal of interest in various area due to their applications [1]. Topology's of the converter varieties from single transistor buck to complex configurations consisting two or four devices and using soft-switching to control the switching losses. There are many different methods of classification of dc-dc converters. One of way of classification of the converter depends on the isolation property. Transformer is used to isolation the primary portion and secondary portion to each other. The control loop is usually made by means of transformer or by means of optocoupler. Consequently, input sides are isolated from output side electrically .On the other hand, non-isolated converters also classified as: step down dc-dc converter, step up dc-dc converter, step up-down dc-dc converter, opposite polarity, step up-down dc-dc converter.

The same approaches are used for investigation and control of these various converters. Therefore investigation, control and balance of switching converters are the leading factors that should be considered. Voltage controller should retain a continuous output voltage regardless of line variation and load resistance uncertainty. Since the plant is nonlinear, linear control system is not compatible to the system to obtain the desired output under uncertain condition, even though it is widely used to control the active performance of the converter [2, 3]. Linear control system is designed using small signal linearized model technique at precise operating point. This technique is easy to implement; but this is difficult to account system parameters variation. System parameters uncertainty and large signal transients that created in the startup or against variations in the load cannot be studied by using this technique. Multiple loop control methods, like current mode control, have significantly enhanced dynamic behavior; however this is challenging particularly for HO converter topologies.

A preliminary work on to the application of fractional order slide mode control is reported in [5] double integrator is presented as the plant to control. A fuzzy fractional order slide controller is adopted to control nonlinear plant. FOSM control approaches of DC-DC buck converters are presented and PWM sets the basis for the control of switched mode buck converters [6-9].

2.2 Review of Other Related Works

In 2004 M. Castilla [11-13] presented voltage mode hysteretic controllers for synchronous buck converter used for various applications. Investigation and design of a hysteretic pulse width modulation controller with improved transient response have been recommended for buck converter in 2004[11]. Switching mode DC-DC buck converters are represent a certain class of the variable structure system. The structure of a buck converter is sporadically reformed by the switching action of controlled switches and uncontrolled diodes. SM controllers are suitable for dc-dc buck converters. Those are well-known using SM controllers to sustain wide operating points.

In 2006 Guo Liping [14] presented nonlinear controllers must be used for DC-DC converters to attain a steady-state, and fast transient reaction in the variable functional points. Fuzzy control has numerous advantages like: precise mathematical models of the plants are not needed in order to design of fuzzy controllers, complications related to nonlinear mathematical investigation are comparatively low, and FL controller can adjust the variations from the operating points. However, fuzzy controllers are generally designed based on professional knowledge of converters, and tuning is required based on a trial and error technique. The tuning can be relatively time consuming and the response cannot be easy to estimate.

In 2008 Siew-Chong Tan, Y. M. Lai, and Chi K. Tse [15] Presented the performance of sliding mode control with conventional linear control of DC-DC buck-boost converter in terms of transient characteristics. Using sliding mode controller, the overshoot is removed while using PID controller it is reduced from 51.3% to 9.245%. It has shown that, the use of sliding mode control method lead to an enhanced robustness in providing reliable transient responses over a wide operating condition.

In 2009 Utkin, Guldner, & Shi.[16] Traditionally, PWM method is used to obtain a desired continuous output function with a discrete control command. In PWM, an external high frequency signal is used to modulate a low frequency desired function to be tracked. However, it seems unjustified to ignore the binary nature of the switching device in these power converters. Instead, sliding mode control uses the discrete nature of the converters to full extent by using state feedback to set up directly the desired closed loop response in time domain. The most remarkable attribute in using SM control is the low sensitivity to uncertainties and parameter variations. The problem of using sliding mode control method is the existence of finite amplitude and frequency oscillations called chattering near the operating point.

In 2010 Md. Shamim-Ul-Alam, Muhammad Quamruzzaman, and K. M. Rahman [17] Design SMC using fuzzy logic technique to a boost converter is proposed. SMC make sure robustness under any conditions and FL control diminish chattering effects that existing by SMC, thus increasing performance and decreasing ripples, and also reduced voltage and current ripples. The SM based FL control plant is simulated in MATLAB/SIMULINK and verified under line and set point voltages variation and confirmed the performance is better than conventional SM controller. The challenges here is the tuning can be rather time consuming.

In 2012 Sumita Dhali, P.Nageshwara Rao, Praveen Mande, and K.Venkateswara Rao [18] presented the general performances of the SM controller with the PID controller and PI controller for PWM based SM controller of a step up converter which operate in CCM. Pulse width modulation based SM controller shows adequate performance compared to traditional controller having lowermost fluctuation from desired set point in internal losses and line voltages variation. SM controller enhances converters applicability for several engineering area.

In 2013 S. S. Muley and R. M. Nagarale [19] presented the performance comparison of SM controller with PID controller. The results showed SM control method delivers best regulation voltage and well suited to boost conversion application. This derived controller/converter system is suitable under supply voltage and parameters variation at a constant load.

In 2015 Betcy Mariam David and Sreeja K.K [20] have been presented the dynamic performance of DC-DC converters highly improved by applying SM Control. SM control system is suitable for VSS like; power converters. The main improvement of SOSM control compared to conventional system is it’s highly robustness in counter to line, load and parameter variations.

In 2016 Iftikhar Ali, Narayan Longani, Fahad Mumtaz Malik [21] has been presented Performance comparison of nonlinear controllers for nominal and perturbed model of buck converter using integral sliding mode control and back stepping for a buck converter which gives a stable output considering variations in supplying voltage or in load resistance, external disturbances, parametric uncertainty or measurement error cause fluctuation in output of DC supply.

In 2017 Maulana Azad National Technology Institute, Bhopal, Madhya Pradesh [17] suggested Integral order sliding mode control algorithm for DC-DC buck converter loop control was suggested. Integral order sliding mode SM controller system was develop to address the issue of variable switching frequency in standard sliding mode-controlled buck converters during loading and supplying differences. The no constant frequency of switching is unwanted as it leads to problems while developing filters for the scheme. ISMC seeks to relieve this issue by transforming the sliding mode control legislation using the modulation system for pulse width.

In 2017 Zewude Tolosa [23] compared the performance of SOSM control with PID control to a buck converter with respect to transient characteristics. Using SOSM control can lead to an improved robustness in providing consistent transient responses. Its main advantages are guaranteed stability and the robustness in contradiction of parameter, line and load uncertainties.

Sliding mode control system is suitable for VSS such as DC-DC buck converters. Using the SM controller, application of buck converters is enhanced that used in various applications. Sliding mode controller ensures robustness against all variation, but the main disadvantage of SM control is that they exhibit chattering. This thesis FOSM controller has been designed for a buck converter with electrolysis load to decrease chattering effect created by sliding controller, by this means improving the performance a converter, decreasing error, voltage ripples as well as current ripple.

2.3 DC-DC Buck Converters

It is a type of non-isolated converter which used to step down high line voltage a desired voltage for specific application and this is suitable for any design that required output always less than the input voltage. The basic topology of a buck converter consists of a misfit switch(S_w), inductor (L), capacitor (C), electrolysis Load (Re) and uncontrolled switch (D), that shown in fig2.1 bellow

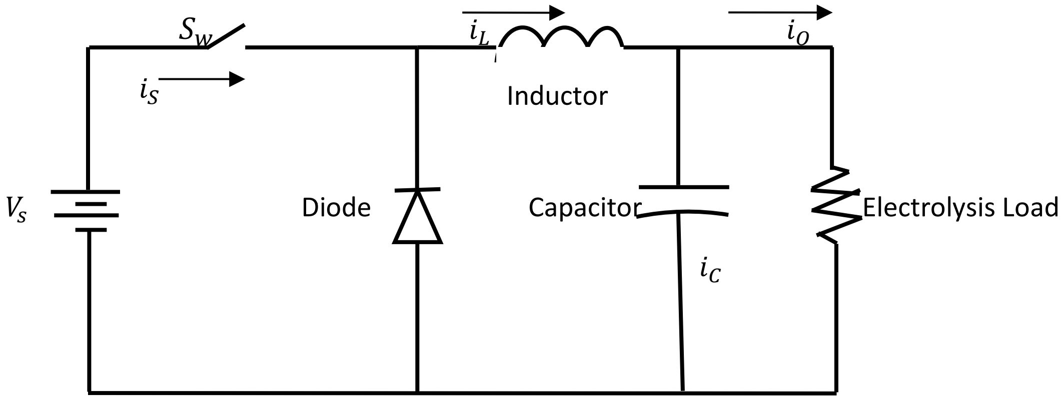


Figure2.1 basic circuit of buck converter topology

2.4 Components of Buck Converter

The basic components of a simple converter are: DC input, eccentric switch, uncontrolled diode, inductor, capacitor, and electrolysis load.

DC source

Inductor: It is a passive electronic component that store electrical energy in the form of magnetic energy. Basically, it uses a conductor that is wound into a coil, and when electricity flows into the coil from the left to the right, this will generate a magnetic field in the clockwise direction. It is used in converters for accomplishing better efficiency as it is able to handle the peak switching currents and thus provides a continuous current power source. It can store the energy and release it with small loss. To sustain a constant output, the circuit uses the energy stored in L, during the on periods, to continue delivering the load during the off periods. Practical (non- ideal) inductor has some resistance, named as winding resistance. It is very small so, in most cases it is ignored. It also has a winding capacitance due to the capacitive coupling between the conducting coils. It is very small and can be unnoticed in most cases, except at high frequencies.

Capacitor: It is a passive electronic component that store energy in electric field form. It filters the ripple inductor current to minimize ripple at output of converter and decrease the voltage overshoot at the output of buck converter as the output can overshoot beyond its desired value while full load is unexpectedly detached from the output. The output capacitor must be sufficient to absorb stored energy to avoid output from overshooting above the stated maximum output voltage

Diode: Since the current that flow through inductor is not change instantly, a path must exist for the inductor current when the switch is off. The path is providing by the freewheeling diode. The purpose of the diode is not to rectify, rather to direct current flow in the circuit and to ensure that there is always a path for the current to flow through inductor.

MOSFET: MOSFET is the main element with high frequency, which leads high efficiency switching applications in the electronics industry. MOSFET(either N−channel or P−channel) that allows to supply voltage to stated load when the transistor is on. The choice of a P−channel or N−channel load switch depends on the specific requirements of the application. The N−channel MOSFET has various advantages than the P−channel MOSFET. For example the N−channel majority carriers (electrons) have a higher mobility than the P−channel majority carriers (holes). For the purpose of high current applications the N−channel transistor is chosen.

Operating Frequency: The converter switching frequency is the speed at which the switching unit is switched on and off. Increased switching frequency decreases the size of related components such as inductors, transformers, resistors and condensers as well as decreased board and case space requirements. This frequency affects the components selection in terms of, physical sizes which becomes smaller at higher frequencies, electrical characteristics, minimum On-time, power losses and more.

The operating frequency determines the performance of the switch. There is now a growing trend in research work and new power converter designs in increasing the switching frequencies. The higher is the switching frequency aims to reduce cost, smaller the physical size and component value. The reason for this is to reduce even further the overall size of the power converter.

A DC- DC buck converter waveforms under CCM operation is shown in the Figure 2.2 here.

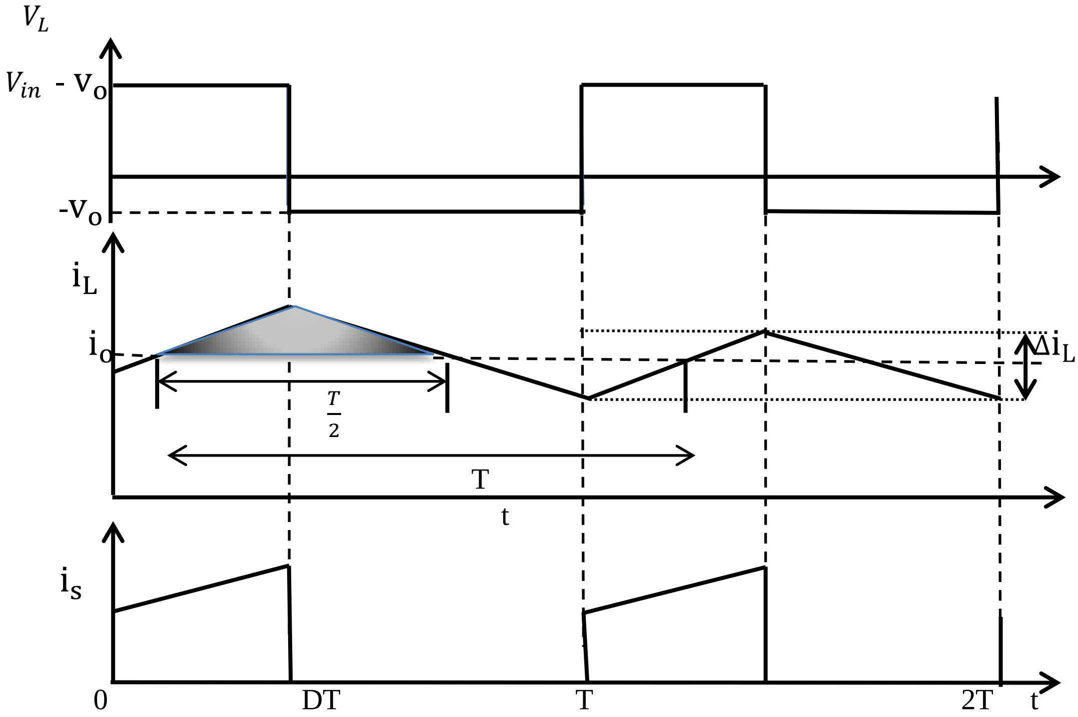


Figure2. 2 waveforms of buck converter for CCM operation [6].

2.5 Operation of Buck Converter

Buck converter delivers DC output voltage smaller in magnitude than the DC input voltage level. The first circuit topology when the switch is ON, and uncontrolled switch reverse biased, energy is transferring through the inductor. The state dynamics of the state variables are expressed below in equation 2.1 & 2.2.

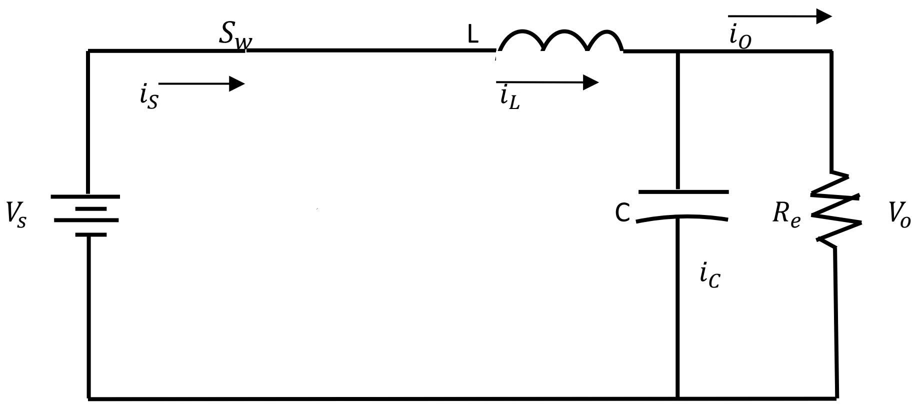


Figure2. 3 buck converter circuit topology when the switch is closed.

$$\frac{di_L}{dt} = -\frac{1}{L}(Vo - Vin) \quad 2.1$$

$$\frac{dV_o}{dt} = \frac{1}{C}\left(i_L - \frac{V_o}{R_e}\right) \quad 2.2$$

Since the duration of ON time is given as $\Delta t = DT$

$$\Delta i_L = \frac{1}{\mathrm{L}}(\mathrm{Vin} - \mathrm{Vo})DT \tag{2.3}$$

The other circuit topology, when uncontrolled switch is forward bias and controlled MOSFET is OFF state. The circuit is shown as below.

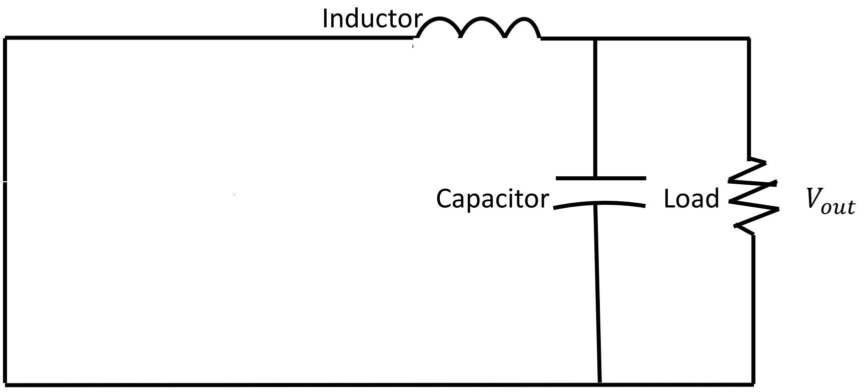


Figure2. 4 basic topology of buck converter.

$$\frac{\mathrm{d}i_L}{\mathrm{dt}} = -\frac{1}{\mathrm{L}}(\mathrm{Vo}) \tag{2.4}$$

$$\frac{\mathrm{dV}_O}{\mathrm{dt}} = \frac{1}{\mathrm{C}}\left(i_L - \frac{V_O}{R_e}\right) \tag{2.5}$$

2.6 Modes of Operation

Basically, there are two types of DC-DC buck converter modes of operation based on the continuity of inductor current flow. These are: Continuous and Discontinuous conduction mode.

2.6.1 Continuous conduction mode (CCM)

For a Continuous Conduction Mode (CCM), there are two phase. These are continuous of charging and discharging during a switching period, and its operation illustrated in fig 2.4(b) below. Buck converter operation in the CCM delivers high current and switching cycle T_s consists of two portions those are D_1T_s and D_2T_s ($D_1 + D_2 = 1$).

During D_1T_s ,inductor current increases linearly (charging) and then in D_2T_s it is decreases linearly (discharging).

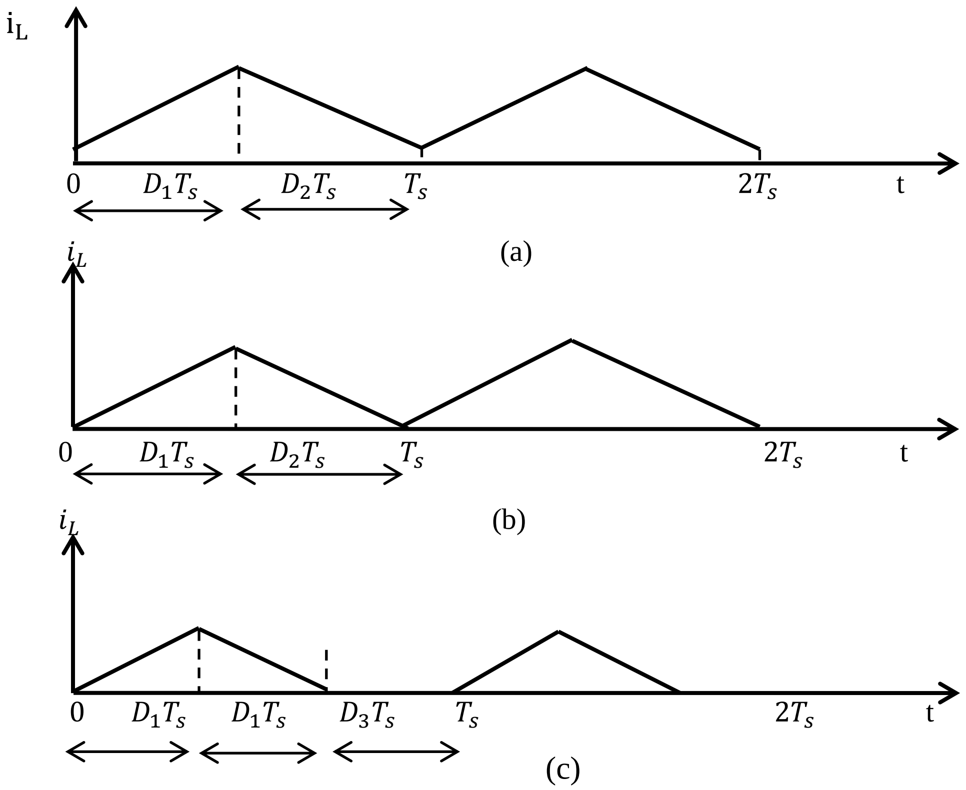


Figure2. 5 the waveform of PWM converter inductor current (a) CCM (b) boundary of CCM and DCM (c) DCM [24]

2.6.2 Discontinuous conduction mode (DCM)

In the discontinuous conduction mode operation, the inductor current has three phase. These are charging, discharging and an interval of no charge and discharge phase. The waveform of inductor current is illustrated in fig 2.4(c). At small load currents, buck converter operates in DCM. The controlled voltage in DCM has a nonlinear relationship to the line voltage. The switching cycle DCM are D_1T_s, D_2T_s and D_3T_s $(D_1 + D_2 + D_3 = 1)$. During the third mode i.e. in D_3T_s, inductor current stays at zero.

2.7 Control Methods for DC-DC Buck Converter

Two commonly used control schemes to adjust the output of converters are VM control and CM control. Both these control method mostly used in the low-voltage and low-power converters integrated circuit design in engineering. Loop system automatically retains exact desired voltage under in line voltage and electrolysis resistance uncertainty environments.

2.7.1 Voltage-mode controlled buck converter

In Voltage Mode Control (VMC) method of a converter, the output is adjusted to be always equal to a fixed value, under line voltage and load resistance variation. Using this approach the link among the input and the output of the system can be adjusted by a controller addition that is generally calculated according to certain values defining the type of chosen response for the system in closed loop. VM control is used extensively because its simplicity to design and implement, and also its good community to uncertainties at the references input. It has only one feedback loop.

2.7.2 Current-mode controlled buck converter

Current mode control arrangement is extensively used in DC-DC converters. This technique has two loops: Those are current and voltage feedback loop. The inductor current (i_L) is used as a feedback at the beginning of the first switching cycle when, the clock signal make the flip-flop (u=1), turning on the (MOSFET) switch. The switch current, which is equal to the inductor current i_L during this cycle, the inductor current linearly increases. In the comparator the actual current is compared to the reference signal i_{ref} from the regulator, and while i_L is somewhat greater, then the comparator output goes high and resets the flip-flop (u=0), thereby turn-off the switch. The switch turned on again by the next clock signal and the same process repeated. The converter operates in CCM.

2.8. PID Controller

It is a classical control method and the mostly extensively used to control industrial process systems. This control mechanism corrects the error that exists between the actual system variable and reference point. Calculation of conventional control contains three distinct constraints. Those are: Proportional (P), Integral (I) and Derivative (D) values. Proportional part controls the response to the present error, Integral part fixes based on the sum of recent errors, while Derivative part determines the reaction to the rate of changes of the error. By "tuning" parameters of PID controller algorithm; it is possible to designed switch action for the system desires. Controller reaction designated on base points of controller action to error, system oscillation and controller overshoots to the desired point [25].

Proportional term: A high proportional gain consequences great change in output for a particular variation in the error. If $k_p$is very high, the system will be. In other ways, a small gain results insignificant output response to a great input error, and a less sensitive controller.

Integral term: Integral part fast-tracks the movement of the system to conventional point and removes the remaining steady-state error that happens with a proportional only controller. However, since the k_i is replying to accrued errors from the past, it may cause the present value to overshoot the set point value.

Derivative term: It slows the speed of change of controller output and this result most obvious near to the controller desired point. It is used to decrease the extent of overshoot formed by the k_i part and advance the collective controller-system stability.

2.9. Sliding Mode Control (SMC)

SMC is multipurpose control system that provides robustness to VS systems under uncertainty condition. It is nonlinear control approach to make steady output(s) system at a definite set point or about a certain trajectory. Compared to other nonlinear controllers, SMC is simple to implement and have higher degree of design flexibility. The main steps in sliding mode control design are sliding surface design and design the control law to drive the system state trajectory starting from any arbitrary initial state to reach the sliding surface in finite time, and at the end it should arrive to a point where the system equilibrium state exists that is in the origin point of the phase plane [26]. Sliding mode controller has two modes. The first one is reaching mode and the second is sliding mode. In reaching mode, the system trajectory moves near the sliding manifold from any arbitrary point. In reaching mode, the state responses are sensitive to system uncertainties and disturbances. The other is in which, the system trajectory drive to equilibrium point alongside the switching surface and trajectory stay for subsequent time on the switching line [27].

As described above there are some advantages of first-order SM control (1 -SMC). In particular, insusceptible to disturbances and parameter variations, no precise plant model is required and the order reduction when system trajectory reaches on user chosen sliding surface. But there are some problems when using the conventional sliding mode control. These are unwanted fast oscillations of state trajectories near the sliding manifold (chattering). Chattering is considered in any first order sliding mode control implementation; because any 1^{st} order control signal is fast switching in nature, so it will lead to oscillation which may excite unmolded high frequency dynamics. Chattering is also caused when the control law is implemented in a sampled system, which is mostly the case; because sampled control systems act as open-loop systems between two sampling instants, it is impossible for any sampled control algorithm to satisfy a constraint with infinite accuracy when acting on a plant with uncertain internal and/or external disturbances.

Relative degree one limitation: Finite-time stability of the state variable at the origin, s = 0, is only guaranteed with a first order SM control (1 -SMC) algorithm if the algorithm can assign the sign of $\dot{s}$ directly. In other words, the input must exist explicitly in the 1^{st} derivative of s, i.e. the system must have relative degree one with respect to s. If more levels of differentiation of s are required before the input appears, i.e., in case of higher relative degree, 1-SMC algorithms might not be able to stabilize the system at all. Some methods were suggested to overcome the above problems. The main idea was to modification the dynamics in small area of the discontinuity surface in order to avoid actual discontinuity and at the same time to preserve the main properties of the whole system. In particular, high-gain control with saturation approximates the sign-function and diminishes the chattering, while online estimation of the so-called equivalent control is used to reduce the discontinuous-control component. However, by using saturation function and equivalent control the accuracy and robustness of the sliding mode were partially lost.

2.10 Sliding Order

Sliding order of HOSM describes the dynamic smoothness degree in the neighborhood of the sliding mode. If the task is to provide for keeping a constraint given by equality of even function S to zero, the sliding order is a number of continuous total derivatives (including the zero one) in the vicinity of the sliding mode. Hence, the r^{th}order sliding mode is determined by the equalities forming an r-dimensional condition on the state of the dynamic system [28]. Standard sliding mode is called 1 -sliding mode. In 1 -sliding mode $\dot{s}$ is discontinuous while in the r^{th}order sliding mode s^{r} is discontinuous, where r is the order of SM. In the following sections FOSM controller is discussed.

2.10.1 Fractional order sliding mode control (FOSMC)

Fractional order sliding mode controller is a special case of higher order sliding mode control, which preserve the desirable properties, particularly invariance and order reduction, but they achieve better accuracy and guarantee finite-time stabilization. Even though, fractional calculus related to a few centuries ago, but its usefulness and significant applications are in center of attention particularly in engineering currently. As stated previously all systems and components are fractional in nature, but they are different in amount of fractionality. The fractional property is not terminating to electrical elements and it's possible to expand it to all systems. The aim of fractional order sliding mode control is to direct s and $\dot{s}$ to zero in finite time. The amazing difference among integer order surface to fractional order surface can be understood easily. The fractional differo-integral operators denoted by aD_t^{α}f(t) (where a is the lower limits and t is the upper limits) are a oversimplification of integration and differentiation of the operators of a fractional order[29-35]. There are different definitions of non-integer differo-integral, but the most common definition are: The Riemann-Liouville definition: It represents oversimplification of integrals and derivatives to arbitrary fractional order. Generally it can be defined as follows:

$$a^{D_t^{\alpha}} = \begin{cases} \frac{d^{\alpha}}{dt^{\alpha}}\ , & Re[\alpha] > 0 \\ 1 & Re[\alpha] = 0 \\ \int_{-a}^{t}(d\tau)^{-\alpha}, & Re[\alpha] < 0 \end{cases} \qquad 2.6$$

Where: $\alpha \in R$ an arbitrary real number, that represents the order of the operation, a is the lower limits and t is the upper limits.

Definition1. In the application of fractional calculus, the Gamma function proposed by Euler is defined by the integral

$$\Gamma(z)=\int_0^{\infty} e^{-t}t^{z-1}dt \qquad 2.7$$

That satisfies Re(z) > 0,and converges in the right half of the complex plane. A number of reputed definitions for fractional derivatives are set forward, but well-known definition is Riemann-Liouville definition.

Definition.2[32]. Riemann-Liouville definition of the αth-order fractional derivative operator $0^{D_t^{\alpha}}$ is given by

$$0^{D_t^{\alpha}} f(t) = \frac{1}{\Gamma(1-\alpha)} \frac{d}{dt} \int_0^t (t-\tau)^{-\alpha} f(\tau) d\tau \qquad 2.8$$

Where $0<\alpha < 1$

Definition.3[32]. Riemann-Liouville definition of the αth-order fractional derivative operator $0^{D_t^{-\alpha}}$is defined by

$$0^{D_t^{-\alpha}} f(t) = \frac{1}{\Gamma(\alpha)} \int_0^t (t-\tau)^{\alpha-1} f(\tau) d\tau \qquad 2.9$$

From the definition, the derivative of a time function with (t) = t^{β}, $\beta > -1$, is evaluated as:

$$0^{D_t^{-\alpha}} t^{\beta} = \frac{\Gamma(\alpha+1)}{\Gamma(\alpha-\beta+1)} t^{\beta-\alpha} \qquad 2.10$$

Definition 4 [32] If the fractional derivative $0^{D_t^{\alpha}} f(t)(t)$ $(k-1 <\alpha< k)$ and a function (t) are integrable, then

$$0^{D_t^{-\alpha}} (0^{D_t^{\alpha}} f(t)) = f(t) - \sum_{j=1}^{k} 0^{D_t^{\alpha-j}} f(t)]\, t = \alpha \frac{(t-\alpha)^{\alpha-j}}{\Gamma(\mu-j+1)} \qquad 2.11$$

CHAPTER THREE

MATHEMATICAL MODELING OF A BUCK CONVERTER

3.1 Introduction

Modeling of a buck converter in the form of state equations by taking inductor current and capacitor voltage as the states of the system the state equations can be obtained. System modeling is the most significant phase for any form of system control design work. To simplify the complex mathematical modeling of a buck converter, assume electrical and semiconductor devices should be considered as an ideal components. It should ensure the equations derived by the use of Kirchhoff's laws must include all the allowable states due to semiconductor devices being ON or OFF. The dynamics of a converter under a CCM is modeled by applying KVL and KCL. The following assumption taken into consideration:

- The switch is closed for time DT and open for time T -DT, where D is duty ratio and T is Switching period.
- The circuit operates at steady state.
- The inductor current is continuous (i.e. always positive),
- Filter capacitor is very large i.e. in order to limit the value of the ripple voltage below a certain value and to minimize voltage overshoot.
- The inductor value must be greater than the minimum inductor to insure CCM and to prevent higher transmission loss in switch, inductor and parasitic Resistances.

3.2 DC-DC Buck Converters Analysis

3.2.1 Calculation for duty ratio

Assume, converter is in steady state and both controlled switch and uncontrolled switch are taking as an ideal, inductive element and also capacitive elements losses is zero, does not include any parasitic resistances, the converter is operating under CCM i.e. $i_L$is always positive. To obtain a duty ratio two state of a buck converter is considered. While the controlled switch ON, the circuit topology of a DC-DC buck converter is as shown Figure 3.1 below.

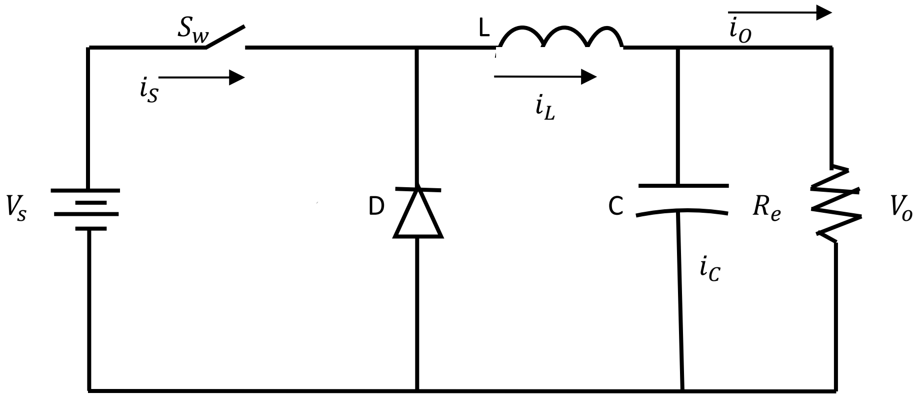


Figure3. 1 buck converter circuit topology when the switch is closed.

$$\frac{di_L}{dt} = -\frac{1}{L}(Vo - Vin) \qquad 3.1$$

$$\frac{dV_o}{dt} = \frac{1}{C}\left(i_L - \frac{V_o}{R_e}\right) \qquad 3.2$$

When the switch ON the duration of time is given as $\Delta t = DT$

$$\Delta i_L = \frac{1}{L}(Vin - Vo)DT \qquad 3.3$$

The other state circuit is while the switch is turned off and current freewheels through the diode. While uncontrolled switch is forward biased and controlled switch is off, the circuit is as shown below:

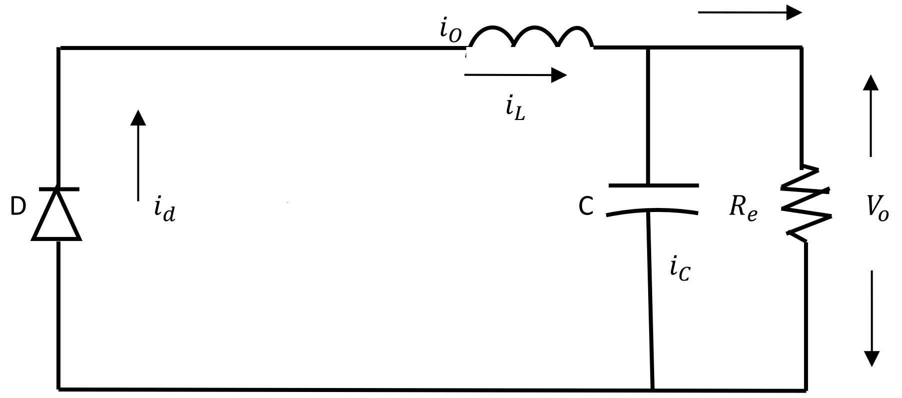


Figure3. 2 buck converter circuit topology when switch is open.

$$\frac{di_L}{dt} = -\frac{1}{L}(Vo) \qquad 3.4$$

$$\frac{dV_o}{dt} = \frac{1}{C}\left(i_L - \frac{V_o}{R_e}\right) \qquad 3.5$$

When the switch OFF the duration of time is given as $\Delta t = (1 - D)T$

$$\Delta i_L = \frac{-Vo}{L}(1-D)T \qquad 3.6$$

Duty Ratio: Buck converter is essentially buck type power converters are used to deliver lower voltage from high supply voltage. The relationship in the input and output voltage of a buck converter is controlled by the switching duty cycle, D, based on the equation below.

$$V_{out} = DV_{in} \qquad 3.7$$

Calculation for Inductor: for inductor calculation let's assume, no power losses is zero. Power absorbed in the electrolysis load and supplied power is equal. Based on the specified maximum inductor current ripple, the critical inductor value and its peak current for buck converter are determined. At steady state operation of the buck converter, the net change of the inductor current over the switching period is zero.

$$\Delta i_{L.period} = \Delta I_{L.closed} - \Delta I_{L.open} = 0 \qquad 3.8$$

At steady states process, average current through the capacitor is should be zero, therefore average current that pass through inductor equal to average electrolysis load current($I_L = I_{out}$)

$$I_L = I_{out} = \frac{V_o}{R_e}) \qquad 3.9$$

The average inductor current equals the average of the minimum and maximum inductor current values, so the maximum and minimum inductor current is given as follows:

$$I_{Lmax} = I_L + \frac{\Delta i_L}{2} \qquad 3.10$$

$$I_{Lmin} = I_L - \frac{\Delta i_L}{2} \qquad 3.11$$

Substituting for I_L and $\Delta i_L$from Equation (3.9) and (3.3) respectively into Equation (3.10) and (3.11) and simplifying gives,

$$I_{Lmax} = \frac{V_o}{R_e} + \frac{V_o}{2L}(1-D)T \qquad 3.12$$

$$I_{Lmin} = \frac{V_o}{R_e} - \frac{V_o}{2L}(1-D)T \qquad 3.13$$

To determine the mode of conduction minimum inductor current value is important. The above equations were resulting based on CCM assumption; in order to keep on valid i_{Lmin} must remain positive. So by setting equation (3.13) equal to zero and rearranging to solve for L, the minimum inductor value can be found to keep the converter in CCM.

$$I_{Lmin} = \frac{(1-D)}{2f} R_e \quad 3.14$$

Where f is the switching frequency ($f = \frac{1}{T}$)

This is inductor value which determines the margin among the CCM and DCM of operation. To operate a buck converter in CCM, inductor value used must greater than a minimum inductor value. The inductor current ripple value, is the difference of maximum and minimum of the inductor current

$$\Delta i_L = I_{Lmax} - I_{Lmin} \quad 3.15$$

Substituting for I_{Lmax} and I_{Lmin} from Equation (3.12) and (3.13) respectively into Equation (3.15) and simplifying gives

$$\Delta i_L = \frac{V_o(1-D)T}{L} \quad 3.16$$

$$L_{min} = \frac{(1-D)}{2f} R \quad 3.17$$

Capacitor calculation: Capacitor output is assumed very large to find constant output voltage. But change in output voltage (ΔVo) with a real value of capacitance calculated by considering the Figure 3.3 below for CCM operation of buck converter. Assume that ripple entire component of inductor current (Δi_L) that flows over a capacitor and the average component that pass in the electrolysis load, the maximum increase of the charge (ΔQ) which is stored in the capacitor C is equal to shaded triangle area. Therefore by calculation the shaded triangle area shown by Figure 3.3 ΔQ is obtained for each cycle.

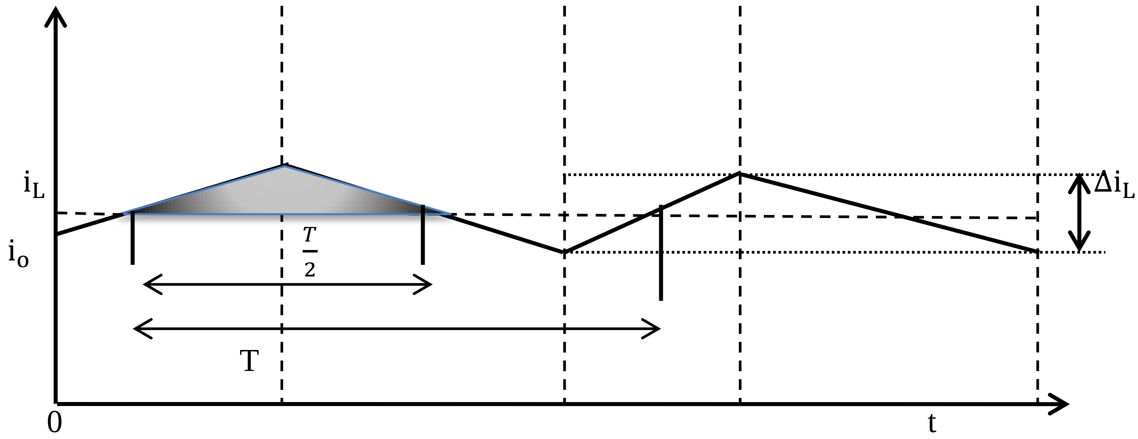


Figure3. 3 waveforms of buck converter for continuous conduction mode operation [6]

$$\Delta V_o = \frac{\Delta Q}{C} \tag{3.17}$$

$$\Delta Q = \frac{1}{2}\frac{T}{2}\frac{\Delta i_L}{2} \tag{3.18}$$

Substituting for ΔQ from Equation (3.17) into Equation (3.18) gives

$$\Delta V_o = \frac{1}{8}\frac{1}{C}(T\Delta i_L) \tag{3.19}$$

Substituting for $\Delta i_L$from Equation (3.16) into Equation (3.19) and rearranging and solving for capacitor,

$$C_{min} = \frac{(1-D)V_o}{8\Delta V_o L f^2} \tag{3.20}$$

This is the minimum capacitance required. In order to limit the value of the ripple voltage under a certain value and to minimize the voltage overshoot, the filter capacitance value must be larger than the minimum capacitance value.

3.3 Mathematical Model of Buck Converter

Buck converters mode can be found by applying basic laws that governs system operation. A state equation of a buck converter operating in CCM can be obtained by means of KVL and KCL.

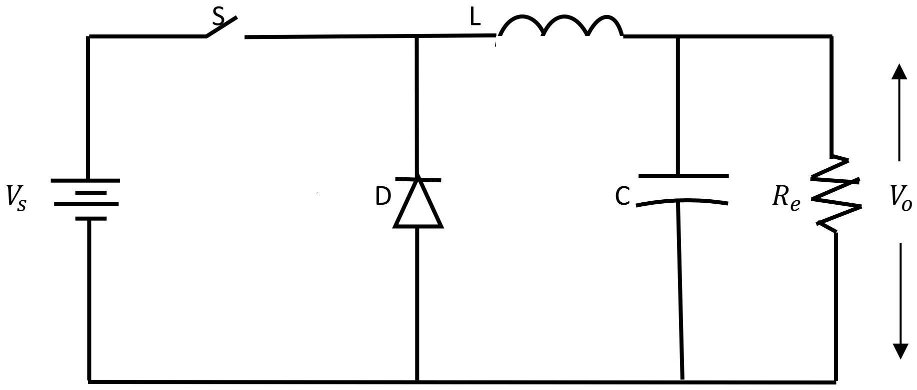


Figure 3. 4 basic buck converter topology.

During ON state, energy is transferring from the source to filter inductor. Uncontrolled switch is reverse bias. Consequently, inductor current increases gradually; state circuit topology is shown in Figure 3.5.

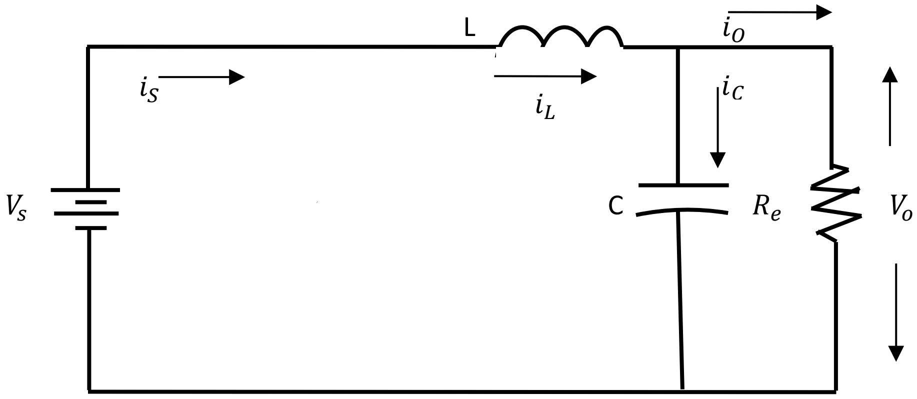


Figure3. 5 while a converter is in ON mode.

State equations related to system variables are given as:

$$L\frac{di_L(t)}{dt} = Vin(t) - i_O(t)R_e \tag{3.24}$$

$$C\frac{dvc(t)}{dt} = i_L(t) - \frac{Vc(t)}{R_e} \tag{3.25}$$

Where $i_o(t)Re = V_o(t)$.By applying KVL and KCL to obtain state equation is

$$\frac{di_L(t)}{dt} = \frac{Vin(t)}{L} - \frac{1}{L}Vc(t) \tag{3.26}$$

$$\frac{dVc(t)}{dt} = \frac{1}{C}i_L(t) - \frac{Vc(t)}{R_eC} \tag{3.27}$$

$$Vc(t) = Vo(t) \tag{3.28}$$

$$i_s(t) = i_L(t) \tag{3.29}$$

Since Vc (t) = V_o(t) the state equation matrices are given as:

$$\begin{bmatrix} \frac{dVo(t)}{dt} \\ \frac{di_L(t)}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_e C} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} Vo(t) \\ i_L(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} Vin(t) \tag{3.30}$$

$$\begin{bmatrix} Vo(t) \\ i_s(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_L(t) \\ Vc(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} Vin(t) \tag{3.31}$$

$$A_1 = \begin{bmatrix} -\frac{1}{R_e C} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \qquad B_1 = \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} \qquad C_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad D_1 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

During OFF state, inductor acts as energy source to the load. In this stage, the diode acts as a conductor and current in the circuit starts to decreases linearly since energy through the inductor starts to discharges as Shown in Figure 3.6

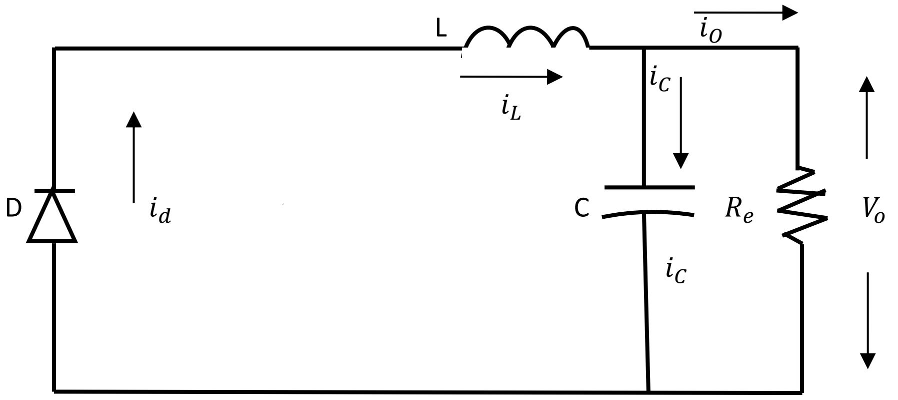


Figure3. 6 while a converter is in OFF mode.

Similarly equivalent circuit of a converter in off mode and diode is forward biased

$$L\frac{di_L(t)}{dt} = -Vo(t) = -i_O(t)\,R_e \tag{3.32}$$

$$C\frac{dvc(t)}{dt} = i_L(t) - \frac{Vc(t)}{R_e} \tag{3.33}$$

By applying KVL and KCL to obtain state equation as:

$$\frac{di_L(t)}{dt} = -\frac{i_O(t)\,R_e}{L} \tag{3.34}$$

$$\frac{dVc(t)}{dt} = \frac{1}{C} i_L(t) - \frac{V_o(t)}{RC} \quad 3.35$$

$$Vc(t) = Vo(t) \quad 3.36$$

$$i_s(t) = 0 \quad 3.37$$

Since:Vc (t)=Vo(t) the state equation matrices is given as,

$$\begin{bmatrix} \frac{dVo(t)}{dt} \\ \frac{di_L(t)}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_e C} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} Vo(t) \\ i_L(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} Vin(t) \quad 3.38$$

$$\begin{bmatrix} Vo(t) \\ i_s(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_L(t) \\ Vc(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} Vin(t) \quad 3.39$$

$$A_2 = \begin{bmatrix} -\frac{1}{R_e C} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \quad B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad C_2 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \quad D_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

3.4 State Space Average Model of Buck Converter

The main objective of averaged switch modeling method is to drive an averaged model for the switch network. This model can be implanted into a buck converter circuit to find a full averaged model of a buck converter. The identical model will be used in many dissimilar converter arrangements. The averaged model makes simple the converter investigation and gives good intuitive considerate about a converter steady state as well as dynamic properties .State space average model is derived by making the average the state equation derived above over switching period. The averaging mode is performed by taking duty cycle as a weighting factor and combine equations into a single averaged state equation. Finally the averaged equation can be given as follow:

$$A = \left[d \begin{bmatrix} -\frac{1}{R_e C} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} + (1-d) \begin{bmatrix} -\frac{1}{R_e C} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \right] = \begin{bmatrix} -\frac{1}{R_e C} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \quad C = \begin{bmatrix} 0 & 1 \\ d & 0 \end{bmatrix}$$

$$B = \left[d \begin{bmatrix} 0 \\ \frac{V_{in}}{LC} \end{bmatrix} + (1-d) \begin{bmatrix} 0 \\ 0 \end{bmatrix} \right] = \begin{bmatrix} 0 \\ \frac{d}{L} \end{bmatrix} V_{in} \quad D = \left[d \begin{bmatrix} 0 \\ 0 \end{bmatrix} + (1-d) \begin{bmatrix} 0 \\ 0 \end{bmatrix} \right] = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Simplifying the above matrices given in Equation (3.9), the state space form of buck converter average model is,

$$\begin{bmatrix} \frac{dVo(t)}{dt} \\ \frac{di_L(t)}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_e C} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} Vo(t) \\ i_L(t) \end{bmatrix} + d \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} Vin(t) \qquad 3.40$$

$$\begin{bmatrix} Vo(t) \\ i_s(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ d & 0 \end{bmatrix} \begin{bmatrix} i_L(t) \\ Vc(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} Vin(t) \qquad 3.41$$

3.5 Small Signal Model of Buck Converter

Since switching DC-DC converter is a nonlinear plant, to design conventional linear control system, first must be construct ac small signal linearized models. It is attained through disturbing and normalizing the averaged model around precise working point [36]. The most important transfer function is derived from ac model. If perturbation is introduce in state variables such that

$$\left.\begin{matrix} i_L = I + \hat{i}_L,\ v_c = V_c + \hat{v}_c,\ i_s = I_s + \hat{i}_s \\ v_o = V_o + \hat{v}_o,\ \hat{v}_{in} = V_{in} + \hat{v}_{in},\ d = D + \hat{d}, \end{matrix}\right\} \qquad 3.42$$

Where the quantity $\hat{\imath}_L$, $\hat{v}_c$, $\hat{v}_{in}$, $\hat{d}$ and $\hat{\imath}_s$ are small alternating current variations around the equilibrium point. Substituting these state variables in the averaged model of buck converter that is given in equation (3.40 and 3.41) gives,

$$\begin{bmatrix} \frac{d(V_o+\hat{v}_o)}{dt} \\ \frac{d(I_L+\hat{i}_L)}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_e C} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} V_o + \hat{v}_o \\ I_L + \hat{i}_L \end{bmatrix} + (D+\hat{d}) \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} (V_{in} + \hat{v}_{in}) \qquad 3.43$$

$$\left.\begin{bmatrix} V_o + \hat{v}_o \\ I_s + \hat{i}_s \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ D + \hat{d} & 0 \end{bmatrix} \begin{bmatrix} I_L + \hat{i}_L \\ V_c + \hat{v}_c \end{bmatrix}\right\} \qquad 3.44$$

From the equation (3.43 and 3.44)

$$\left.\begin{matrix} \frac{d(V_o+\hat{v}_o)}{dt} = -\frac{1}{R_e C}(V_o + \hat{v}_o) + \frac{1}{C}(I_L + \hat{i}_L) \\ \frac{d(I_L+\hat{i}_L)}{dt} = -\frac{1}{L}(V_o + \hat{v}_o) + \left(D + \hat{d}\right)\left(\frac{1}{L}\right)(V_{in} + \hat{v}_{in}) \\ V_o + \hat{v}_o = V_c + \hat{v}_c \\ I_s + \hat{i}_s = \left(D + \hat{d}\right)(I_L + \hat{i}_L) \end{matrix}\right\} \qquad 3.45$$

From Equation (3.45) equate current and direct current quantities and proceed with alternating current equations by neglecting second order alternating terms (since they are nonlinear, eliminate the product of any ac terms, as they comprise multiplication of time-varying signals and also they are very smaller coppered to the 1st order alternating terms) gives,

$$\left.\begin{aligned} \frac{C d\hat{v}_o}{dt} &= \hat{i}_L - \frac{1}{R_e}\hat{v}_o \\ \frac{L d\hat{i}_L}{dt} &= -\hat{v}_o + D\hat{v}_{in} + V_{in}\hat{d} \\ \hat{v}_o &= \hat{v}_c \\ \hat{i}_s &= D\hat{i}_L + v_L\hat{d} \end{aligned}\right\} \quad 3.46$$

Than take Laplace transformation of equation (3.46)

$$\begin{aligned} Cs\hat{v}_o(s) &= \hat{i}_L(s) - \frac{1}{R_e}\hat{v}_o(s) \\ Ls\hat{i}_L(s) &= -\hat{v}_o(s) + D\hat{v}_{in}(s) + V_{in}\hat{d}(s) \\ \hat{v}_o(s) &= \hat{v}_c(s) \\ \hat{i}_s &= D\hat{i}_L(s) + I_L\hat{d}(s) \end{aligned} \quad 3.47$$

The most important converter transfer function is variation of output voltage with variation of input voltage. Therefore, transfer function obtain by making $\hat{d}$(s) =0. Since the transfer function from the input voltage to the output voltage expresses the effect of the input voltage changes on the output voltage only when the input voltage works, which means the perturbation of the duty cycle, is equal to zero. When $\hat{d}$(s) =0 equation (3.47) reduced as below,

$$Cs\hat{v}_o(s) = \hat{i}_L(s) - \frac{1}{R_e}\hat{v}o(s) \quad 3.48$$

$$Ls\hat{i}_L(s) = -\hat{v}_o(s) + D\hat{v}_{in}(s) \mid \hat{d}(s) = 0 \quad 3.49$$

$$\hat{i}_s = D\hat{i}_L(s) \quad 3.50$$

From the equation (3.47) solve for $\hat{\imath}_L(s)$ gives

$$\hat{i}_L(s) = \left(Cs + \frac{1}{R_e}\right)\hat{v}_o(s) \quad 3.51$$

Substitute for $\hat{\imath}_L(s)$ into Equation (3.51) from Equation (3.51) gives

$$Ls(Cs + \frac{1}{R_e})\hat{v}_o(s) = -\hat{v}_o(s) + D\hat{v}_{in}(s) \quad 3.52$$

By rearranging and simplifying Equation (3.52) above, the transfer function is given in equation 3.53 below

$$\frac{\hat{v}_o(s)}{\hat{v}_{in}(s)} = D\left[\frac{\frac{1}{LC}}{S^2 + \frac{1}{R_e C}s + \frac{1}{LC}}\right] \qquad 3.53$$

3.6 Model of SM Voltage Controlled Buck Converter.

There are two types of control modes of switching power converters: voltage mode control and current mode control. Here, VM control is used, i.e. output voltageV_o, is the state variable that to be controlled. The diagram of a SM voltage mode controlled buck converter shown in figure 3.7 below. The state space representation of a buck converter using SMV control technique, where control variables are the output voltage error and error dynamics defined in the fig 3.7 below.

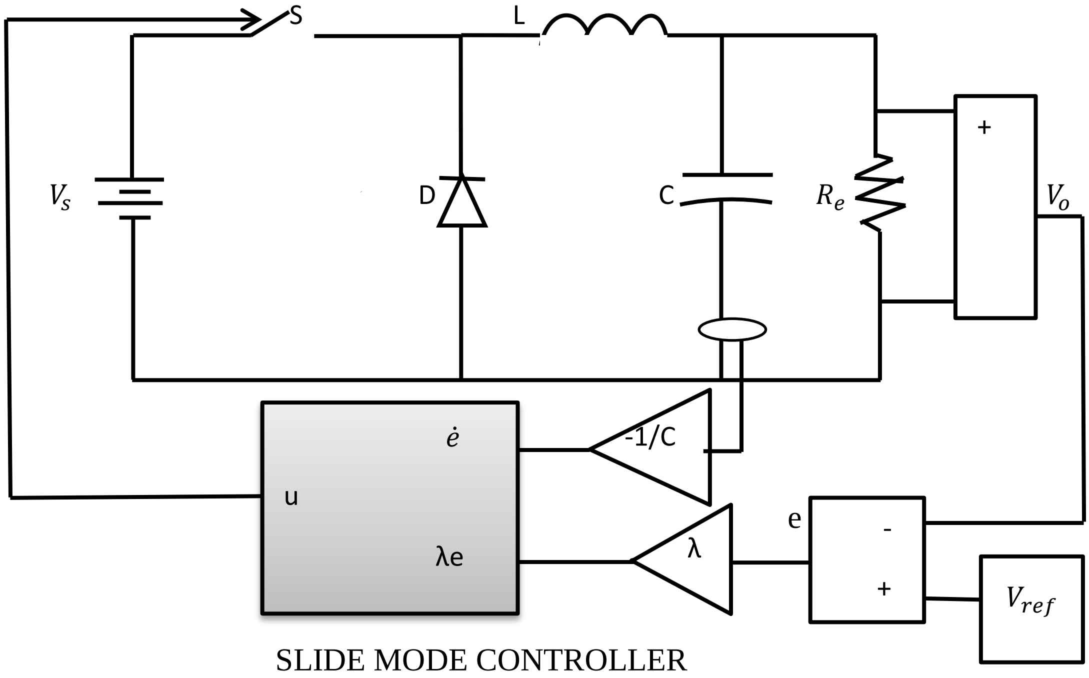


Figure 3. 7 schematic of SMV controlled buck converter

Hence voltage error and error dynamics under CCM of a converter operation with electrolysis load can be expressed as:

$$\begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} V_{ref} - Vo \\ \frac{d}{dt}(V_{ref} - Vo) \end{bmatrix} \qquad 3.54$$

The equivalent circuit when switch is closed and the diode in reverse biased is shown in

Since V_{ref} is constant $\frac{\mathrm{dV_{ref}}}{\mathrm{dt}} = 0$ so that

$$\dot{e} = \frac{de}{dt} = -\frac{dV_o}{dt} = -\frac{i_C}{C} \qquad 3.55$$

Where: V_{ref} Represent the desired tracking trajectory, V_o is output voltage, and i_C is represent capacitor current. By assuming the V_{ref} is constant. Then, by differentiating with respect to time

$$\dot{e} = -\frac{i_C}{C} \qquad 3\ .56$$

$$\ddot{e} = -\frac{1}{C}\frac{d}{dt}i_C \qquad 3.57$$

When the switch is on state equation of capacitor current written as:

$$i_C = i_L - io \qquad 3.68$$

Substituting the capacitor current in to equation number 3.57 gives equation number 3.59

$$\ddot{e} = -\frac{1}{C}\left[\frac{d}{dt}i_L - \frac{d}{dt}io\right] \qquad 3.59$$

From state space buck converter model

$$\frac{d}{dt}i_L = \frac{Vin - V_o}{L} \qquad 3.60$$

Since $io = \frac{V_o}{R_e}$ results in

$$\ddot{e} = -\frac{1}{C}\left[\frac{Vin - V_o}{L} - \frac{d}{dt}\frac{V_o}{R_e}\right] \qquad 3.61$$

After rearranging it gives the equation 3.62

$$\ddot{e} = -\frac{Vin}{LC} + \frac{V_o}{LC} + \frac{1}{R_e C}\frac{dV_o}{dt} \qquad 3.62$$

Since the output voltage, V_o=V_{ref} - e Substituting equation into the above equation leads to:

$$\ddot{e} = -\frac{1}{LC}e - \frac{1}{R_e C}\dot{e} - \frac{Vin}{LC}u + \frac{Vref}{LC} \qquad 3.63$$

The state space equations using state variables e and $\dot{e}$ can be stated as:

$$\begin{cases} \dot{e} = -\frac{i_C}{C} \\ \ddot{e} = -\frac{1}{LC}e - \frac{1}{R_eC}\dot{e} - \frac{Vin}{LC}u + \frac{V_{ref}}{LC} \end{cases} \quad 3.64$$

3.7 Electrolysis Load Model

Hydrogen is an ideal energy transporter because: it can be produced from and converted into electricity at relatively high efficiencies; the main hydrogen resources is water; it can stored in many ways like: in gaseous, liquid and some other form; there are more possible ways convert into other forms of energy and the conversion more efficient than any other fuel; hydrogen is ecologically compatible because its production, storage, transportation and end use do not produce pollutants, or any other harmful effects on the environment. The water can be decomposed into hydrogen and oxygen by applying energy. Energy and water are obtained in the reverse process instead. Process of separation of water in the electrolyzer by supplying electricity named as electrolysis. The reverse direction of electrolysis; the combustion of hydrogen and oxygen gas in fuel cell water plus energy is obtained. Supply external energy needs for electrolysis process, the recombination of hydrogen and oxygen can provide energy instead. The most promising possibilities of obtaining hydrogen gas from renewable source of energy are through electrolysis using solar as electricity source. Solar systems as well as electrolysis are known technologies. But coupling those technologies are still challenging. The intermittent operation and highly capricious power output due to the nature of solar system are the main handicaps. At very low loads the rate at which hydrogen and oxygen are produced may be lower than the rate at which these gases permeate through electrolyte, and thus mix with each other; this may form dangerous conditions in the electrolyzer.

Before studying the characteristics of electrolysis load, understood well about electrolysis. Electrolyze occurs, when proper voltage is provided for electrodes that placed under a solution inside the Electrolayzer. During the process, hydrogen gas and oxygen gas goes to cathode, and anode respectively. The voltage level of 1.23-2.05V is enough for the decomposition of the water. Electrolyzer, in fact, acts as nonlinear resistance when the reaction is takes place, and this nonlinearity of the process determined by a chemical structure of reactants, pressure of electrolyzes stack, process temperature and any other elements that exist in electrolyzer during a process [37]. After considering all the factors the electrolyzer model is given as Equation 3.65 below [5].

$$R_e = R_{e0}\left[1 + \alpha\left(\frac{I_e}{I_{e_{base}}}\right)^{\beta}\right] \qquad 3.65$$

In Equation 3.65, R_{eo} is initial resistance, and α and β are constant, which determined by nonlinear characteristics of electrolyzer model. For this typical application α value is selected with the range 0.35-0.65, and β value is selected with the range 2-4. After these substituting the values of R_{eo}, α, and β in equation number 3.65, the electrolysis load model can be written as Equation 3.66. Electrolysis load is determined by electrolysis current as a nonlinear function which is given in Eqn 3.66. Electrolysis resistance model is simulated in MATLAB/Simulink.

$$R_e = 0.08\left[1 + 0.5\left(\frac{I_e}{50}\right)^{3}\right] \qquad 3\ .66$$

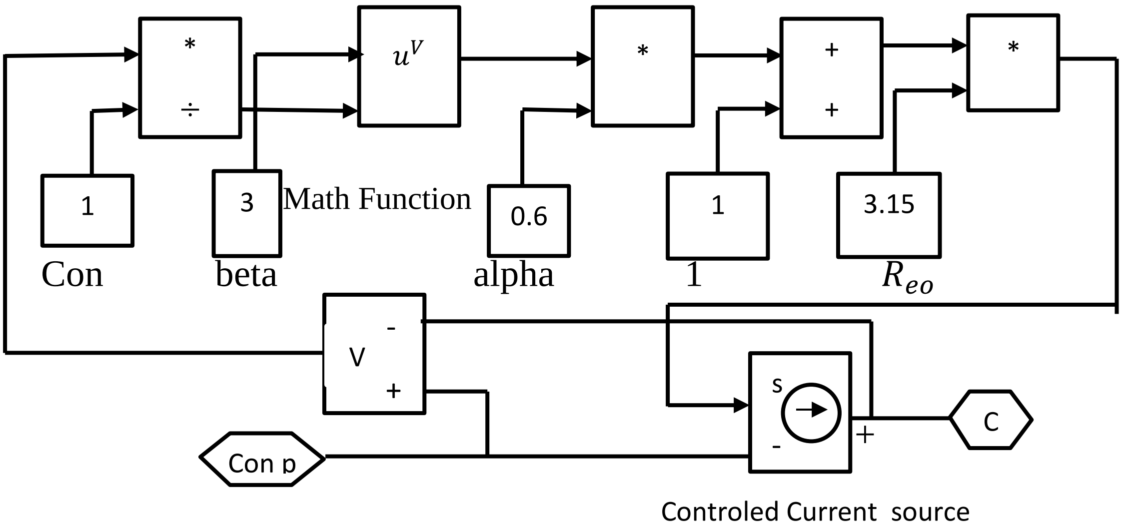


Figure3. 8 MATLAB/Simulink model of nonlinear electrolysis model.

CHAPTER FOUR

CONTROL SYSTEM DESIGN

4 .1 Design of Proportional Integral Derivative Controller for Buck Converter

A PID controller is conventional feedback loop controlling method that fixes the error among actual value and a desired value as per requirement. Its calculation includes $\mathrm{k_p}, \mathrm{k_i}\ and\ \mathrm{k_d}$ gains. The weighted sum of these three actions is used to regulate the process via a control component. By "tuning" the parameters of PID controller, it can provide a control action designed for particular requirements.

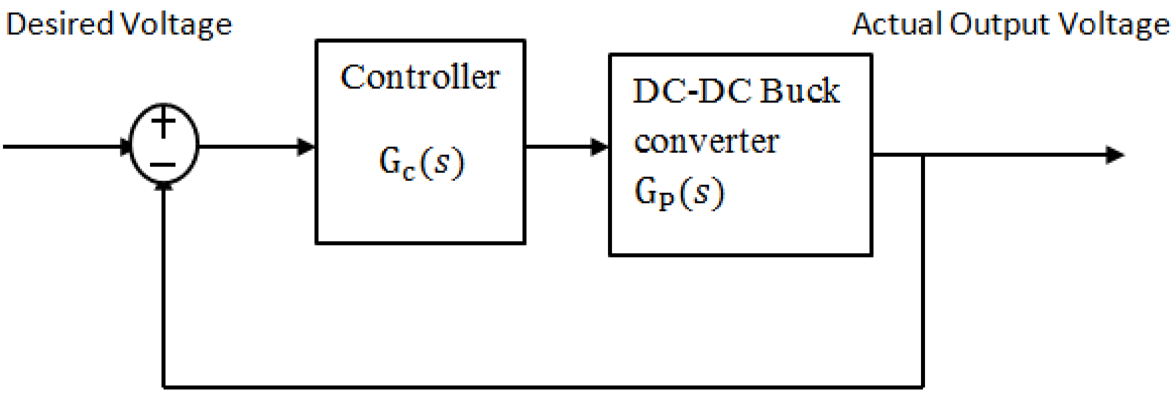


Figure4. 1 block diagram representation of closed loop system

Open loop transfer function($G_{P(s)}$) of the buck converter from equation (3.55) given as,

$$G_{P(s)}=\frac{\hat{v}o(s)}{\hat{v}in(s)} = D\left[\frac{\frac{1}{LC}}{S^2+\frac{1}{R_eC}S+\frac{1}{LC}}\right] \quad 4.1$$

To design conventional controller, Let consider a transfer function of conventional PID controller need to control second order plant ($G_{p(s)}$)

$$\mathrm{Gc(s)} = \mathrm{K_p} + \frac{\mathrm{K_i}}{\mathrm{S}} + \mathrm{K_d s} = \frac{\mathrm{K_d S^2 + K_p S + K_i}}{\mathrm{s}} \quad 4.2$$

Where: K_p: Proportional gain

K_i: Integral gain

K_d: Derivative gain

Second order plant transfer function characterized by (open loop)

$$\mathrm{Gp(s)} = \frac{\mathrm{K}}{\mathrm{S^2+2\xi^{ol}w_n^{ol}s+(w_n^{ol})^2}} \qquad 4.3$$

Where: ξ^{ol}: Damping ratio

w_n^{ol}: Natural frequency

K: open loop gain

The parameters used to carry out the simulation studies are given below

Table 4.1 Parameters used to carry out simulation studies

No	Description	Parameter	Value	Unit
1	Input voltage	V_{in}	12-22	V
2	Reference voltage	V_{ref}	2	V
3	Capacitance	C	2500	µf
4	Inductance	L	500	µh
5	Load resistance	R_e	0.08	Ω
6	Switching frequency	F	100	KHz
7	Duty cycle	D	0.5	-

$$CL = 2500 * 10^{-6} * 500 * 10^{-6} = 1.25 * 10\text{^} - 7$$

$$\mathrm{k} = \frac{\mathrm{D}}{\mathrm{CL}} = \frac{0.5}{1.25 * 10\text{^} - 7} = 4 * 10\text{^}6$$

$$w_n^{ol} = \sqrt{\frac{1}{CL}} = 2.828427*10\text{^}3$$

$$\xi^{ol} = \frac{1}{2R_eCw_n^{ol}} = 0.8839$$

$$G_p = \frac{4 * 10\text{^}6}{S^2 + 4999.5S + 7.9999993 * 10\text{^}6}$$

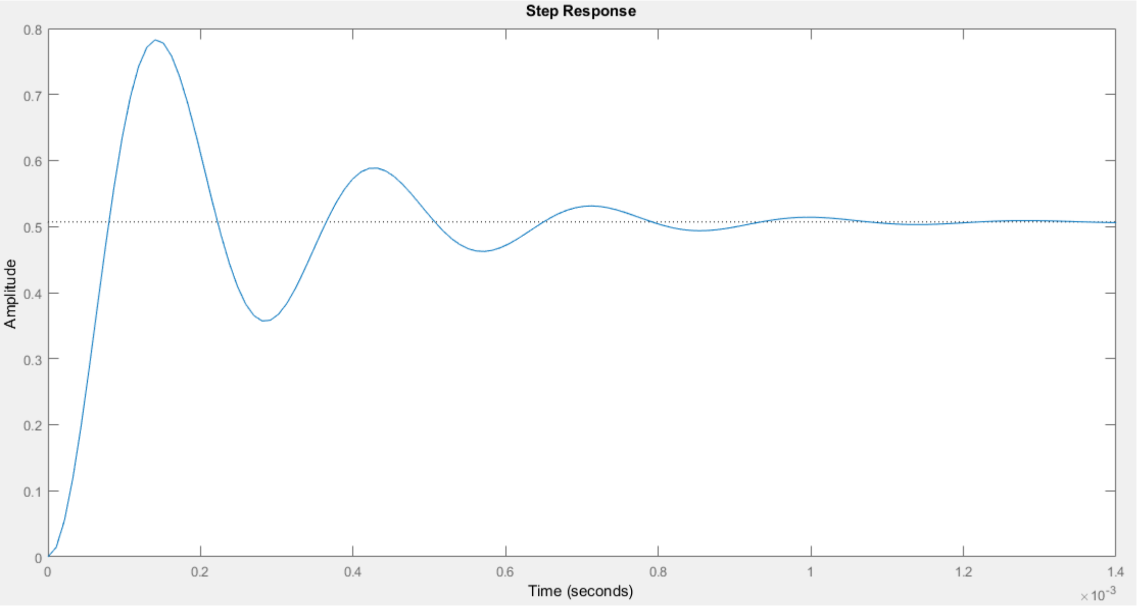


Figure 4. 2 Unit step response of open loop system

4.2 Design of SM Control for Buck Converter

Switching Converter has variable structure features and it is a time variable plant. Sliding mode control has good dynamic response and stability for constraints change and it is easy for implementation.

4.2.1 Design of second order sliding mode controller for buck converter

In SM control system, controller uses sliding surface to make decision on its control signal u to the system. In SMV control method, a switching signal, u that corresponds to state of a buck converters switch, which is decided using the sliding surface [38-41]. The SM control strategy has three steps. Those are: sliding surface Selection, Calculation of the controller, and Stability analysis.

4.2.1.1. Design of the sliding surface

Select sliding manifold to a buck converter to attain voltage regulation is given as,

$$S = \lambda e + \dot{e} \qquad 4.4$$

Where: $e = V_{ref} - V_o$

Since the voltage dropped across inductor is,

$$L\frac{di_L}{dt} = uV_i - V_o \qquad 4.5$$

$$i_L = \int \frac{(UV_i - V_o)}{L} dt \quad 4.6$$

$$S = \lambda\,(V_{ref} - V_o) - \left(\frac{1}{C}(i_L - i_o\right) \quad 4.7$$

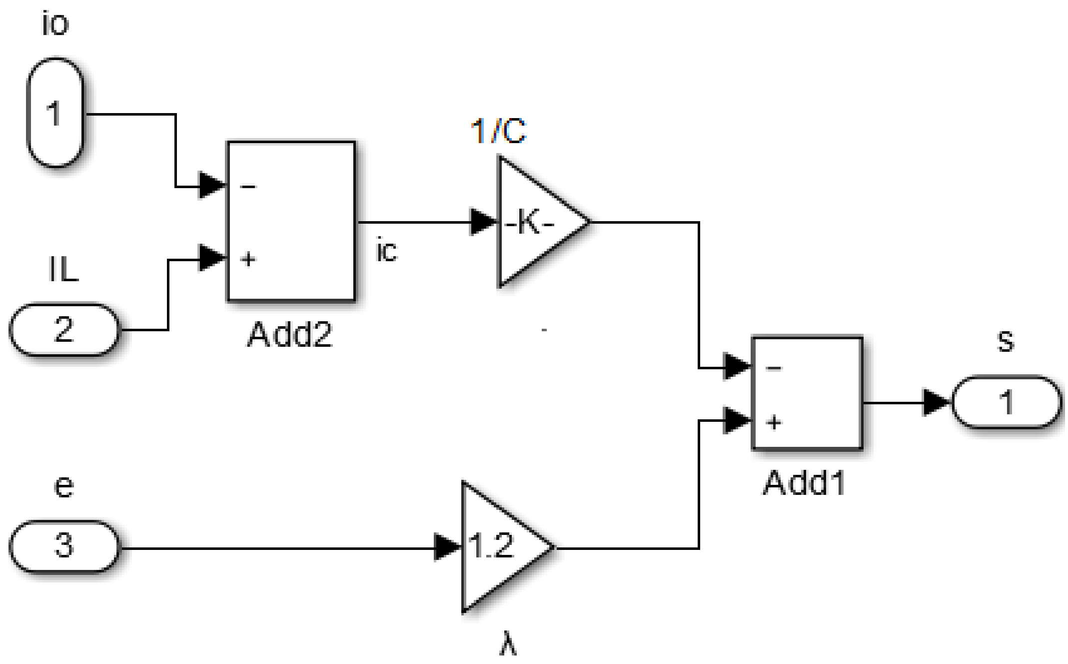


Figure4. 3 MATLAB/Simulink model of SO sliding surface.

The surface derivative is given by

$$\dot{S} = \lambda \dot{e}_1 + \dot{e}_2 \quad 4.8$$

$$\dot{e} = \frac{de}{dt} = \frac{dVo}{dt} = \frac{\lambda}{C} ic \quad 4.9$$

Since

$$i_C = i_L - \frac{Vo}{R_e} \quad 4.10$$

$$L\frac{di_L}{dt} = uV_i - V_o \quad 4.11$$

$$\frac{di_L}{dt} = \frac{1}{L}(uV_i - V_o) \quad 4.12$$

$$\ddot{e} = -\frac{1}{C}\left[\frac{Vin - V_o}{L} - \frac{d}{dt}\frac{V_o}{R_e}\right] \quad 4.13$$

After making some rearrangement on equation 4.13 gives equation 4.14

$$\ddot{e} = -\frac{Vin}{LC} + \frac{V_o}{LC} + \frac{1}{R_e C}\frac{dV_o}{dt} \qquad 4.14$$

Since the output voltage, $V_o = V_{ref}$ - e Substituting this equation into the above equation (4.14) leads to

$$\ddot{e} = -\frac{1}{LC}e - \frac{1}{R_e C}\dot{e} - \frac{Vin}{LC}u + \frac{Vref}{LC} \qquad 3.15$$

$$\dot{S} = \lambda\dot{e} - \frac{1}{LC}e - \frac{1}{R_e L}\dot{e} - \left(\frac{V_{in}}{LC}\right)u + \frac{Vref}{LC} \qquad 4.16$$

$$\dot{S} = \lambda\dot{e} - \frac{1}{LC}e - \frac{1}{R_e L}\dot{e} - \left(\frac{V_{in}}{LC}\right)u + \frac{Vref}{LC} = 0 \qquad 4.17$$

$$\left(\frac{V_{in}}{LC}\right)u = \lambda\dot{e} - \frac{1}{LC}e - \frac{1}{R_e L}\dot{e} + \frac{Vref}{LC} \qquad 4.18$$

$$u_{eq} = -\left(\frac{1}{LC}\right)e\frac{LC}{V_{in}} - \left(\frac{1}{R_e C}\right)\dot{e}\frac{LC}{V_{in}} + \lambda\dot{e} + \left(\frac{Vref}{LC}\right)\frac{LC}{V_{in}} \qquad 4.19$$

$$u_{eq} = -\frac{1}{V_{in}}e - \frac{L}{R_e V_{in}}\dot{e} + \lambda\dot{e} + \frac{Vref}{V_{in}} \qquad 4.20$$

$$u_{eq} = -\frac{1}{V_{in}}e - \frac{L}{R_e V_{in}}\dot{e} + \frac{LC\lambda}{V_{in}}\dot{e} + \frac{Vref}{V_{in}} \qquad 4.21$$

$$u_{eq} = -\frac{1}{V_{in}}e + \frac{L}{V_{in}}\left(C\lambda - \frac{1}{R_e}\right)\dot{e} + \frac{Vref}{V_{in}} \qquad 4.22$$

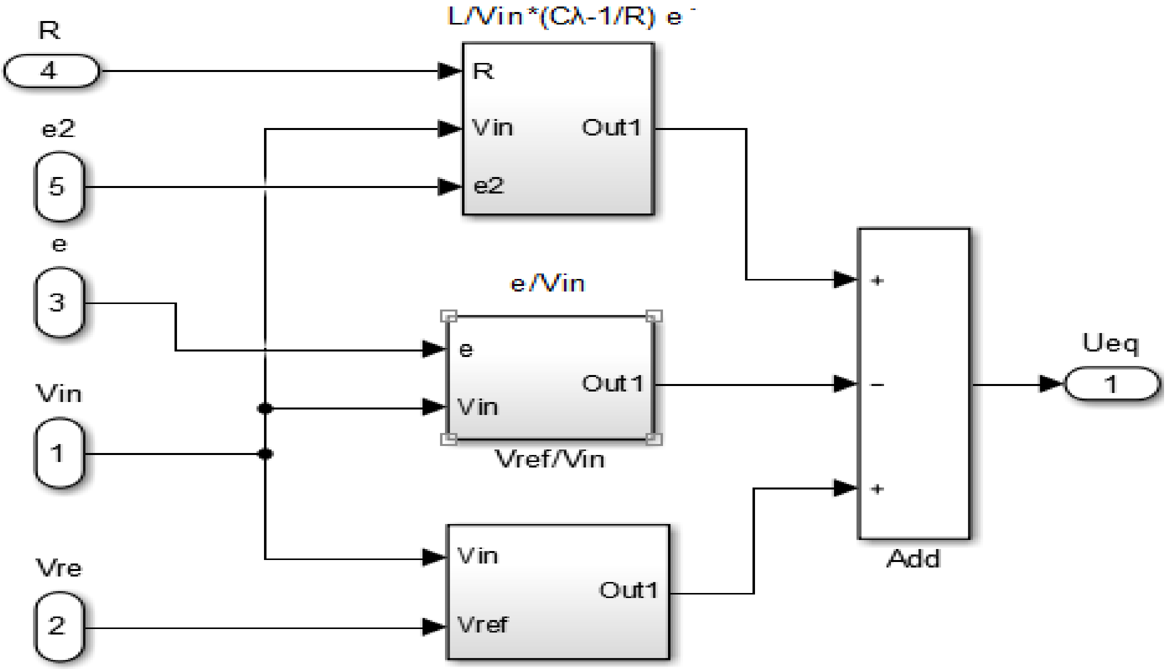


Figure4.4 MATLAB/Simulink model of second order slide mode control equivalent signal.

4.2.1.2. Design of the control law

Control signal u comprises two modules. Those are discontinuous components u_n and continuous component u_{eq}. Continuous component used to insures motion of state to user chosen surface, whenever state trajectory is on the surface. Equivalent part to satisfy sliding mode fulfills the next condition $\dot{s} = 0$. However this component a control signal cannot move the state to sliding mode. The discontinuous components drive the states trajectory on to the user chosen surface. Therefore switch control should be applied together with equivalent control.

4.2.1.3 Derivation of SM existence condition

Control law from equation number (4.22) gives only the information about the system trajectory as it is moved towards the user chosen sliding manifold. To be insured as the state trajectory is stay on user chosen surface for subsequent time, existence condition of the operation, by using Lyapunov second method asymptotic stability should be fulfilled. Let's select positive definite Lyapunov function V. To insure system stability and surface S attractive; the time derivative of selected function should be negative definite; such situation leads to following inequality:

$$V = \frac{1}{2}S^2 \qquad 4.23$$

$$S\dot{S} = S\left(\lambda\dot{e} - \frac{1}{LC}e - \frac{1}{R_eL}\dot{e} - \left(\frac{V_{in}}{LC}\right)u + \frac{Vref}{LC}\right) < 0 \qquad 4.24$$

To satisfy equation number 4.24 condition a discontinuous control part defined by

$$u_n = -ksign(S) \qquad 4.25$$

4.2.2 Fractional order sliding mode controller (FOSMC) design

First defined the FO sliding surface by using Caputo's definition as:

$$S = \lambda e^p + D_t^{\mu-1}\dot{e} \qquad 4.26$$

Where $e = V_{ref} - V_o$, λ is positive constant, and 0<μ.

$$S = \lambda\, e^p + D_t^{\mu-1}\left(\frac{1}{C}(i_o - i_L)\right) \qquad 4.27$$

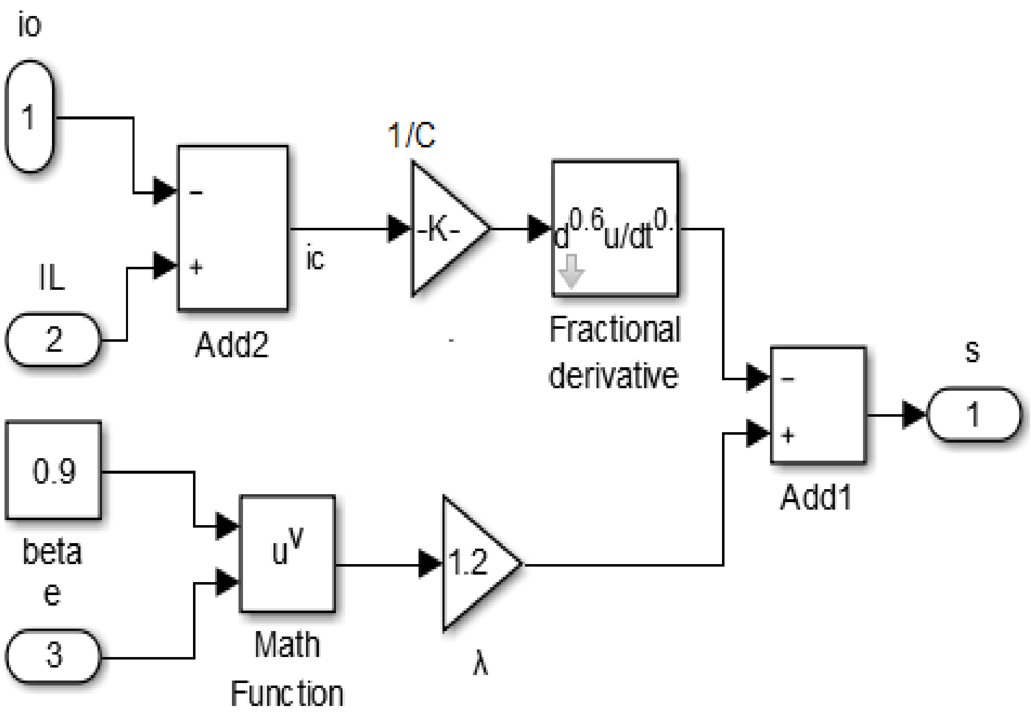


Figure4. 5 MATLAB/ Simulink model of FO sliding surface.

The derivative of a sliding surface to the order unity yields;

$$\dot{S} = \lambda p e^{p-1}\dot{e} + D_0^{\mu-1}\ddot{e} \qquad 4.28$$

$$\dot{S} = \lambda p e^{p-1}\dot{e} + D_0^{\mu-1}\left(\frac{-1}{LC}e - \frac{1}{R_eC}\dot{e} - \frac{V_{in}}{LC}u + \frac{Vref}{LC}\right) \qquad 4.29$$

$$\dot{s} = \lambda p e^{p-1}\dot{e} + D_0^{\mu-1}\left(\frac{-1}{LC}e - \frac{1}{R_e C}\dot{e} - \frac{V_{in}}{LC}u + \frac{Vref}{LC}\right) \quad 4.30$$

To satisfy the sliding mode, setting $\dot{s} = 0$. Then equivalent control is easily derived as follow:

$$\dot{s} = \lambda p e^{p-1}\dot{e} + D_0^{\mu-1}\left(\frac{-1}{LC}e - \frac{1}{R_e C}\dot{e} - \frac{V_{in}}{LC}u + \frac{Vref}{LC}\right) = 0 \quad 4.31$$

$$u_{eq} = -\frac{e}{V_{in}}e + \frac{L}{V_{in}}\left(\lambda c p e^{p-1} D_0^{1-\mu} - \frac{1}{R_e}\right)\dot{e} + \frac{Vref}{V_{in}} \quad 4.32$$

Where: $0<p<1$, $\lambda>0$, $0<\mu<1$, so that states e and $\dot{e}$ converge to zero infinite time, and also, the system will be in the terminal SM.

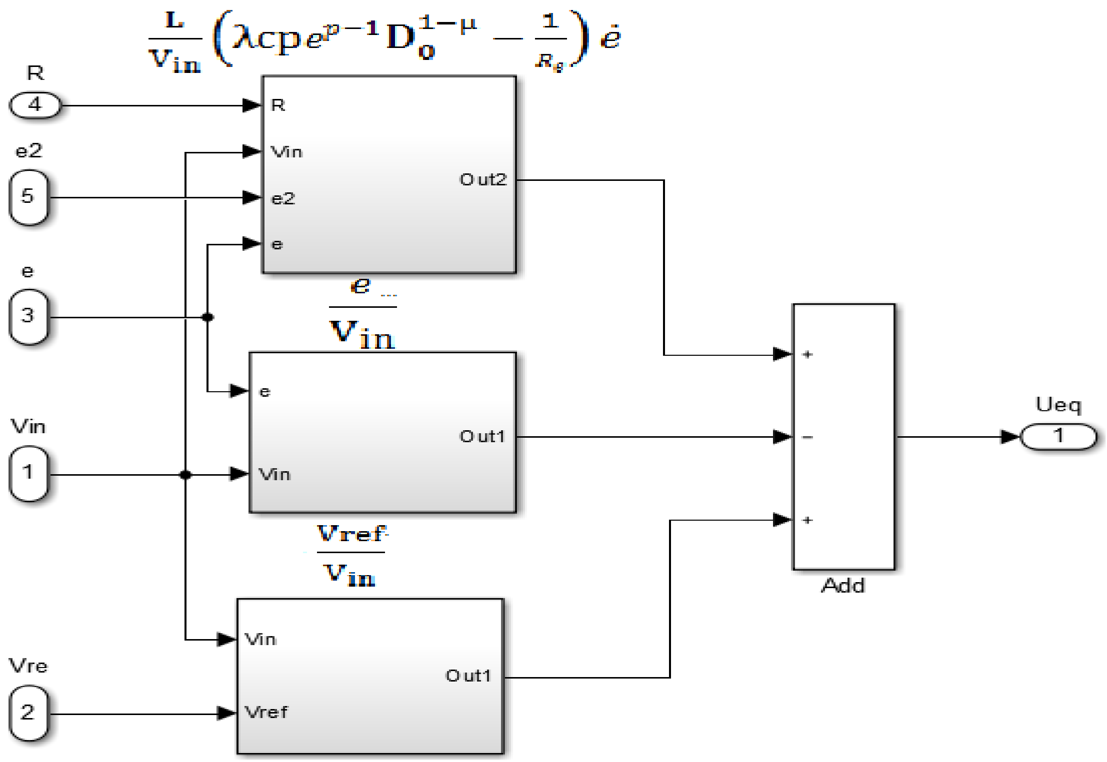


Figure4. 6 MATLAB/Simulink model of fractional order slide mode control equivalent signal.

The discontinues component u_n by using Gao's reaching law is selected $(-\,ksign(S))$. Where: k positive constant. So the non-linear component u_n defined as

$$u_n = -\,ksign \quad 4.33$$

Since the controller is fractional order, this structure can be modified to satisfy the stability condition.

$$u = u_{eq} + u_n \qquad 4.34$$

Finally, the global based on FOSM controller *u* will be

$$u = -\frac{e}{V_{in}} e + \frac{L}{V_{in}} \left(\lambda c p e^{p-1} D_0^{1-\mu} - \frac{1}{R_e} \right) \dot{e} + \frac{Vref}{V_{in}} + (-k\,sign(s)) \qquad 4.35$$

Let consider a positive definite Lyapunov function V defined as follows: To assure steadiness of the system and to make the surface "s" attractive. The derivative of Lyapunov the function should be negative definite. This leads to the following inequality:

$$\dot{v} = s\dot{s} = s(\lambda p e^{p-1} \dot{e} + D_0^{\mu-1} \ddot{e}) \qquad 4.36$$

$$s\dot{s} = s\left(\lambda p e^{p-1} \dot{e} + D_0^{\mu-1} \ddot{e}\right) \qquad 4.37$$

$$\dot{v} = s(\lambda p e^{p-1} \dot{e} + s D_0^{\mu-1} \left(\frac{-1}{LC} e - \frac{1}{R_e C} \dot{e} - \frac{V_{in}}{LC} u + \frac{Vref}{LC} \right)) \qquad 4.38$$

Substituting (4.35) into (4.38) the result is written follow:

$$\dot{v} = s(-k\,sign(s)\,) = -k|s| \qquad 4.39$$

Since K is positive constant, the value of $V>0$ and $-\dot{v}>0$ are positive. That means the controlled system satisfies the reaching condition.

CHAPTER FIVE

RESULTS AND DISCUSSIONS

The proposed PV supplied buck converter, with electrolysis load using FOSMC, SOSMC and PID controllers are simulated using MATLAB/Simulink software.

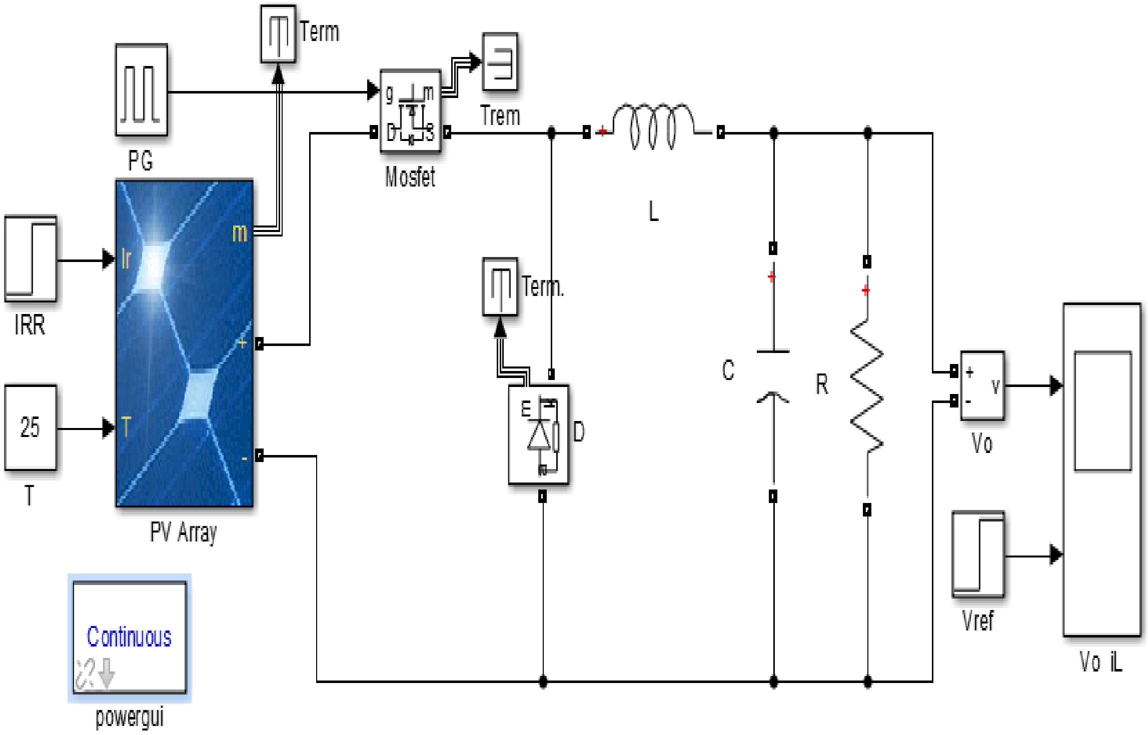


Figure 5. 1 MATLAB/Simulink model of buck converter using PV input supply.

From the designed buck converter 20V input voltage is obtained for converter from the solar PV module, which gives an output voltage of 2V and it is designed for electrolysis load application. The buck converter circuit parameter values are calculated with 100 kHz switching frequency, and 4% change at output voltage.

5.1 Performance of Buck Converter using PID Controller

Converter performance with a PID controller is investigated and verified using MATLAB/Simulink given in the figure 5.1.

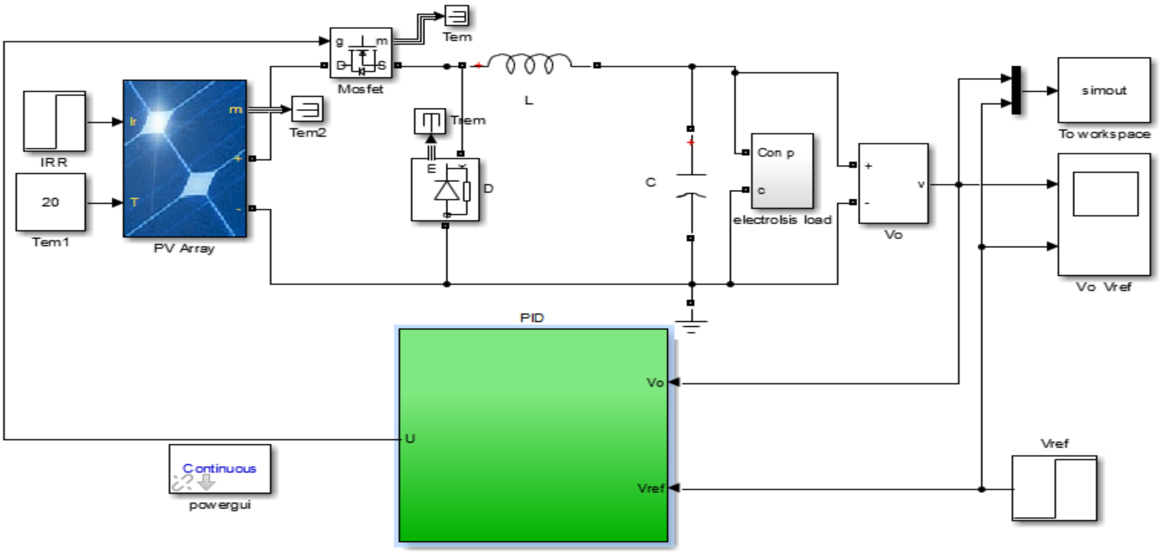


Figure 5. 2 MATLAB/Simulink model of buck converter with PID control.

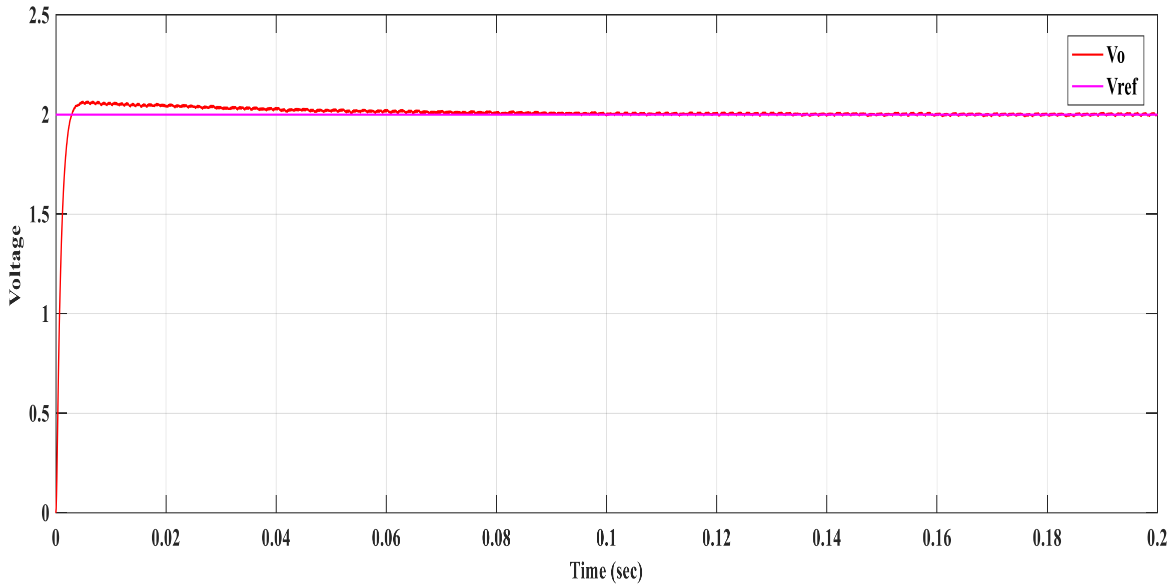
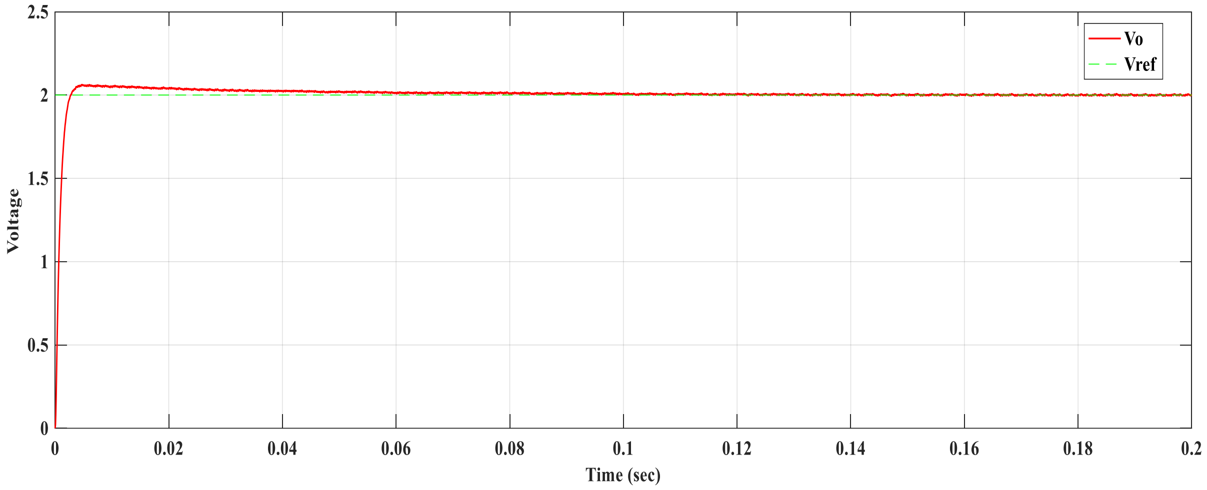


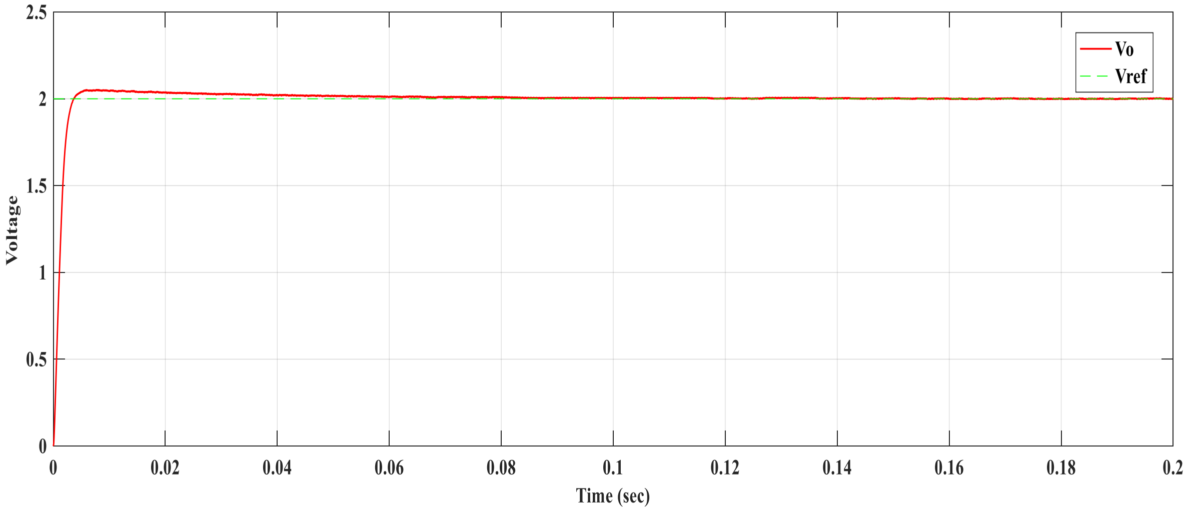
Figure5. 3 Output of a buck converter using PID controller.

The result obtained in Figure 5.3 above; using PID controller the overshoot is reduced from 46.3% to 5.208% compared with overshoot of a converter without controller.

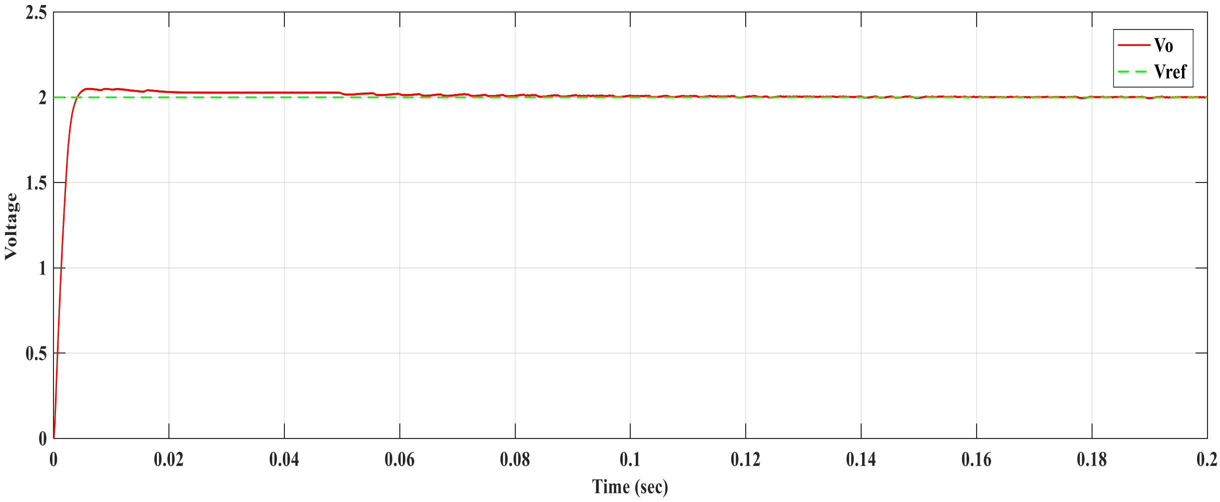
To test performance of a converter under input voltage variation, let increase a line voltage from 20V to 22V and decrease to 12V respectively. Increase and decrease the electrolysis load to test the effect of electrolysis load variation. Result is shown in the Fig 5.4 below.



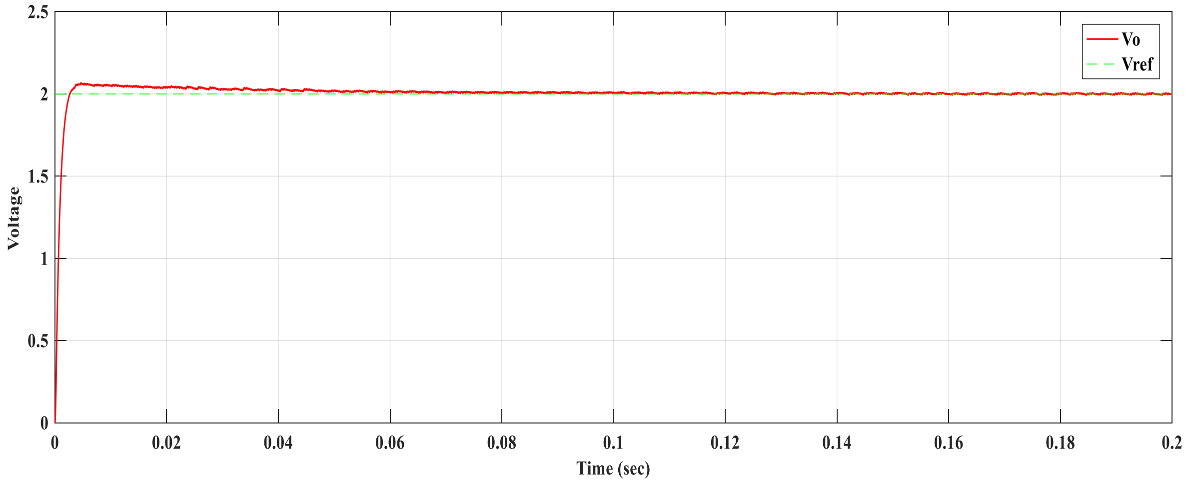
(a) Output voltage responses when Input voltage 20 V



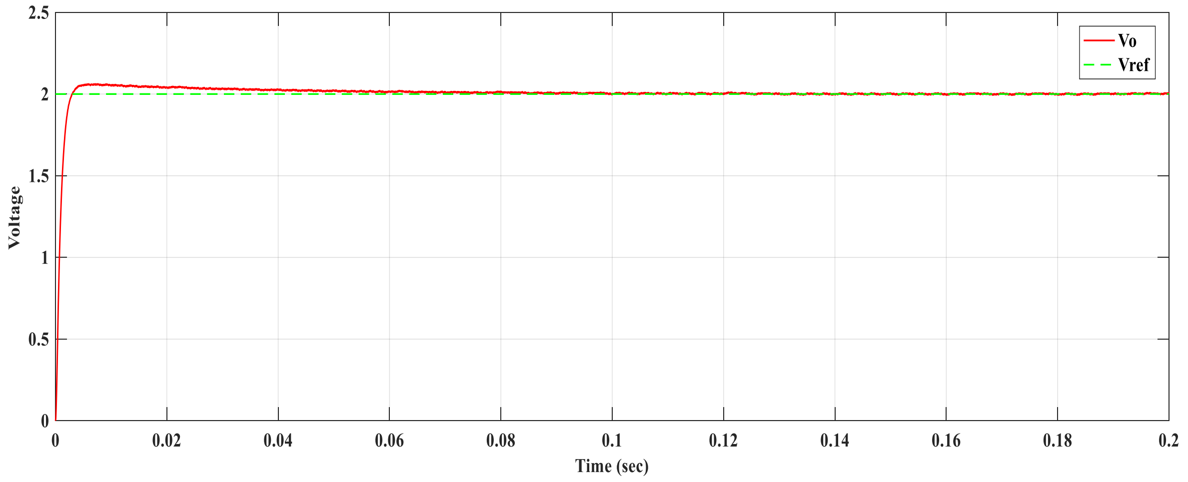
(b) Output responses when Input voltage changes from 20 to 15V



(c) Output voltage responses when Input voltage changes from 20 to 12V



(d) Output voltage responses when the electrolysis load increased at 20V input voltage.



(e) Output voltage responses when the electrolysis load decreased at 20 V input voltage.

Figure5. 4 Simulation results of buck converter by using PID controller under input voltage and electrolysis load variation.

The simulation result shows using PID controller, reducing the overshoot to with small value while the settling and rise time are increased (Figure 5.4). The output of a converter does not affected by variation of electrolysis load to have desired voltage (Fig 5.4 (c) and (d)). Similarly output voltage of a converter does not affected by decrease of input voltage from operating point (Figure 5.4 (b)). But for the increase in the input voltage from operating point the converter does not give constant desired output voltage by using PID controller. The overshoot is increased and the rise and settling time become longer (Figure 5.4 (a)). This is because of the buck converter is nonlinear system. But the linear controller was designed using ac small signal principle of a converter after linearization. Controller designed by small signal model methods was not able to react efficiently to a variation in operating point. So that using linear controller the desired output voltage does not obtained under increase in the input voltage from operating point. Therefore to overcome the disadvantage of linear controller, nonlinear controllers are required.

5.2. Performance of Buck Converter with SOSM Controller.

A buck converter performance is demonstrated with SOSM controller using in MATLAB/Simulink.

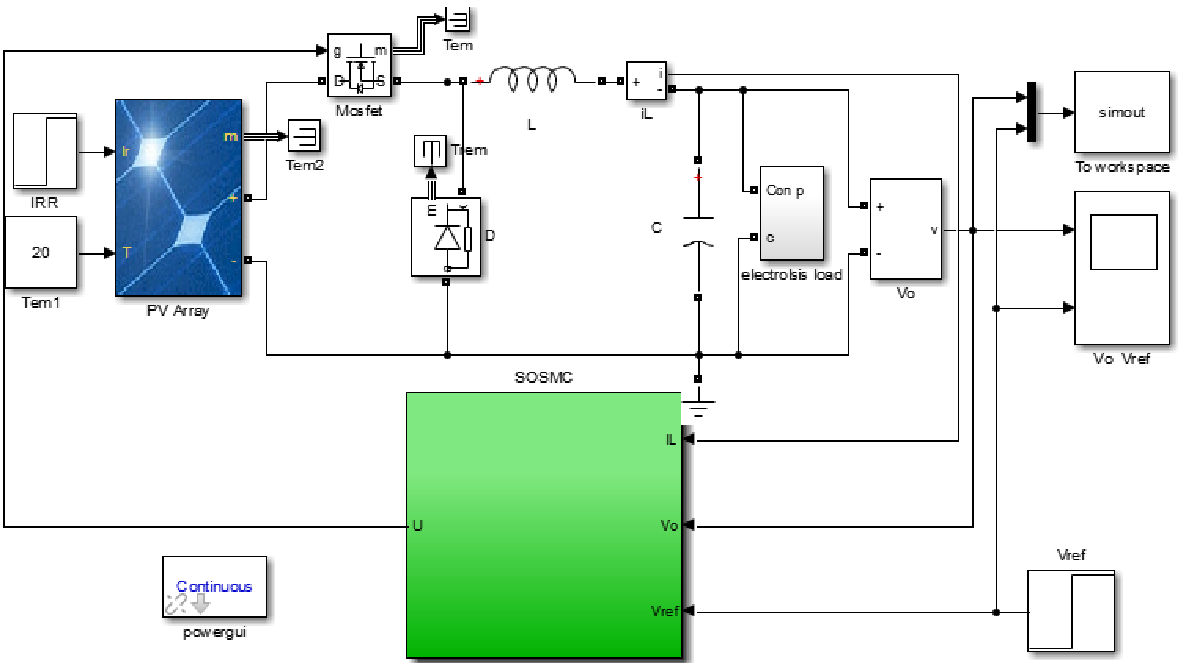


Figure5. 5 buck converter Simulink model with SOSM controller.

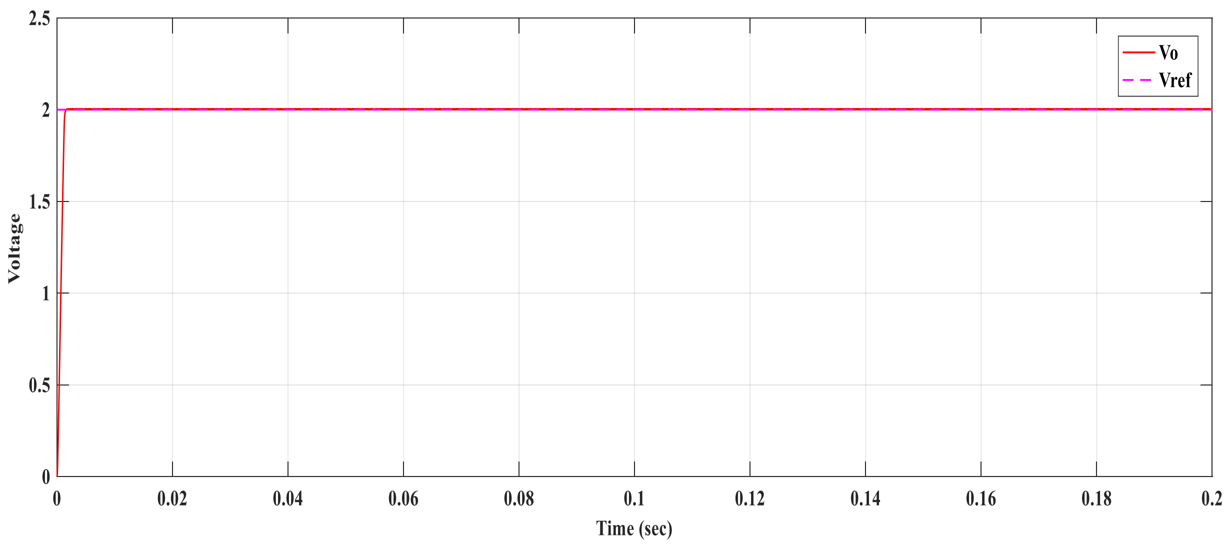
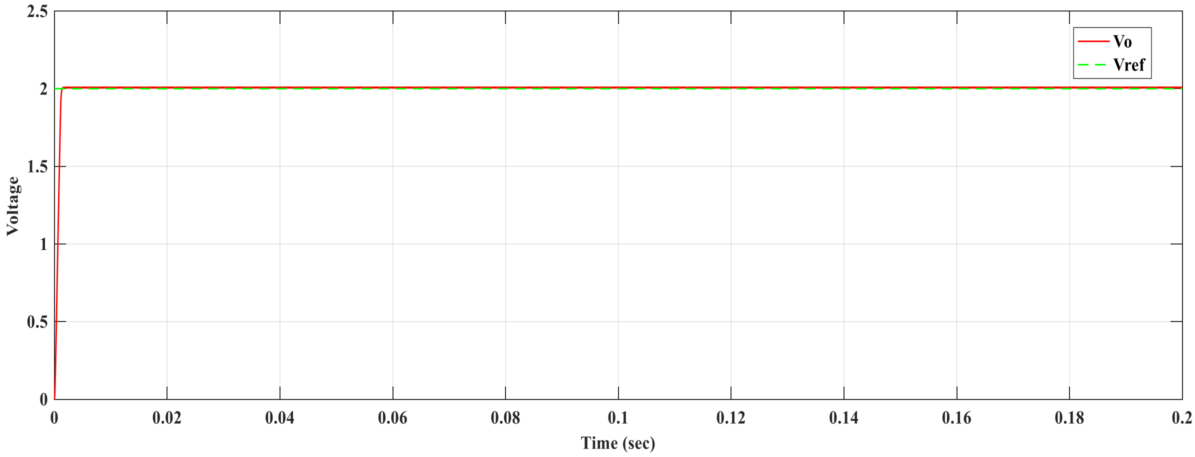


Figure5. 6 Output voltage of the converter with SOSM controller.

To test performance of a converter with SOSM controller under input voltage variation, the input voltage increased from 20 to 22V and decreased to 15V respectively. The simulation results are shown in Figure 5.7.



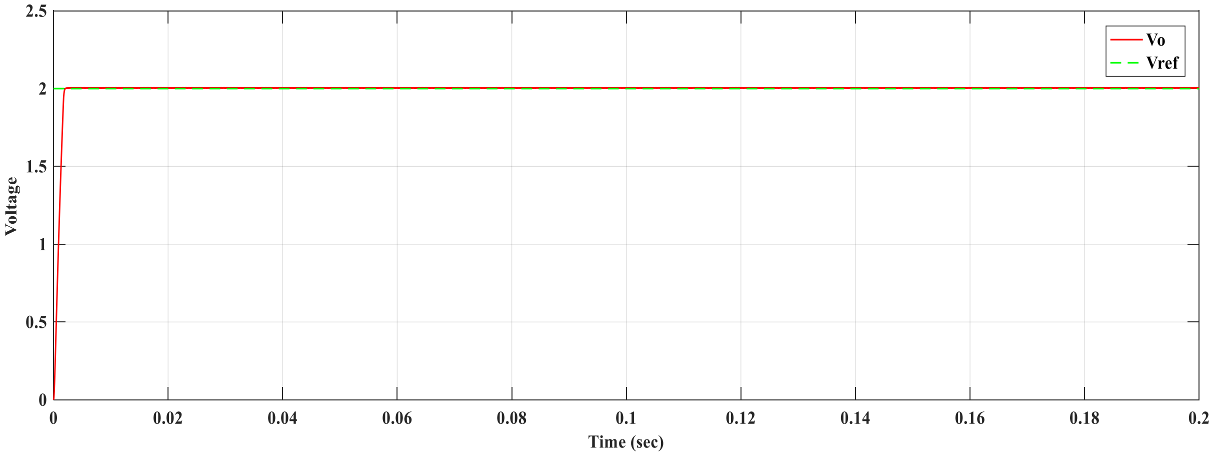


Figure5. 7 (a) Shows the output voltage when the input voltage increased from 20 to 22V, (b) Shows the output voltage when the input voltage decreased from 20 to 15V.

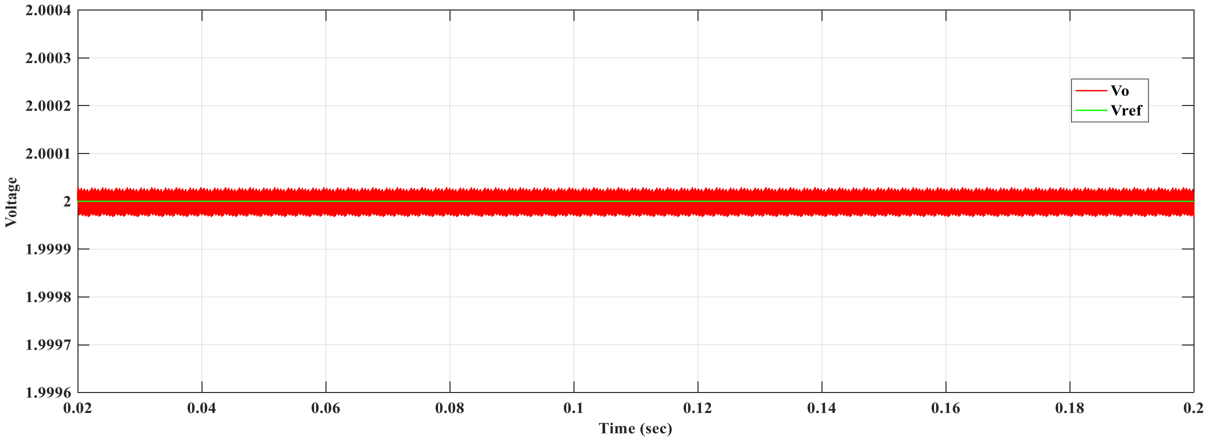


Figure5. 8 Chattering effect of SOSMC.

5.3 Performance of Buck Converter with Fractional Order Sliding Mode Controller

To demonstrate performance of converter with FOSM controller in Simulink, and using parameters values of a converter that are given in table 4.1. MATLAB/Simulink model of a buck converter using FOSM controller is given in Figure 5.9 below.

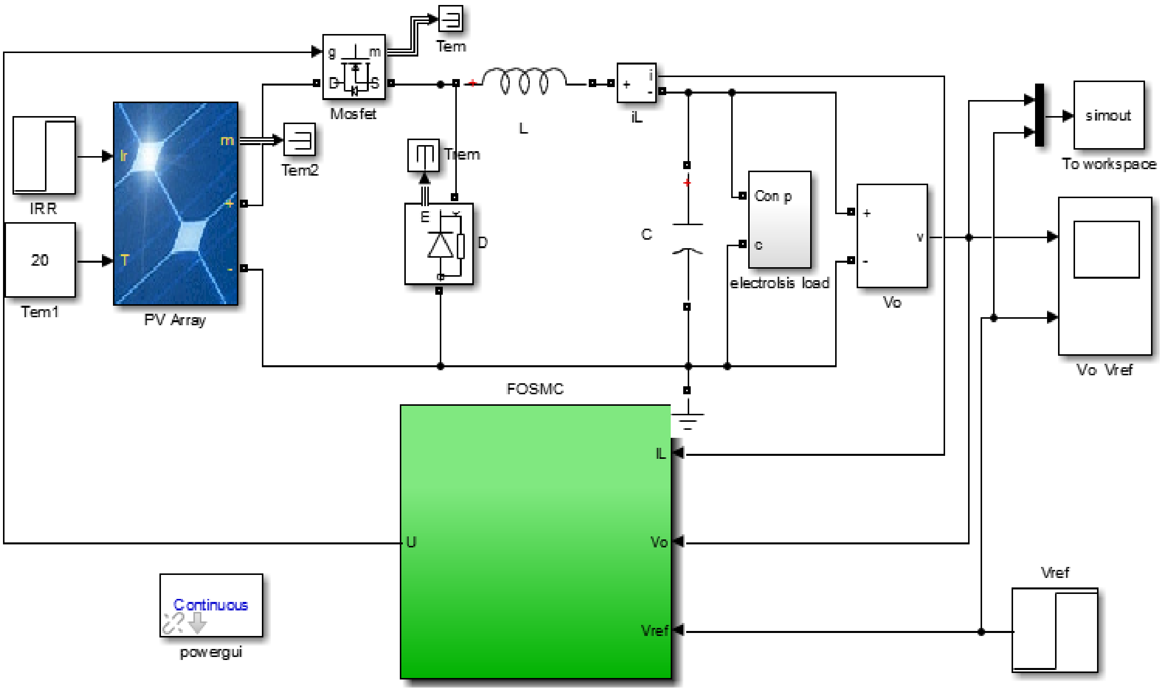


Figure5. 9 Simulink model of buck converter with FOSM controller.

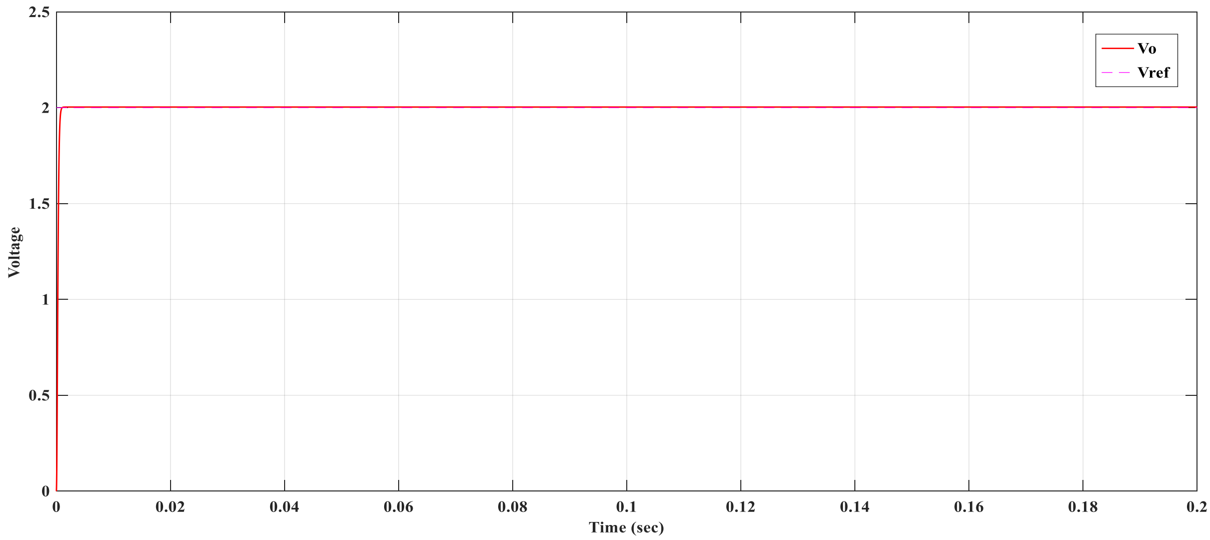


Figure5. 10 Output of the converter with FOSM controller.

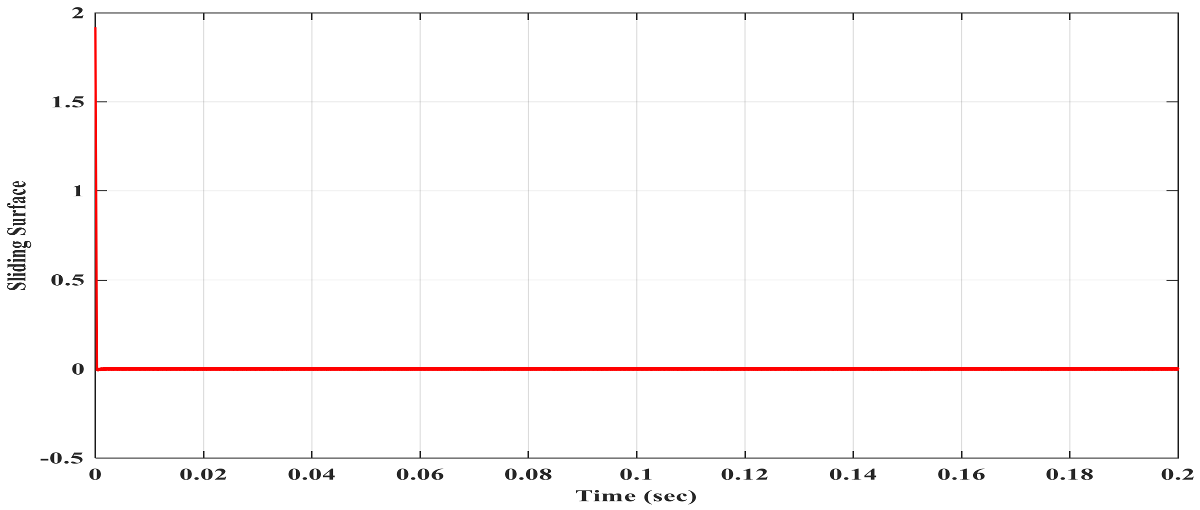


Figure5. 11 Sliding surface.

Figure (5.11) Shows that converter sliding surface comes to zero at 0.00014s (zero second). Besides to that, the sliding surface has no oscillation in another word there is no chattering throughout simulation time (0.2) seconds. This is one main objective of FOSM controller.

5.4 Performance of a Buck Converter with FOSM Controller under Disturbance in Line Voltage and Electrolysis Resistance

To test performance of converter with FOSMC under line voltage variation; increased the line voltage from 20 to 22V and decreased 15 and 12V respectively. Also to test the effect of electrolysis load variation, checked by increasing and decreasing the load. The results are shown in Figure 5.12 below

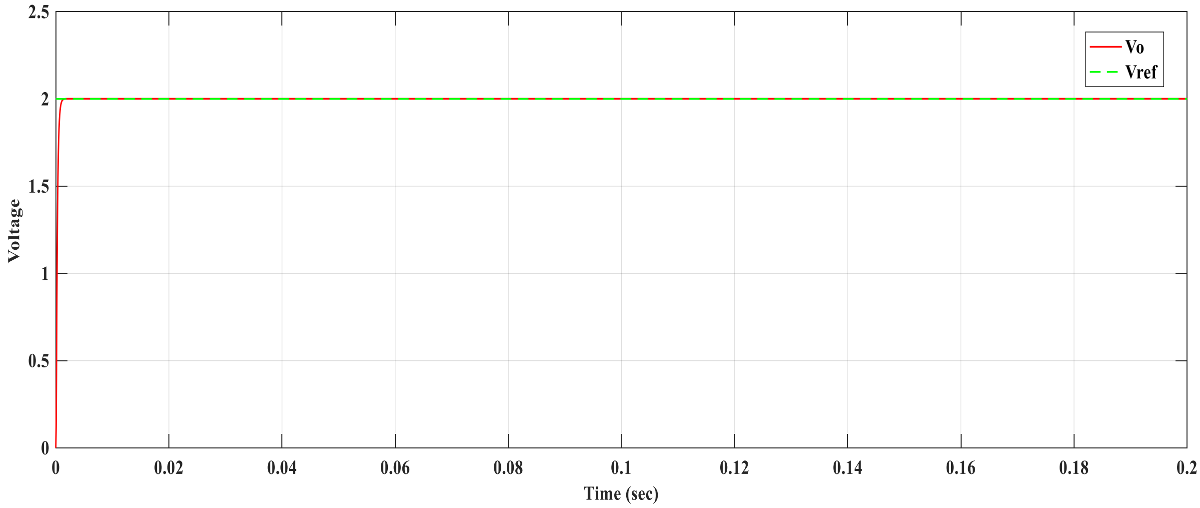


Figure5. 12 Shows the output voltage response when the input voltage is 20V

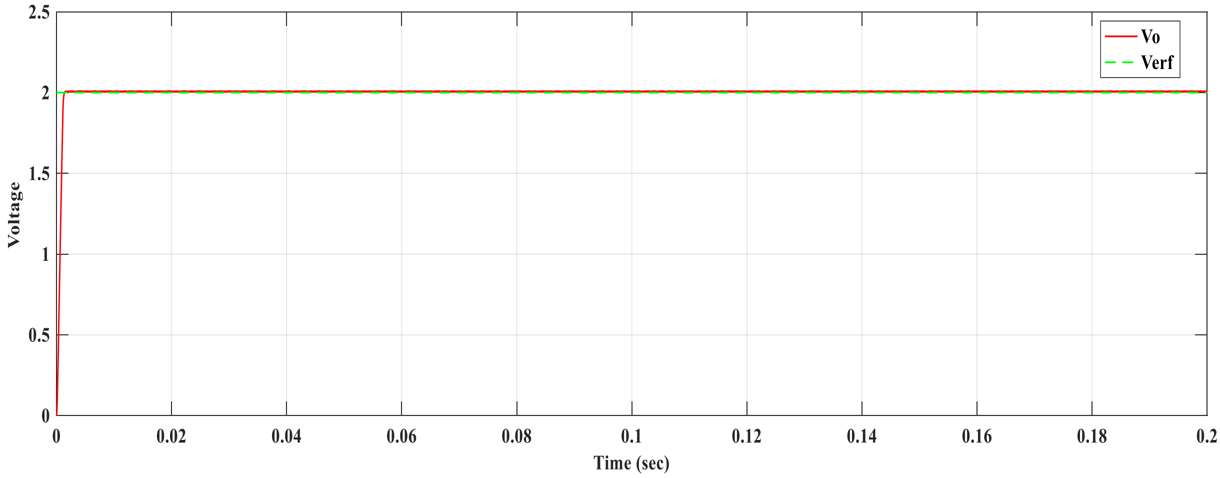


Figure5. 13 Output responses when Input voltage changes from 20to 22V

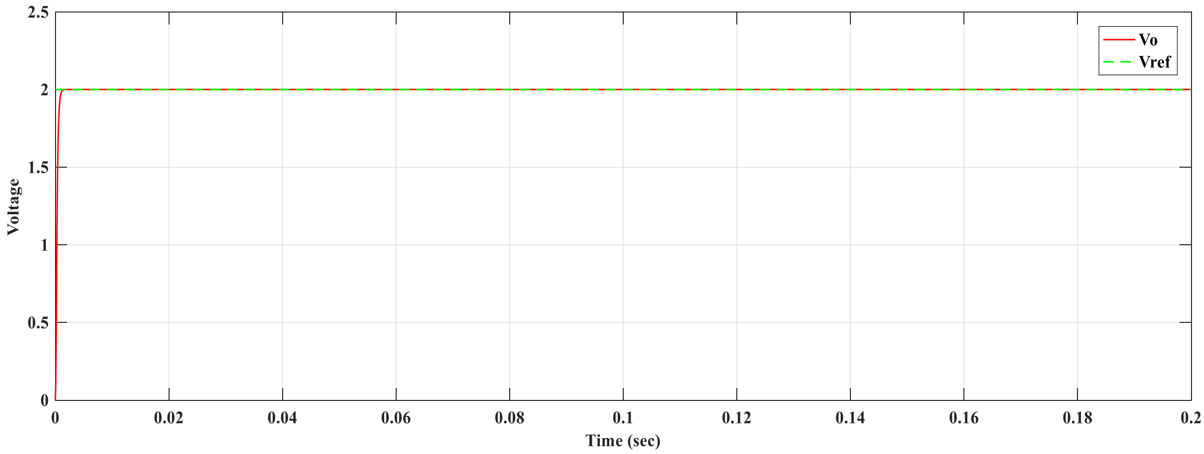


Figure5. 14 For input voltage change from 20 to 15V

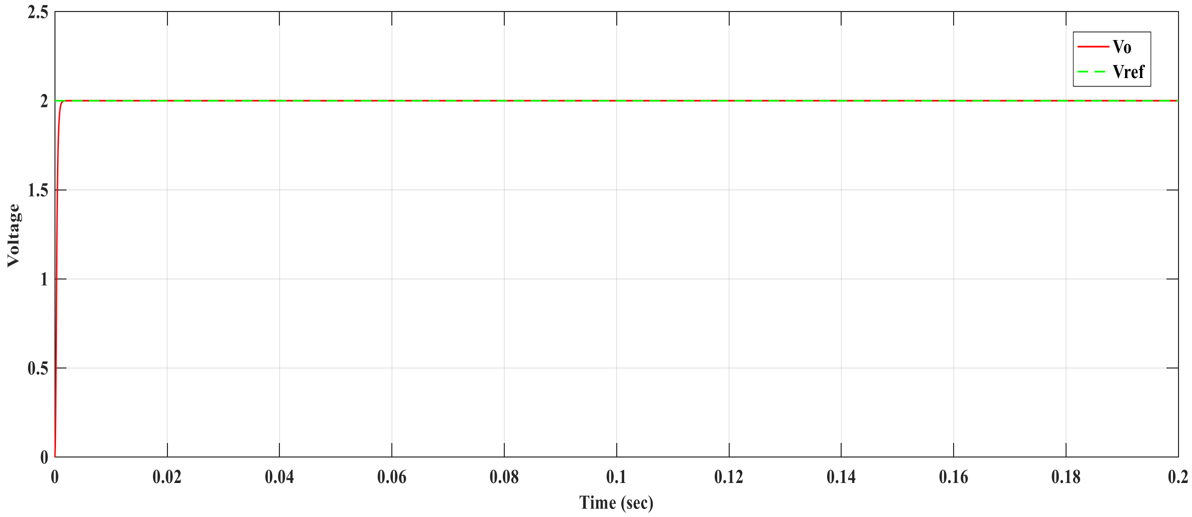


Figure5. 15 For input voltage change from 20 to 12V

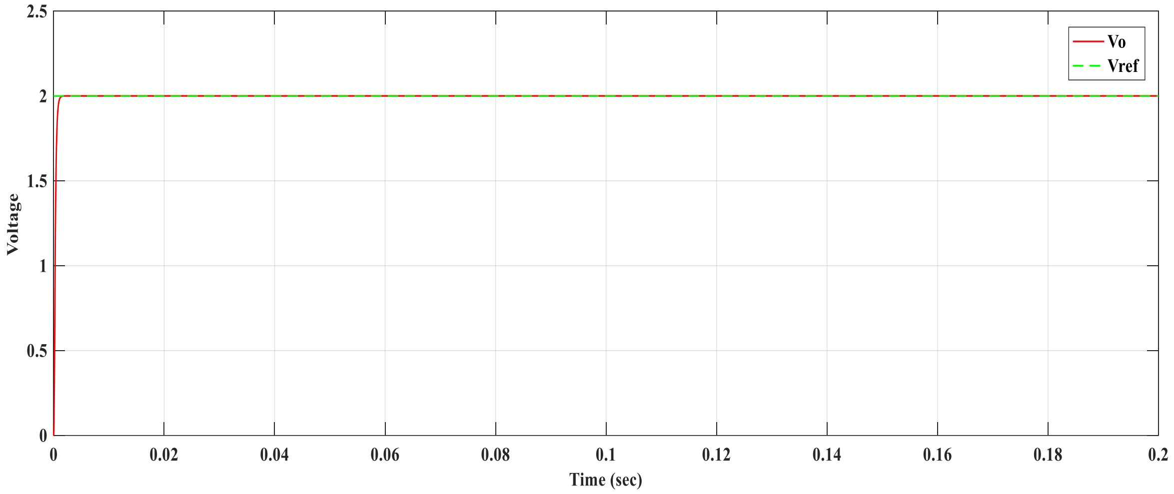


Figure5. 16 Output voltage responses due to the electrolysis load resistance increased

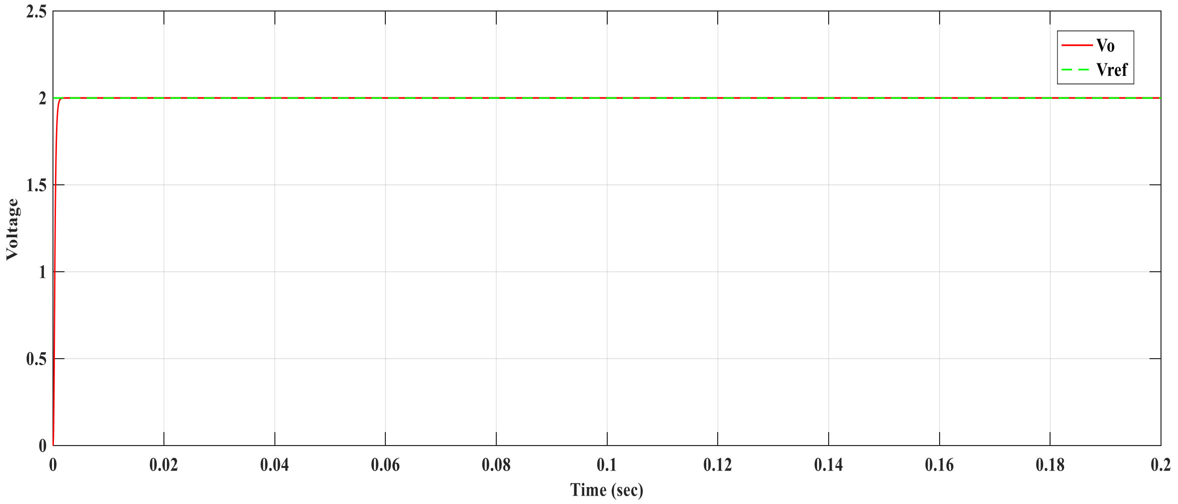


Figure5. 17 Output voltage responses when the electrolysis load resistance decreased.

From the result obtained in Figure above (Fig 13,14,15,16 and 17) using FOSM controller; the buck converter can overcome a line and electrolysis load variations. The desired and actual output voltages are overlaps. This shows converter output voltage does not affect by supply voltage and electrolysis resistance variations to give desired output voltage.

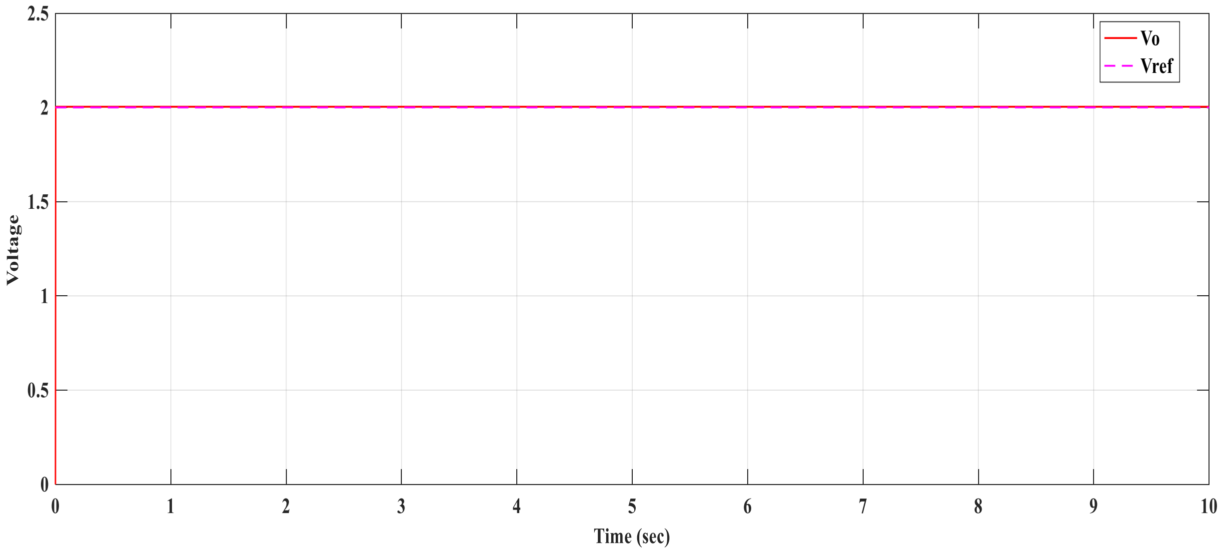


Figure5. 18 Shows the output voltage FOSM control when the input voltage is 20V

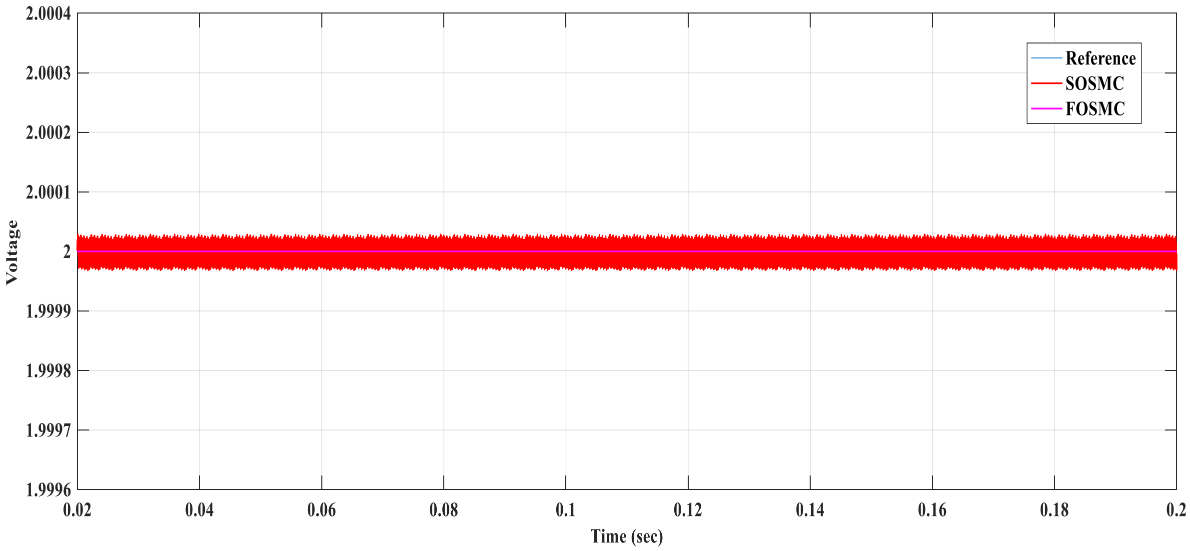


Figure5. 19 Chattering effects of SOSMC and FOSMC.

5.5 Performance Comparison of FOSM Control, SOSM Control and PID Control for Buck Converter

It is clear that fractional order based SM controller gives desired output voltage more rapidly than SOSM controller and PID controller. Rise and settling time are very small in the case of FOSM control compared to SOSM controller and PID controller.

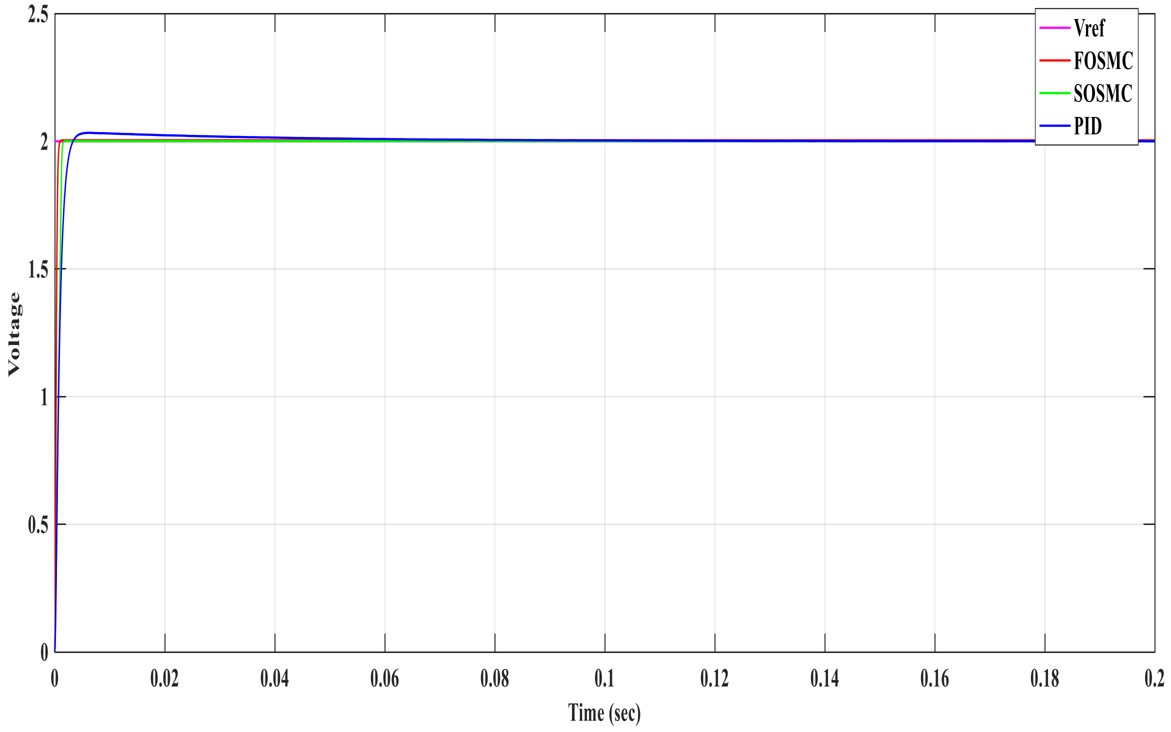


Figure5. 20 Output voltage of buck converter using PIP, SOSMC and FOSMC control.

The transient performance and the output voltage deviation from desired value for input voltage variation is given in the Table 5.2 below.

Table 5.1 Performance evaluation of PID, SOSM and FOSM

Controller	Rise time (ms)	Settling time(ms)	Overshoot (%)
PID	1.798	15.301	5.208
SOSM	0.00861	0.00587	0.501
FOSM	0.00405	0.00439	0.25

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATION

6.1. Conclusions

In this paper three different control systems for voltage regulation of a buck converter have been investigated. The first one is PID controller; the second methodology is SOSM technique, while the third method is fractional order sliding mode (FOSM) technique. The performance of buck converter is tested by MATLAB/Simulink for all controllers (under load variation and line variation). In the case of PID controller, the rise time and settling time is longer, but overshoot is reduced from 46.3% to 5.455%. The second order sliding mode controller revealed very smaller rise and settling time; while FOSM controller showed slight reduction in rise and settling time than SOSM controller. Overshoot is totally removed in both SOSM and FOSM controller. The variation of electrolysis load had no effect in SOSM and FOSM controller. PID controller cannot be produce desired voltage quickly, if supply voltage increases, while SOSM and FOSM controller withstand effect of increased line voltage and give desired output more rapidly. FOSM controller shows comparatively best performance improvement over SOSM in terms of high reduction of unwanted oscillation in addition to rise time, as well as settling time improvements. The FOSM controller is showing a promising future application of a buck converter to compensate converters non-linearity behavior. Finally, from the above arguments and results, it confirms that FOSM control technique is the most effective based on its rise time, settling time and precision.

6.2 Recommendations

Theoretically voltage regulation of buck converter designed using FOSM control has been validated by computer simulations; it would be useful to investigate its practical implementation.

Modification of the basic buck converter system model by replacing conventional IO inductor and capacitor by FO inductor and FO capacitor in the filter circuit, would give more precise control of output voltage than that in IO system. So, this could be another possible research topic.

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APPENDIX

A: Parameter Specification of Buck Converter

This converter is designed for low power application and high switching frequency. So that converter parameters value used for MATLAB/simulink is given as follows:

The switching frequency is 100 kHz.

The input voltage is taken as 20V.

The desired output voltage is 2V.

The load resistance is taken as 0.08Ω.

Assume the capacitor ripple voltage is 0.4% of the output voltage.

Now, based on these parameters it is possible to determine the minimum inductor that limits the boundary among the CC and DC mode. It can be also calculated the minimum capacitor to limit ripple voltage under certain value and to minimize overshoot.

The minimum inductor is given as,

$$L_{min} = \frac{(1-D)}{2f} \text{ R} = 300\mu\text{H}$$

The converter is designed for CCM only, so the inductor value should be larger than the minimum value. Therefore to ensure CCM of operation the value inductor; so that 500µH.

The minimum capacitor required is given by

$$C_{min} = \frac{(1-D)V_o}{8\Delta V_o \text{L} f^2} = 5.06776\mu f$$

To limit the value of ripple voltage under a certain value and to minimize the voltage overshoot, the value of capacitor should be greater than the minimum value. So that

$$C = 2500\mu f$$

Table 6.1 the parameters used to carry out the simulation studies.

No	Description	Parameter	Value	Unit
1	Input voltage	V_{in}	12-22	V
2	Reference voltage	V_{ref}	2	V
3	Capacitance	C	2500	µf
4	Inductance	L	500	µh
5	Load resistance	Ro	0.08	Ω
6	Switching frequency	F	100	KHz