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Voltage Controller for Simulating Transition between Boost –Buck -Boost Converter

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VOLTAGE CONTROLLER FOR SIMULATING TRANSITION BETWEEN BOOST –BUCK - BOOST CONVERTER

by

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In the present work, a voltage tracking controller is developed for DC-DC Buck-Boost converter using software model. The software developed can track the voltage and the mode of operation (Buck or Boost), which depends on the value of the duty cycle ratio (D). The error between V_{oref}(reference voltage) and output voltage is minimized by using step input as reference. The simulation results show that the designed software controller can successfully track the voltage with low error and with short settling time. The values for the Buck-Boost circuit components, the capacitor and the inductor, are tuned and selected so that the system is robust for large variation in the input voltage.

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Aula Jameel Al-Kamil

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol

V_o	Output Voltage
$Vref$	Reference Voltage
PWM	Pulse-Width Modulation
BJT	Bipolar Junction Transistor
IGBT	Insulated Gate Bipolar Transistors
D	Duty Cycle Ratio
$\Delta \boldsymbol{v_c}$	The Ripple Voltage
ΔI	The Ripple Currents
PID	Proportional Integral Derivative
PI	Proportional-Integral
DAQ	Data Acquisition Card
DC-AC	Direct Current to Alternating current
DC−DC	Direct Current to Direct current
DCM	Discontinuous Conduction Mode
CCM	Continuous Conduction Mode
NN	Neural Network
NFS	Neural Fuzzy Systems
ANNs	Artificial Neural Networks
RBS	Radial Basis Function
FLN	Functional Link Net
MLP	Multi-Layer Perceptron
OLNNC	Online Learning Neural Network Control
FLCs	Fuzzy Logic Controls
FALCON	Fuzzy Adaptive Learning Control Network
ANFIS	Adaptive Network based Fuzzy Inference System
FUN	Fuzzy Net

SONFIN	Self Constructing Neural Fuzzy Inference Network
PV	Photo Voltaic

CHAPTER 1

INTRODUCTION AND RESEARCH OBJECTIVE

1.1. Introduction and Background

The control of electric power or power condition is not usually used in the form in which it was generated or distributed. The power electronics circuit which transfers electric energy from the source to the load can be classified in different types. One of the most important types is the DC-DC converter.

Nowadays, DC-DC power converters are active devices in a variety of applications, including power supplies for personal computers, telecommunications, and office equipment [1]. The switched mode DC-DC converters are some of the simple power electronic circuits that can convert one form of DC energy into another DC form, so it can provide high efficiency, smooth acceleration control and fast dynamic response [2]. There are three basic topologies of switching regulators that can be used to transfer energy from input to output [1]. In general, the basic types of DC-DC converters are voltage step-down, voltage step-up and voltage step-up-down**.** Several algorithms and techniques have been developed to control the operation of DC-DC converters [3]**.** One of the most important DC-DC converters is the Buck-Boost converter [1]. It is a type of switched mode power supply that has an output voltage might be less than or greater than the input voltage [4]. It's known as an inverting converter because the output voltage polarity is the opposite the input voltage. It is typically used in industrial applications, and these converters are particularly helpful for PV maximum power tracking purposes and as a step down/up DC transformer. Usually there are two modes of operation DC-DC converters: continuous and discontinuous. In the continuous mode, the output current of the converter never falls to zero. In the discontinuous mode, the output current falls to zero during the time when the switch is turned off [5]. There are wide range of topologies to DC-DC converters. Simplicity, specificity, robustness, efficiency, and effectiveness are main differences in the use of the topologies. Generally used control methods for DC-DC converters are pulse width modulated (PWM) voltage mode control, PWM current mode control with proportional (P), proportional integral (PI), in addition to proportional integral derivative (PID) controller, Neural network, fuzzy controller, or hybrid control system methods [5].

Therefore, the objective of this thesis is to improve the voltage tracking performance of a DC-DC Buck-Boost converter.

1.2. Problem Statement

In a DC-DC converter, a controller is designed to control the converter's operation and obtain regulated output, improved efficiency, and provide a smooth transition despite variations in input voltage or the change in load conditions. Mathematical linear control theory has been used to obtain the control laws for the DC-DC converters. However, the switching technique of the DC-DC converter causes the system to be nonlinear. To improve DC-DC converter's performance, intelligent controllers have been used. These controllers are based on different techniques; some of them need offline training, some are complex and time consumptions, high overshoot and long settling time that characterized the performance of other controllers.

CHAPTER 2

LITERATURE REVIEW

Controller design of controllers for DC-DC converters have been studied by many researchers. Al-Isawi and Al-Nabi proposed how to design a compensator for continuous conduction mode of the feedback PID controller for the buck boost converter system. From their work, the small signal of the Buck- Boost is derived to find the line-to-output then control-to-output transfer functions. They designed a feedback controller and a system stability [6]. In another study, A. Bakar et al. discussed a neural network control scheme of a DC-DC Buck-Boost converter by using online learning method. In this method, a back-propagation algorithm is used to stabilize the output of the converter voltage and to improve performance of the converter through transient operations [7].

Vijayalakshmi and Raja designed a discrete PID controller control system of the converter by using digital PWM technique. The controller is designed by simulating the converter using MATLAB/Simulink [8]. The aim of their method is to improve the dynamic performance and to achieve robust change in the circuit components and input load variations.

Sahin and Okumus proposed an FLC of the Buck-Boost DC-DC converter of a PV for a battery-load System [9]. Reshmi et al. used the hybrid fuzzy PI controller to achieve output voltage with less variation [10]

Utomo, W. M. et al. presented an online learning neural network control (OLNNC) technique for Buck-Boost converter. They designed a neural network control system intended to stabilize the output voltage of the Buck-Boost DC-DC converter through transient operations to improve its performance [7]. To investigate the effectiveness of the planned controller, some processes in this system such as starting-up and reference voltage variations are confirmed. The mathematical simulation results from this system is for a back-propagation algorithm. When comparing this controller and the conventional PI-Controller for this system, OLNNC performance better than the PI-Controller. The advanced OLNNC has the ability to learn immediately and adapt its own controller parameters based on outside disturbance overshoot, rise time of the output voltage, and internal variation of the converter with minimum steady state error. Simulation results show that the OLNNC is effective and it has a fast response to track desired output voltage.

Rubaai, A. et al. presented how to control DC-DC converter by combining fuzzy inference system and neural networks within the framework of adaptive networks. DC–DC converters are usually divided into two groups, hard-switching converters, and soft-switching converters. In hard-switching converters, the power switches cut off the load current in the turn-on and turn-off times. By adjusting the ON time of the power switch, the output voltage is controlled [3]. In soft-switching converters, the resonant components, are used to make current waveforms or oscillatory voltage go to zero before the power switches are turned off. The advanced adaptive network-based fuzzy inference system (ANFIS) can learn about the nonlinear dynamics and outside disturbances of the converter in order to produce a stable output, fast disturbance rejection, and small steady error [3]. Research have been done to verify the validity of the suggested ANFIS and to provide well-regulated DC–DC power conversion, efficiency, and reliability. There is another the other features of the controller are lower implementation cost, higher fault tolerance and higher flexibility [3].

Shaker et al. have used two different methods to design controllers for DC motors drives applications. They used Gaussian membership function in fuzzy logic control and back-propagation algorithm used in neural network control. They designed and simulated Buck –Boost converter with MATLAB/Simulink simulation [11]

2.1. Goals and Objectives

The objective of this work is to design a software model controller for the DC-DC Buck-Boost converter that can successfully track the voltage with minimum error, short settling time, short rising time, less overshoot, and smooth switching between Boost-Buck operation.

CHAPTER 3

ANALYSIS AND MODELING OF DC-DC BUCK-BOOST COVERTER

3.1. DC-DC Converter

A DC–DC converter is an electronic circuit that converts any DC voltage level to another desired and regulated dc voltage [2]. It converts a DC input voltage, $v_g(t)$, to a DC output voltage, $V_o(t)$, with a magnitude. To control the output voltage, by the control signal δ(t), the converter includes one or several transistors(s). Figure 3.1 below shows DC-DC converter as a black box

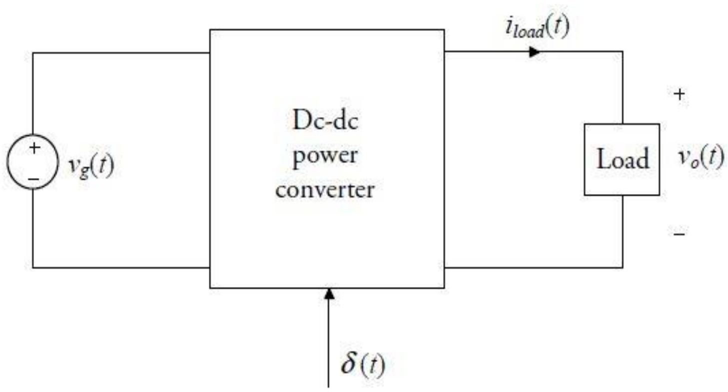

Figure 3.1 A DC-DC Converter [12]

DC-DC power converters are active agent in variety of application such as computers, traction motor control in electric automobiles, and input source for some of equipment. They provide high efficiency, smooth acceleration control, and fast dynamic response. There are two types of DC-DC converters; linear and switched. Switched converters have several advantages over linear converters. For example, the passive components are smaller, lower losses, and have simplified thermal management because of the higher switching frequency. Also in a switching converter, the energy stored by an inductor is transformed to the output voltage [4]. The input voltage from the Buck converter is bigger than the output voltage.

The input voltage from buck is bigger than the input voltage from Boost or Buck-Boost. The Buck-Boost has reverse polarity at the output, through a transformer the input voltage can be transferred to supply electrical isolation between the input and the output. The type of inductor based for the buck or boost and Buck-Boost are non-isolated DC-DC converter. The input to a DC-DC converter is an unregulated voltage but the output is regulated.

3.1.1. DC-DC Converters Switching Mode Regulators

A DC-DC converter can be used to regulate DC voltage. The regulation is normally accomplished by using PWM to switch a transistor at fixed or variable frequency [1,4]. DC-DC converters may be connected in series / parallel to invert voltage polarities and for increase or decrease in the magnitude of the DC voltage. There are for basic topologies of switching converters that can be used to transfer energy from input to output using diodes, inductor, capacitors, and a power switches. The three basic topologies are [1].

- Buck regulators
- Boost regulators
- Buck-Boost regulators

3.2. Buck Converter

It is a voltage step –down DC-DC converter with the average output voltage less than the input voltage [4].

3.2.1. How Does a Buck Converter Work?

In a Buck converter, an inductor and capacitor are used to store energy and aperiodic switch is used to transfer the energy from input to the output [1,13]. The switch is turned (time on t_{on}) and off (time off t_{off}) and the period is T

T=t_{on}+ t_{off} (3.1)

and the duty cycle ratio is given by

D=ton/T (3.2)

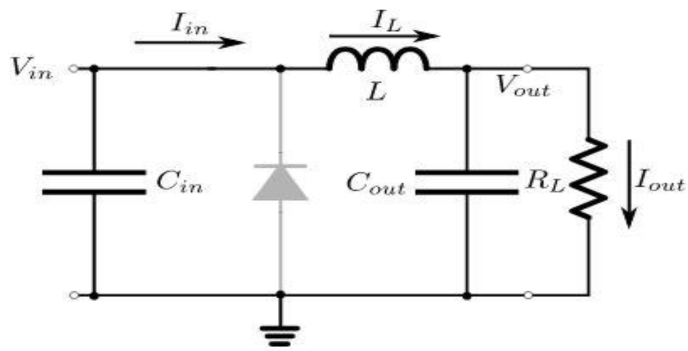

Figure 3.2 Buck Converter Circuit (Switch Closed) [13]

When the switch is on, the inductor capacitor is charged and power is supplied to the load. Equation (3.3) and (3.4) describe the mode when the switch is on. Equation (3.3) shows the rate of rise of charge in the inductor and (3.4) is current change in the inductor.

$$\frac{dI_L}{dt} = \frac{V_{in}-V_{out}}{L} \quad (3.3)$$

$$\Delta I_L^+ = \frac{V_{in}-V_{out}}{L} t_{on} \quad (3.4)$$

where V_{in} is the input voltage and V_{out} is the output voltage.

In the mode, when the switch is off, the inductor discharges into the load. Equation (3.5) shows the rate of the discharge of the current in the inductor [13].

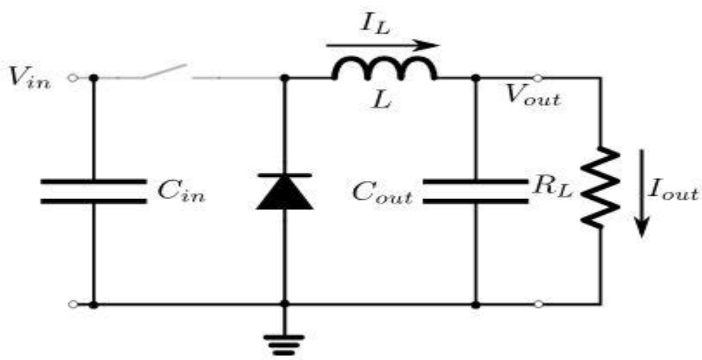

Figure 3.3 Buck Converter Circuit (Switch Open) [13]

$$\frac{dI_L}{dt} = \frac{0 - V_{out}}{L} \tag{3.5}$$

During the overall cycle at different time a buck converter (step down) can be more clarified by investigative the current waveforms [13]. The input voltage is greater than the output voltage and the average input current is less than the average output current. For a good design Buck converter, efficiencies greater than 85% may be expected [13]. The Figure 3.4 shows the waveforms of the Buck converter.

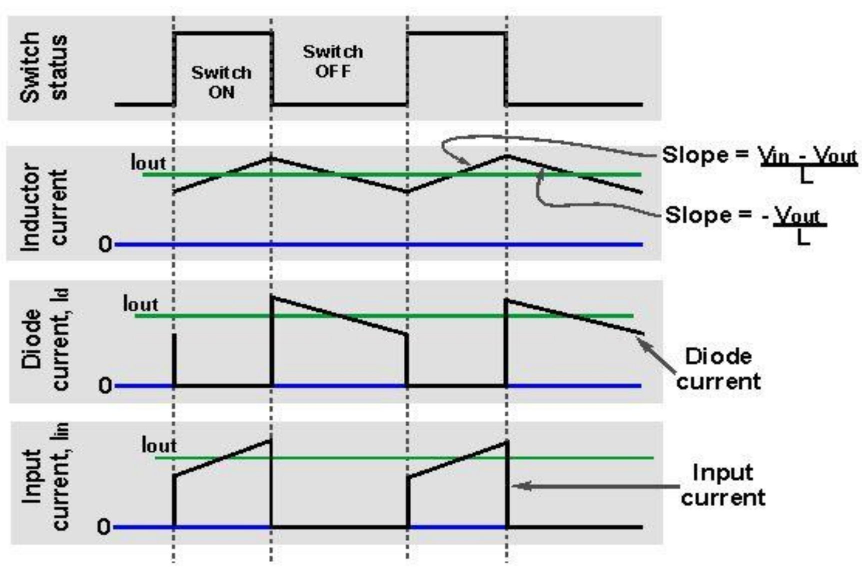

Figure 3.4 Current Waveforms for the Buck Converter [13]

3.3. Boost Converter

The Boost converter, shown in Figure 3.5, is a one type of switch DC-DC converter in which the input voltage is less than the output voltage, it is using a power MOSFET in power switching [1,14]

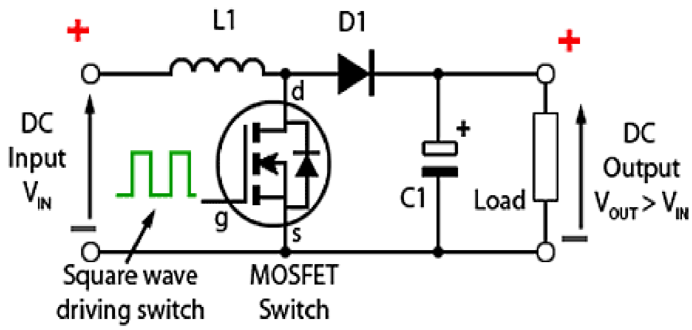

Figure 3.5 Boost Regulator Circuit [14]

3.3.1. How Does a Boost Converter Work?

Figure 3.6 shows the circuit behavior when the switch is turned on [1,14]. The diode is reversed biased and the inductor is charged. The charge stored in the capacitor is used to supply the load [14].

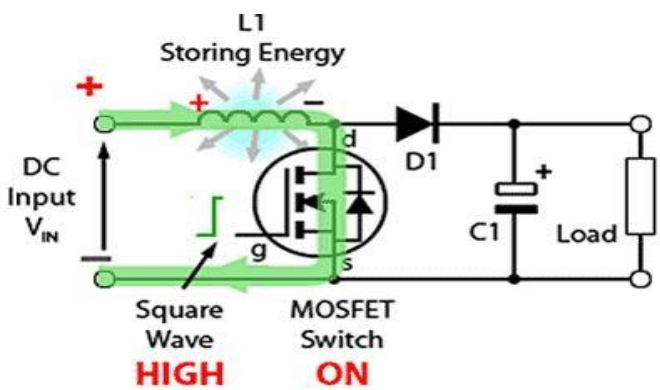

Figure 3.6 Boost Converters Act at Switch ON [14]

Figure 3.7 describes the converter when the switch is turned off. The charge in the inductor is used to supply the load (in addition to being charged by the input voltage) [14].

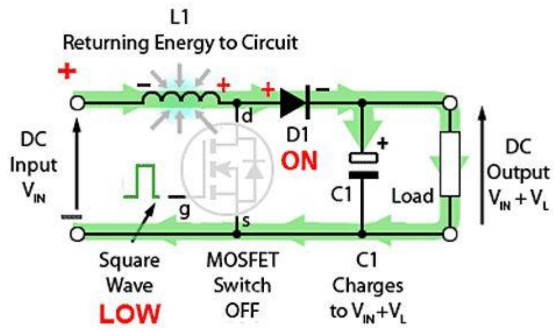

Figure 3.7 Current Path with MOSFET OFF [14]

Figure 3.8 shows the capacitor discharging

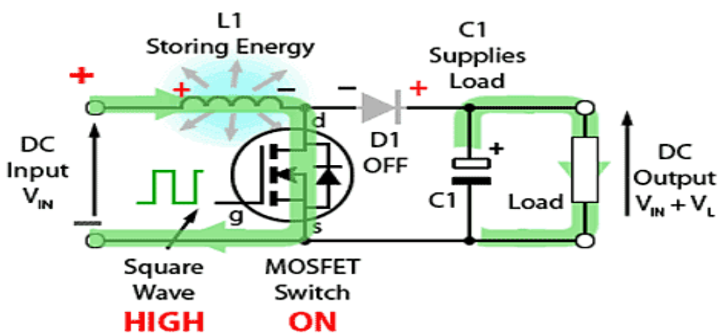

Figure 3.8 Current Path with MOSFEET ON [14]

3.4. Buck-Boost Converter

The Buck-Boost converter has an output voltage less than or greater than the input voltage. This DC-DC converter is typically used in industrial applications and helpful for PV maximum power tracking purposes [1,15].

Buck–boost converter is known as an inverting converter. The output voltage polarity is the opposite the input voltage. The converter combines the principles of Boost and Buck converters [14].

3.5. Design of Buck-Boost Converter

The schematic diagram of Buck-Boost converter is Figure 3.9

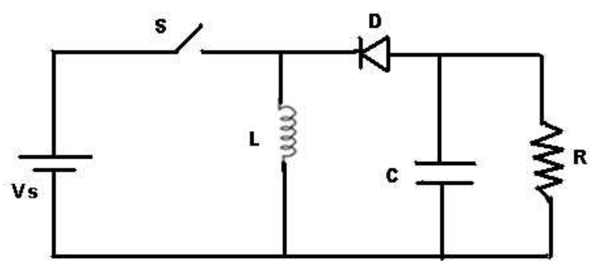

Figure 3.9 Schematic of Buck-Boost Converter [8]

The input voltage is V_s and the output voltage is V_o the relationship between the input voltage and the output through this equation

$V_o = V_s$ d/(1-D) (3.6)

where is D is the duty-cycle ratio.

The current ripple in the inductor and voltage ripple in the capacitor are given by (3.7) and (3.8), respectively.

$$\Delta I = \frac{V_{in}\ D}{L} \quad (3.7)$$

$$\Delta v_c = \frac{I_o\, D}{f_c} \quad (3.8)$$

where I_o is the output current and f_c is the switching frequency.

There are several topologies of the Buck-Boost converter including the fallowing: Figure 3.10 shows a converters circuit when the switch is off. The polarity of the output voltage is negative.

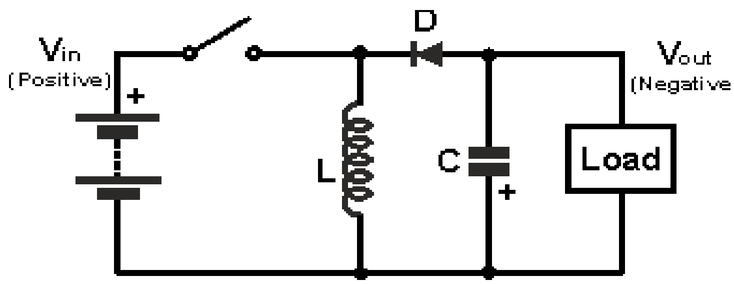

Figure 3.10 Buck-Boost Converter Circuit Uses Similar Number of Components [15]

Figure 3.11 shows a Buck-Boost converter circuit with two switches (SW1 and SW2) that work together; the switches are opened and closed at the same time [15]. The input voltage and output voltage have the same polarity.

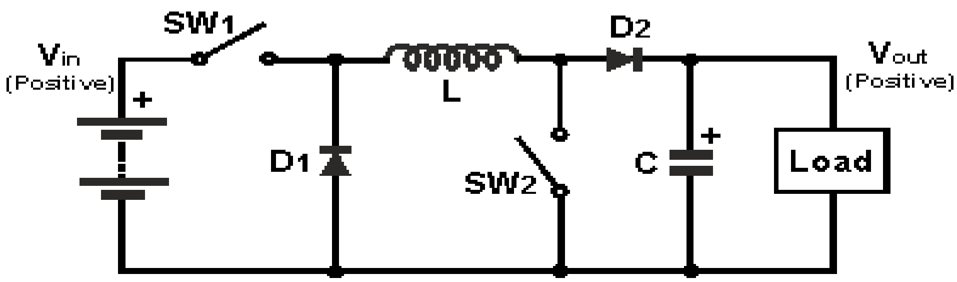

Figure 3.11 Buck-Boost Converter Circuit with the Same Input and Output Polarity [15]

3.5.1. Buck–Boost Converter in Continuous Conduction Mode

The current through the inductor never goes to zero and remains continuous [16].

Figure 3.12 shows waveforms of voltage and current for Buck- Boost converter in continuous mode

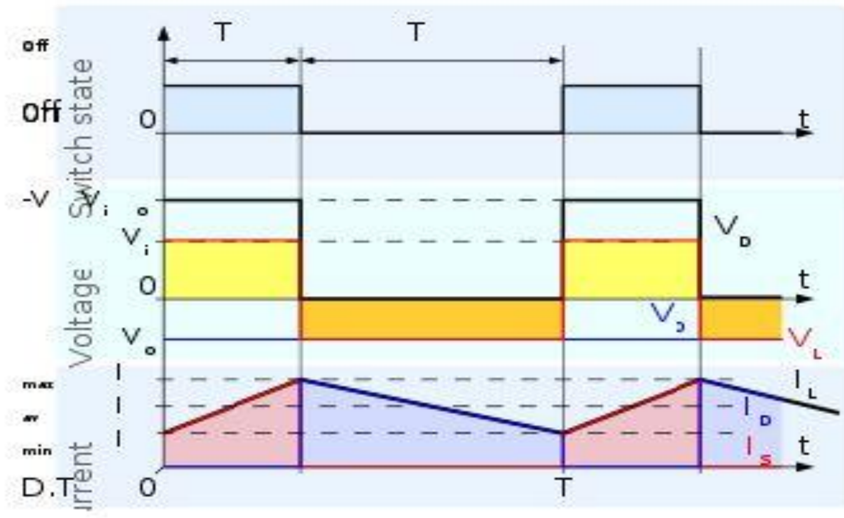

Figure 3.12 Voltage and Current Waveforms for Buck-Boost Converter Operation in CCM [13]

The current through the inductor never falls to zero during a commutation. cycle. Figure 3.13 shows the timing on the waveforms.

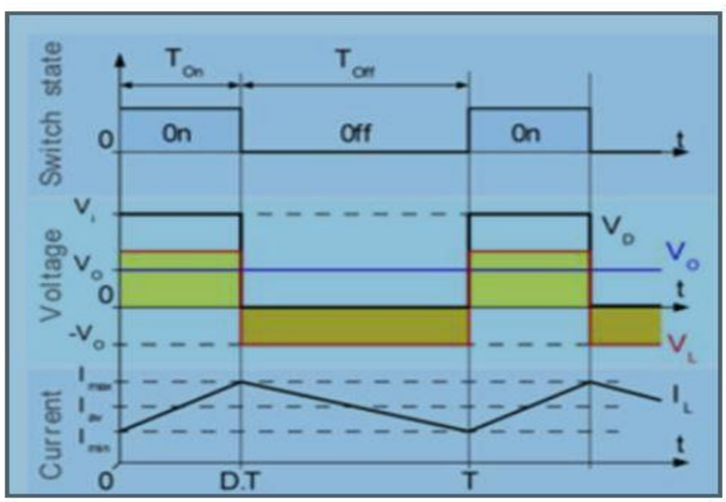

Figure 3.13 Timing of the Waveforms [16]

When the switch is closed, the converter is in on-state from $t = 0$ to $t = DT$.

The rate of change in the inductor current is given by

$$\frac{dI_L}{dt} = \frac{V_i}{L} \tag{3.9}$$

where V_i is the input voltage.

The inductor ripple voltage is given as

$$\Delta I_{LON} = \int_0^{DT} dI_L \quad = \int_0^{DT} \frac{v_i}{L} dt = \frac{v_{i\ DT}}{L} \tag{3.10}$$

The duty cycle ratio *D*, represents the fraction of the period *T* when the switch is on.

When the switch is ON, the inductor also supplies the load current flows by the load. The charge on the capacitor maintains the output voltage constant.

When the switch is off, the rate of discharge of the inductor is given by

$$\frac{dI_L}{dt} = \frac{V_0}{L} \tag{3.11}$$

The ripple current in the inductor is given by

$$\Delta I_{Loff} = \int_0^{(1-DT)} dI_L = \int_0^{(1-DT)} \frac{v_o\, dt}{L} = \frac{v_{o\,(1-D)\,T}}{L} \tag{3.12}$$

The energy in the inductor is given by

$$E = \frac{1}{2} L I^2{}_L \tag{3.13}$$

The sum of the energy stored in the inductor when the switch is on and when the switch is off must be zero [16] that is,

$$\Delta IL_{ON} + \Delta IL_{OFF} = 0 \tag{3.14}$$

substituting ΔIL_{ON} and $+\Delta IL_{OFF}$ from (3.10) into (3.14) leads to

$$\Delta IL_{ON} + \Delta IL_{OFF} = \frac{V_i\ DT}{L} + \frac{V_O\ (1-D)T}{L} = 0 \tag{3.15}$$

This can be written

$$\frac{V_0}{V_i} = \frac{-D}{1-D} \tag{3.16}$$

And duty cycle ratio is given as

$$D = \frac{V_o}{V_o - V_i} \tag{3.17}$$

The polarity of the output voltage is continuously negative, and depending on the value of *D*, converter can either be step-down (as a Buck converter) or step-up (as Boost converter) [13,16].

3.5.2. Buck–Boost in Discontinuous Conduction Mode

The current through inductor goes to zero, and the inductor is completely discharged [16]. Figure 3.14 shows waveforms of voltage and current for Buck Boost converter in discontinuous conduction mode

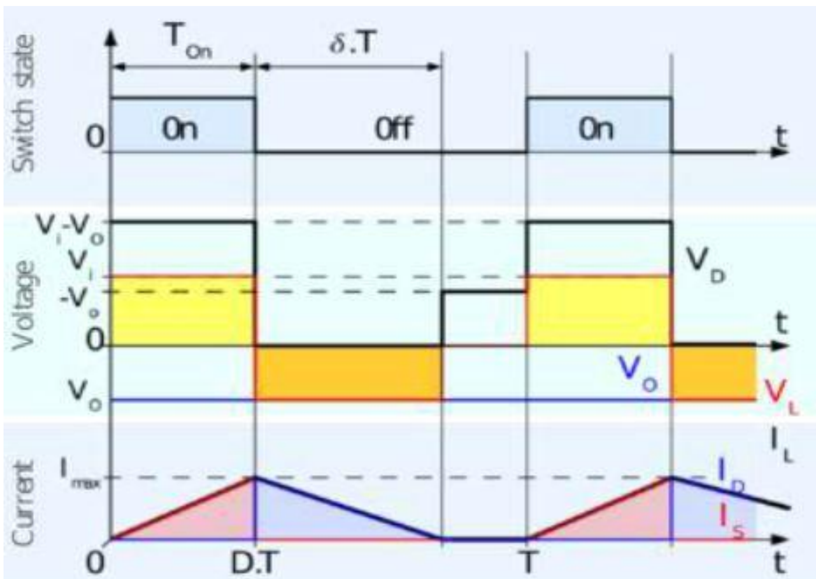

Figure 3.14 Voltage and Current Waveforms of the Buck–Boost Converter Operation in DCM [16]

Within the turn-off period the current in the inductor goes to zero. [13,16].

The maximum current (during the on-time) in the inductor is given by

$$I_{Lmax} = \frac{\boldsymbol{V_i\ DT}}{\boldsymbol{L}} \tag{3.18}$$

The current in the inductor goes zero after δT

$$I_{Lmax} + \frac{V_o\ \delta T}{L} = 0 \tag{3.19}$$

And from (3.19) δ is given by

$\delta = -\frac{V_i \ D}{V_o}$ (3.20)

The load current I_L and the average diode current I_D are equal, as shown in the Figure 3.15

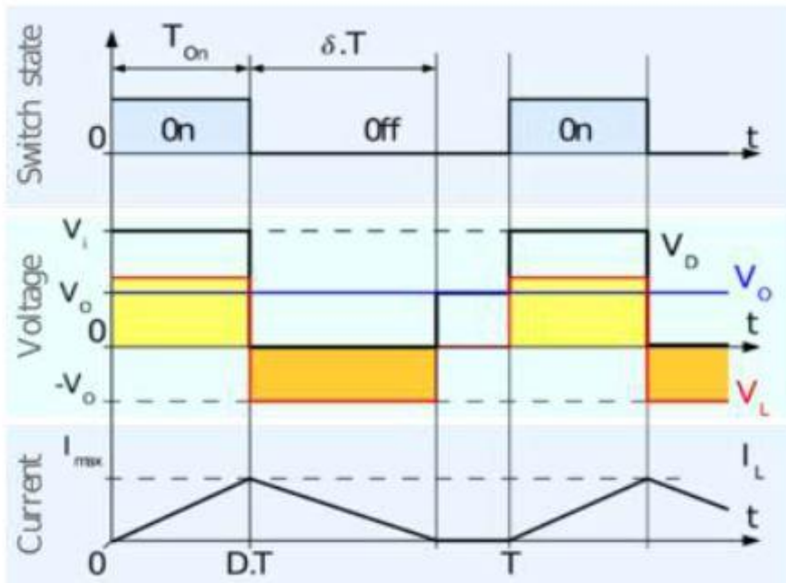

Figure 3.15 Voltage and Current Waveforms Showing Buck Converter Operation in DCM [16]

The output current can be written as

$I_o = I_{\bar{D}} = \frac{I_{Lmax}}{2}\delta$ (3.21)

Substituting I_{Lmax} from(3.18) and δ from (3.20) into (3.12) leads to

$I_o = -\frac{V_i \, DT}{2L} \frac{V_i \ D}{V_o} = -\frac{V_i^2 \, D^2 \, T}{2Lv_o}$ (3.22)

From (3.22) the output gain voltage is given as

$\frac{v_o}{v_i} = -\frac{v_i \, D^2 T}{2LI_o}$ (3.23)

In discontinuous operation, the output voltage depends on the input voltage, inductor value, duty cycle ratio and the output current [13,16]

3.6. Modeling of Buck-Boost Converter

The simulation of the Buck-Boost converter can be carried out using several of inputs like step, ramp, or impulse function input.

The state vector for the Buck-Boost converter is define as [8]

$$X(t)= \begin{bmatrix} I_L \\ V_C \end{bmatrix} \tag{3.24}$$

where I_L, is the current through the inductor and V_C is the voltage across the capacitor. The following set of state space equations are for continuous time domain analysis

$$\dot{X}(t)=AX(t)+BV_s(t) \tag{3.25}$$

$$Y(t)= CX(t) + DV_s(t) \tag{3.26}$$

where:

A, B, C, D are the state coefficient matrices.

The Buck-Boost converter state space model is for CCM and has two modes [7,8]:

Mode 1: M1 is ON and M2 OFF

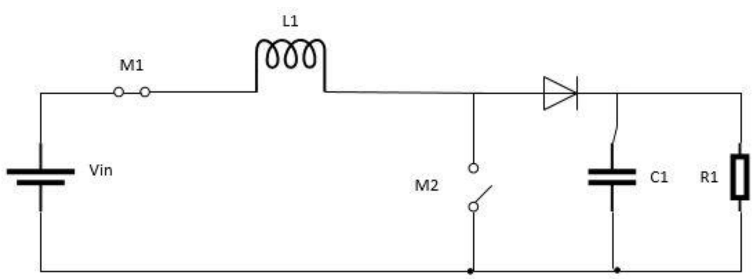

Figure 3.16 Buck-Boost Operation in Mode 1

$$\dot{X}(t)= A_1X(t)+B_1V_s(t) \tag{3.27}$$

where

$$A1 = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{R} \end{bmatrix} \tag{3.28}$$

$$B1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \tag{3.29}$$

Mode 2: S is OFF and D ON

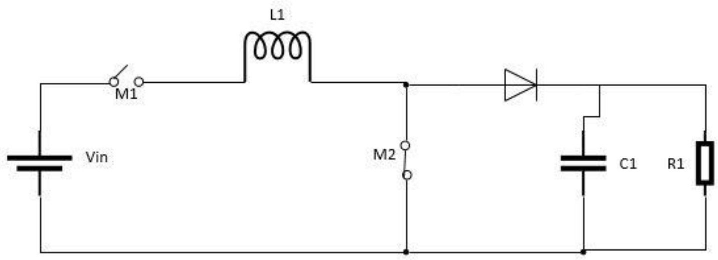

Figure 3.17 Buck-Boost Operation in Mode 2

$$\dot{X}(\mathrm{t}) = A_2 \mathrm{X}(\mathrm{t}) + B_2 V_s(\mathrm{t}) \tag{3.30}$$

where

$$A2 = \begin{bmatrix} 0 & \frac{-1}{R} \\ \frac{1}{c} & \frac{-1}{Rc} \end{bmatrix} \tag{3.31}$$

$$B2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{3.32}$$

the following is the average model:

$$\dot{X}\ (\mathrm{t}) = [A][X] + [B][u] \tag{3.33}$$

where

$$A = dA_1 \ + (1\text{-d})A_2 \tag{3.34}$$

$$B = dB_1 + (1\text{-d})A_2 \tag{3.35}$$

$$A = \begin{bmatrix} 0 & \frac{d-1}{L} \\ \frac{1-d}{c} & \frac{-1}{Rc} \end{bmatrix} \tag{3.36}$$

$$B1 = \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix} \tag{3.37}$$

$$Y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} I_L \\ V_c \end{bmatrix} + [0]\ v_s(\text{t}) \tag{3.38}$$

The state space equation can be changed into transfer function as

$$\dot{X}\ (\text{t})=\text{AX(t)+B}V_s(\text{t}) \tag{3.39}$$

$$\text{Y(t)}= CX(t) + DV_s(\text{t}) \tag{3.40}$$

Discrete system can be treated in similar fashion as continuous.

3.7. Modeling of Pulse-Width Modulator

Pulse-width modulation (PWM) is very important for control in power electronics and as integral part of the feedback control loop it must be properly modeled. A constant-frequency modulator can be modeled with constant DC gain [17]. PWM may also be used for harmonic elimination at the output. Equivalent PWM current controller can be very effective for converters operating in steady state. The duty cycle ration is constant in PWM applications [17].

3.8. DC-DC Buck-Boost Converter Control Methods

There are several techniques used to control the operation of the DC-DC Buck-Boost converters for better performance and with low errors.

3.8.1. PID Controller

The analog PID control system has been used effectively in many industrial control systems. Digital controllers are simpler to design for all types of converters. It is a nonlinear control equation and very flexible; it has excellent performance and lower in cost than to analog counterparts also, it is easier to handle, and can have nearly any desired degree of computational accuracy. Digital controller is proposed for the Buck -Boost converter in this thesis. It will improve the dynamic performance for this type of converters, in addition to robustness and fast switching transient [8]. Discrete PID controller is used for the Buck-Boost converter controller. The controller design includes two steps. First step, in continuous time domain for the Buck-Boost converter design an analog controller. Second step, converters contiguous domain into discrete domain through estimated the behavior of an analog controller with digital controller. The second step will be discrete time domain controller design [8].

The general block diagram of the Buck-Boost converter for the system with the whole set up is shown in Figure 3.16.

The output voltage of converter is compared to the desired value of the reference voltage by comparator 1. The Digital compensator is a discrete PID controller.

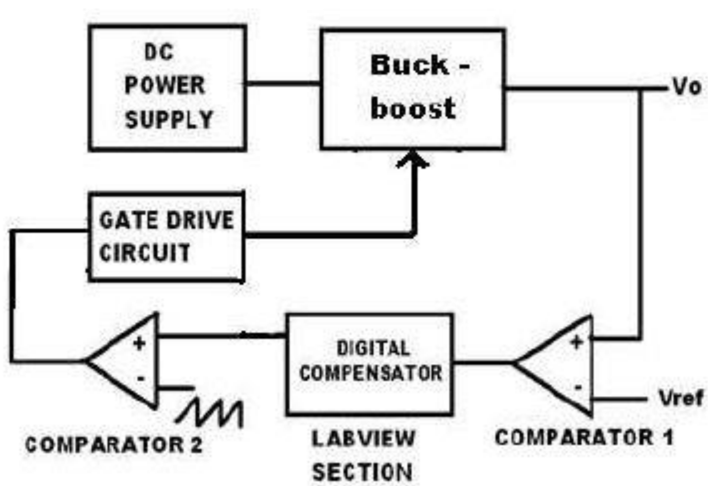

Figure 3.18 Digital Control of a Buck-Boost Converter [8]

3.8.2. Artificial Neural Networks (ANNs)

The term neural network usually refers to a circuit or network of biological neurons. Artificial neural networks (ANNs) are made up nodes or artificial neurons. ANNs are used to solve complex problems because they do not require detailed information about the system [8].

The use of ANNs to solve power systems problems has increased dramatically in the last years. ANN might be used to gain an understanding of biological neural networks, or for solving artificial intelligence problems. The actual biological nervous system is very complex, and ANN algorithms try to address this complexity [5]. Neural networks (NN) have been used in many applications such as, optimization, pattern classification, pattern recognition, automatic control, and prediction. All NNs applications are singular cases of vector mapping that require of training paradigms and different structures. The application of NNs in diverse power system applications and control strategies have been very successful.

An ANN needs the sets of inputs and outputs for its training. Through the training, the output from the ANN is compared with the desirable output to reduce error by employing some algorithm [5]. The training is recurrent till the actual output obtains an acceptable level. Managed ANN might be an advance or nonrecurrent network such as, a feedback ANN, Functional Link Net (FLN), Multi-Layer Perceptron (MLP), recurrent ANN and Radial Basis Function (RBS).

Figure 3.17 illustrates a Multilayer Perceptron Neural Network Model with three layers such as, input layer, hidden Layer and output layer

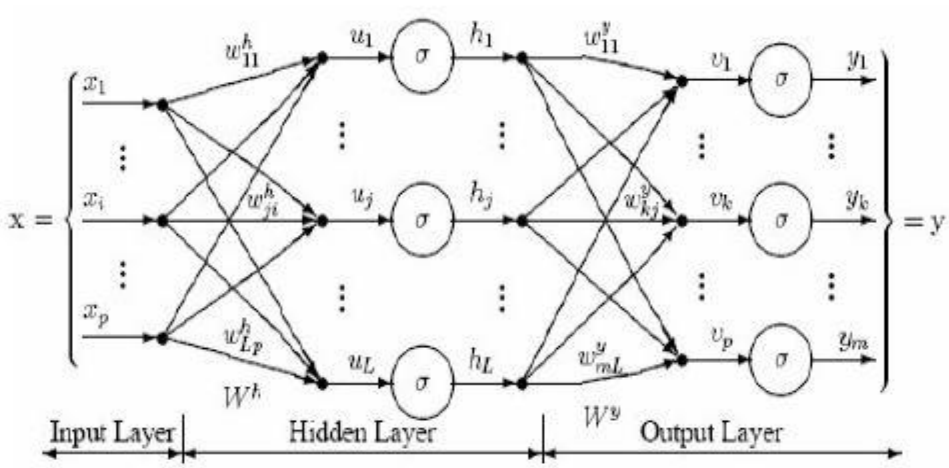

Figure 3.19 Perceptron Neural Network Model with Three Layers [12]

This network contains an input layer with three neurons, hidden layer with three neurons also, and an output layer with three neurons. Each layer has some neurons that are connected to the next layer by link.

The input layers have variables ($x_1...x_p$) with range between (-1 to 1). ANN has been used to control a Buck-Boost converter. The controller is intended to stabilize the output voltage of the converter through transient operations to improve performance of the Buck-Boost converter [7].

3.8.3. Fuzzy Logic Control (FLC)

Fuzzy Logic Controls (FLCs) systems have been successful in power electronic and it is simple and fast. It is simple and fast methodology system. Experienced human operators are still available for providing qualitative rules to control. It can be complex and does not need any exact mathematical model. The important part of the fuzzy logic controller is the linguistic control rules relating the compositional rule of inference and concepts of fuzzy implication [18]. The construction of fuzzy controller consists of fuzzification inference engine and defuzzification block. The structure of fuzzy controller is shown in Figure 3.18

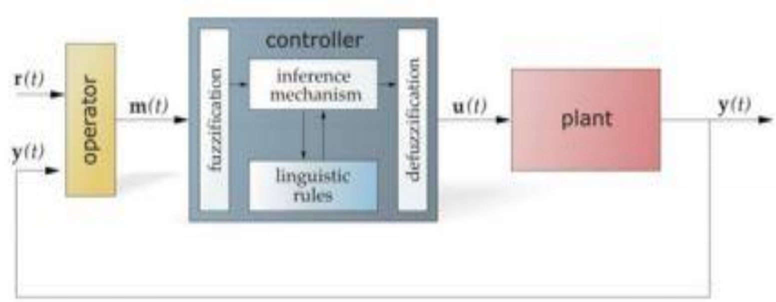

Figure 3.20 The Structure of Fuzzy Controller [18]

The figure shows how input variables are changed. The output variable is the stabilizing voltage (V_{stab}).

3.8.4. Hybrid Neural Fuzzy Controllers

Hybrid neural-fuzzy system is defined as a fuzzy system that uses a learning algorithm based on gradients to determine its parameters by the patterns processing input and output using fuzzy rules. The system can completely be created from input-output data or prepared with a previous knowledge using same method of fuzzy rules [17]. The result from the fusing fuzzy systems and neural networks systems has advantages of learning by data patterns. There are several ways to developed hybrid neural-fuzzy systems are neuro-fuzzy systems are represented through neural networks that can be implemented by logical functions. The representation by neural networks is more appropriate because it allows visualization of data flow through the system and the error signals that are used to inform the parameters [17]. Another benefit is to allow the comparison of the different models and visualize structural differences.

Our proposed method is based on checking of the ratio R between V_o and V_{oref}, based on this ratio the value of the new duty cycle ratio D is calculated and the converter will work in Buck or Boost conversion mode. The calculation of the duty cycle ratio is done in comparing the ratio R to predefined ranges, then the increment or decrement of the new D value is determined. The structure of our proposed method is similar to the Fuzzy control system, but different in the implementation since no fuzzy block or membership functions are used in the simulation which results in shorter implementation time.

CHAPTER 4

PROPOSED CONTROLLER METHOD: SYSTEM DESIGN

This chapter presents the design of the modules developed for this thesis, which includes the Buck-Boost converter, and the software control module. The analysis and discussion of the results are in Chapter 5. MATLAB and Simulink is used to simulate the design of the Buck-Boost converter controller.

4.1. The Design of the Buck-Boost Converter Controller System

The Buck-Boost converter was designed with the software model control, as shown in Figure 4.1. To generate the required duty cycle ratio D, the output voltage V_o is the feedback signal of the control, the output voltage (V_o) is compared with the reference voltage (V_{oref}).

The PWM is a modulation technique is used to control the width of the pulse signal. The main use of the PWM is to control the power supply of the electrical device. The PWM controls the switch based on calculated D.

4.1.1. Buck-Boost Converter: Proposed Design

The hardware design of the Buck-Boost converter is shown in Figure 4.2. The input signal is designed to support the change in the input voltage of the Boost-Buck-Boost or Boost-Buck operational mode. The key for the successful design is carefully selecting the capacitor and the inductor values. Table 4.1 shows the values of the parameters selected for the design. In Chapter 5, the process for selecting the capacitor and the inductor is discussed. Figure 4.2 shows the MATLAB/Simulink schematic diagram used for the simulation.

Table 4.1: Simulation Parameters of the DC-DC Buck-Boost Converter

	Inductor (µH)	Capacitor (µF)	Resistor (Ω)
Value	50	150	30

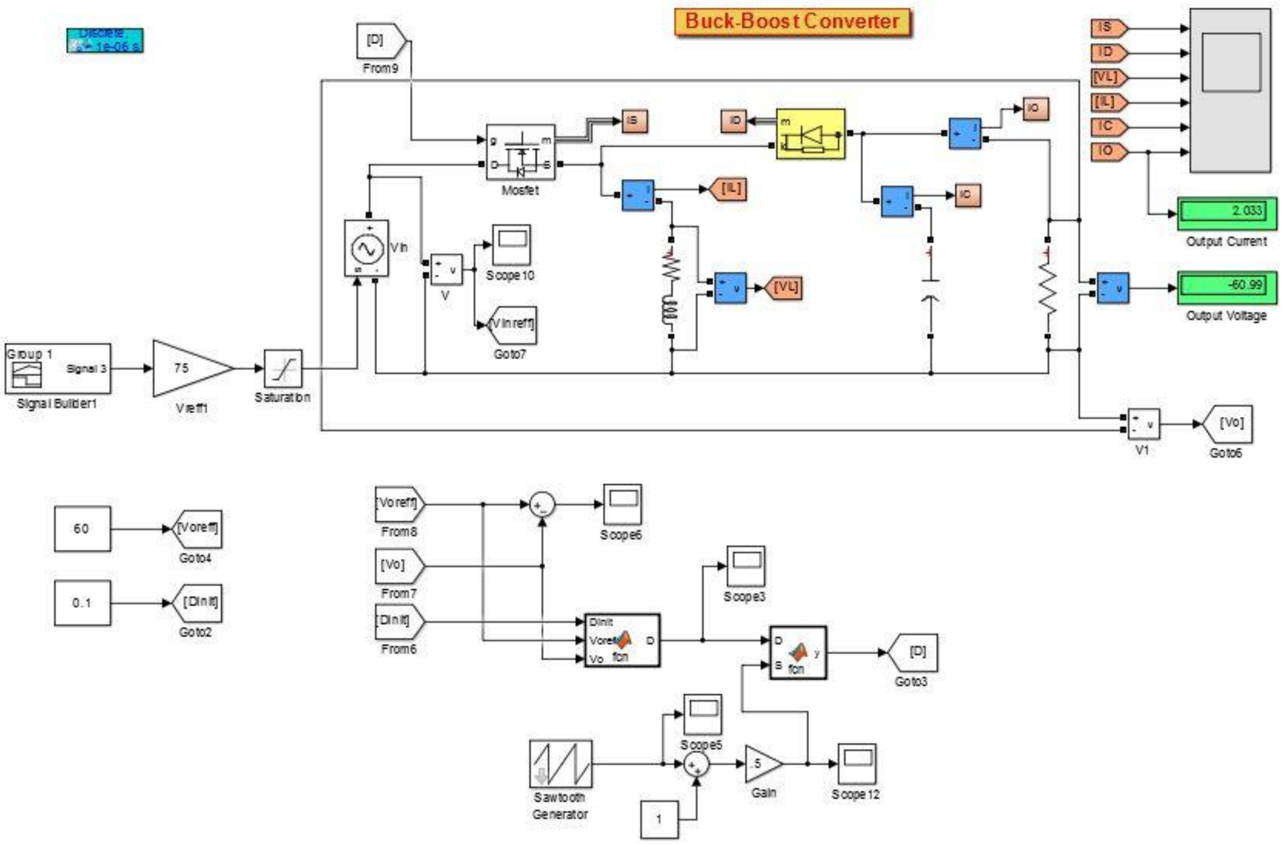

Figure 4.1 Design of the Buck-Boost Converter Controller System

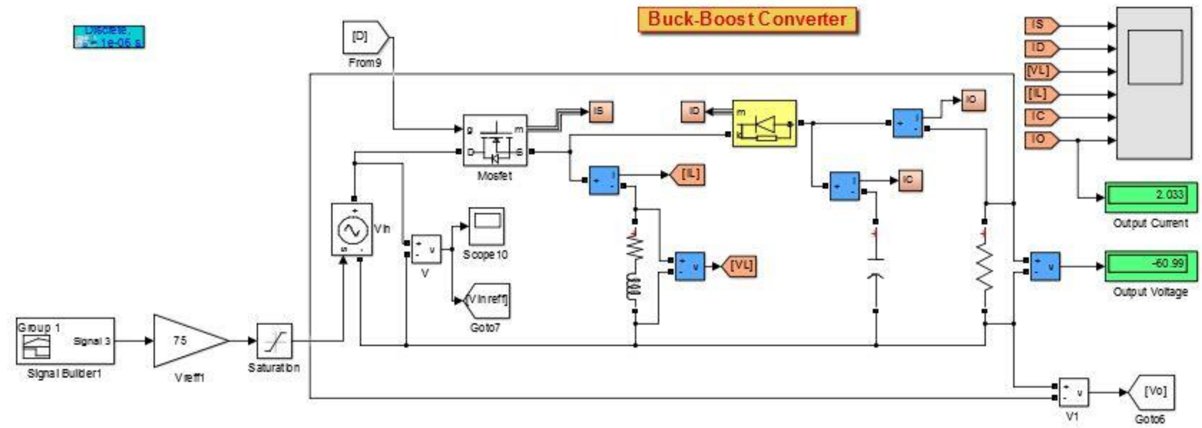

Figure 4.2 Buck-Boost Converter: Hardware Design

4.1.2. Buck-Boost Converter: Software Model

To control the duty cycle ratio *D* and the converter operational mode Buck or Boost, a software model is presented. The input parameters for this model are the output voltage (V_o), the output voltage reference, and the initial value of *D* which has been selected to be 0.1. Figure 4.3 shows the generation of the duty cycle ratio *D*.

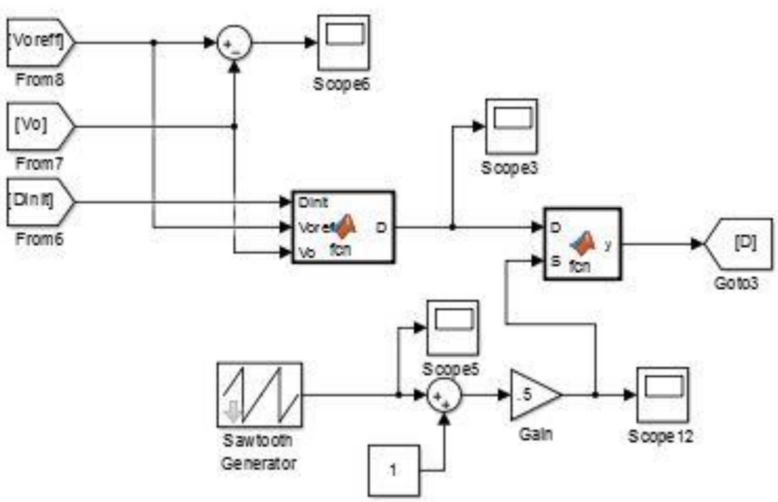

Figure 4.3 Design of the Duration (D) Circuit Generation

The ratio between the output voltage V_o and the output reference voltage V_{oref} is calculated as

R=V_o/V_{oref} (4.1)

and based on the value of R, the new value *D* is determined and used to generate the Sawtooth signal. Figure 4.4 shows the flowchart for the proposed software model.

If *R* is less than 1, which means that the V_o is less than V_{oref} the converter is operating in the Boost mode and *D* needs to be increased, conversely, if *R* is greater than 1, which means that V_o is greater than V_{oref}, the converter will operate in the Buck mode and the duration *D* must be decreased. The amount of *D* increment or decrement is based on how much is V_o is bigger or less than V_{oref}. The accepted value of R is in the range 0.97 to 1.03. If *R* is within this range then *D* must be increased or decreased accordingly.

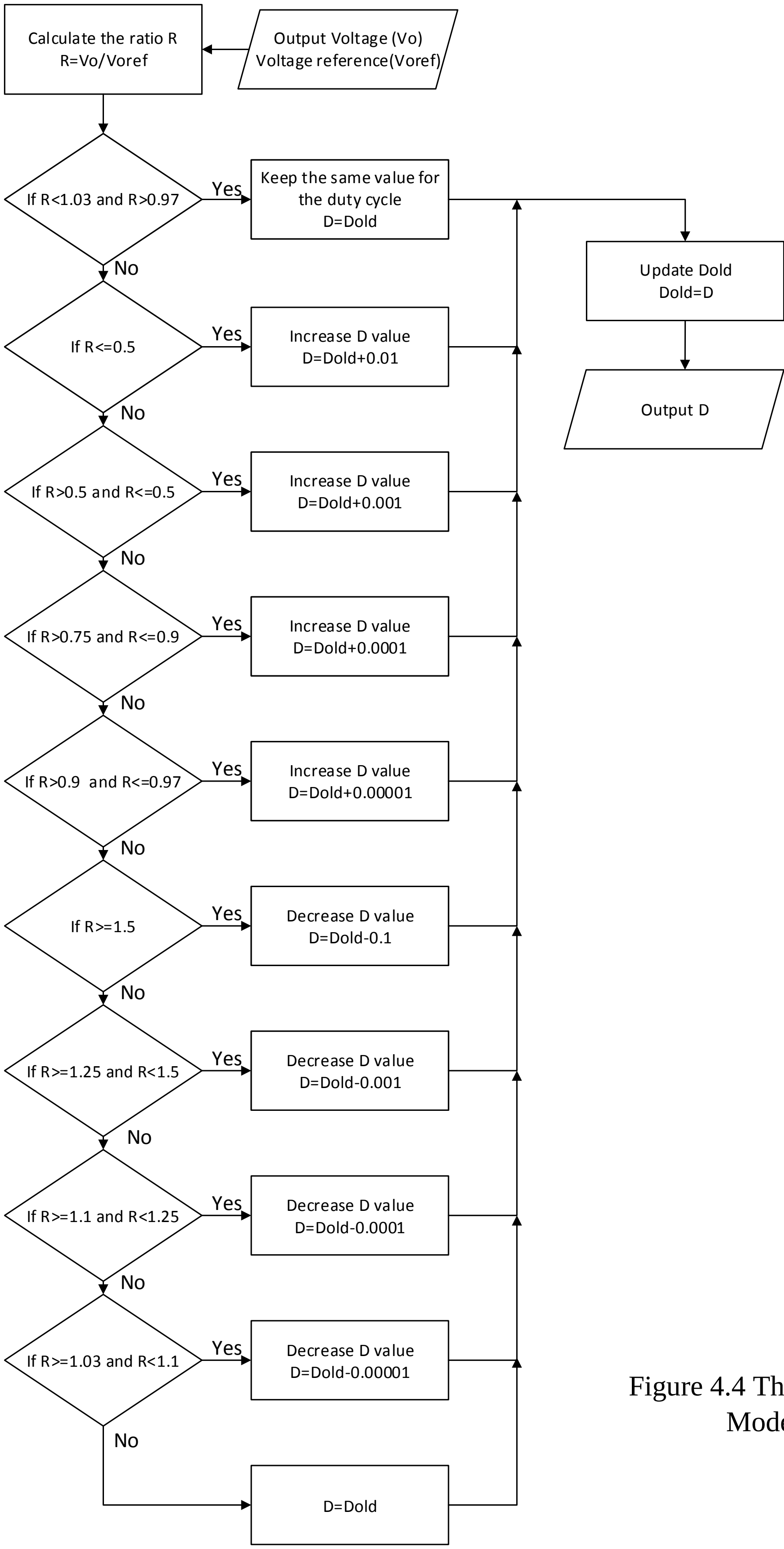

Figure 4.4 The Proposed Software Model Flowchart

CHAPTER 5

RESULTS AND DISCUSSION

The converter circuit and control are developed and analyzed by using MATLAB/SIMULINK software. The values for the capacitor and inductor used are shown in Table 4.1. Two operational modes are considered; Boost-Buck-Boost and Buck-Boost.

5.1. Boost-Buck-Boost Operation Mode

In this mode, the input voltage is less than and greater than the V_{oref}, so that the circuit operates in Boost, Buck, then Boost mode. The design tested produced different output voltages that match the desired voltage. Figures 5.1 to 5.20 show examples of the output voltage waveforms for the circuit operation with different reference voltages. For each reference voltage, the output voltage, settling time, the transition Boost-Buck-Boost, the ratio R, and the error between V_o and V_{oref} are shown.

1. Voltage reference 25V

V_{oref}=25V, input voltage lower limit is 15V, and upper limit is 35V

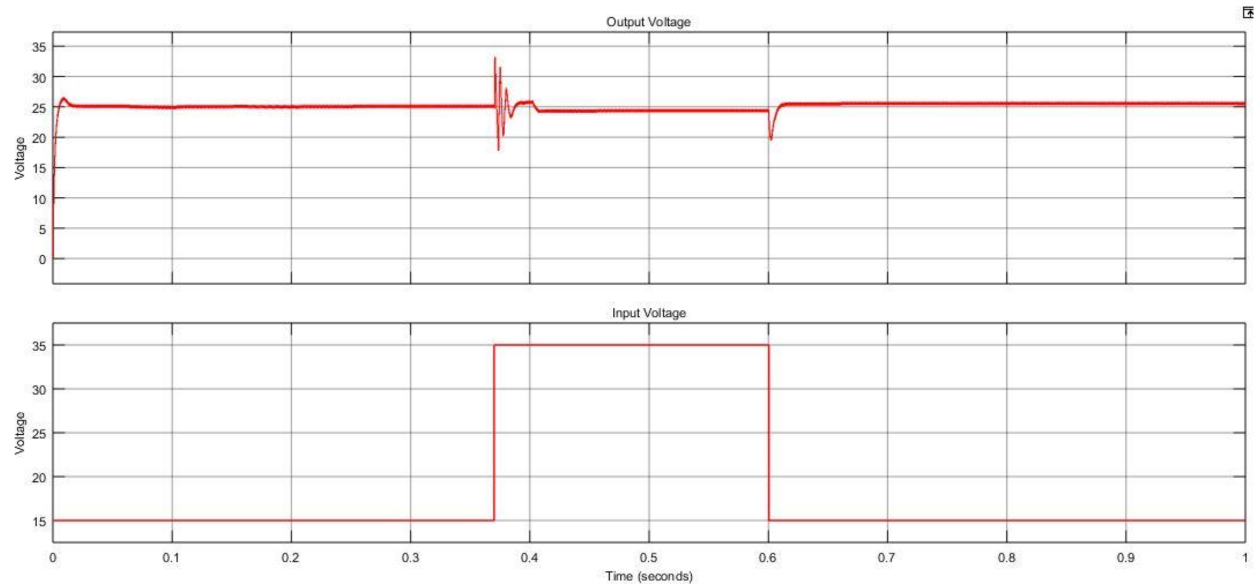

Figure 5.1 Output Voltage, V_{oref}=25V

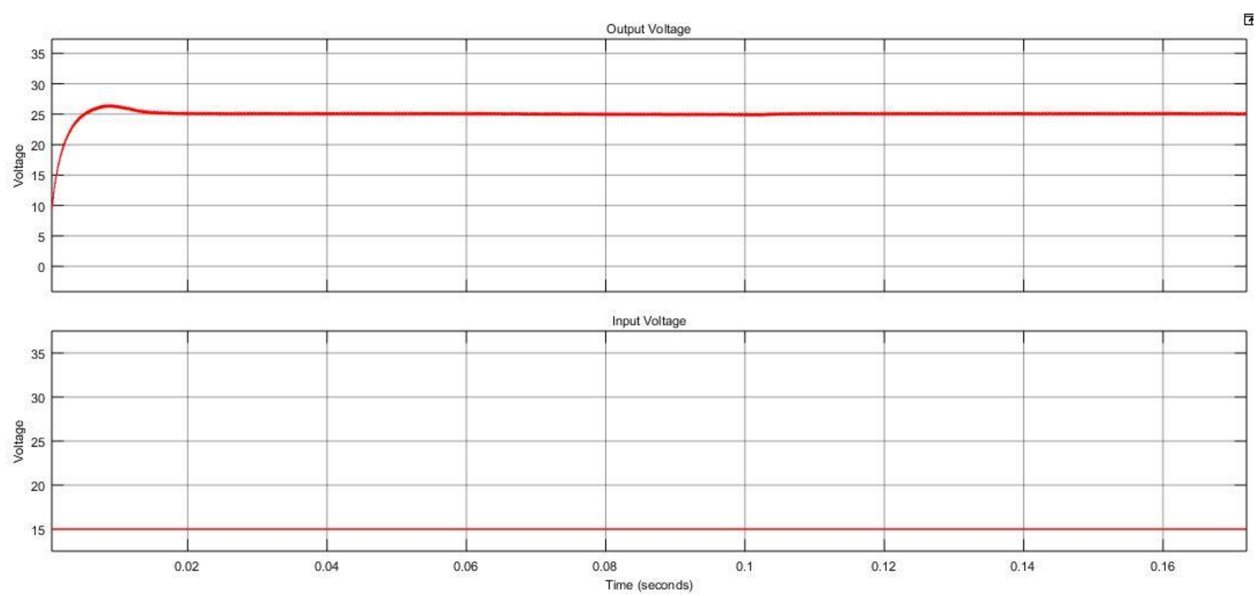

Figure 5.2 Settling Time <0.018 s, V_{oref}=25V

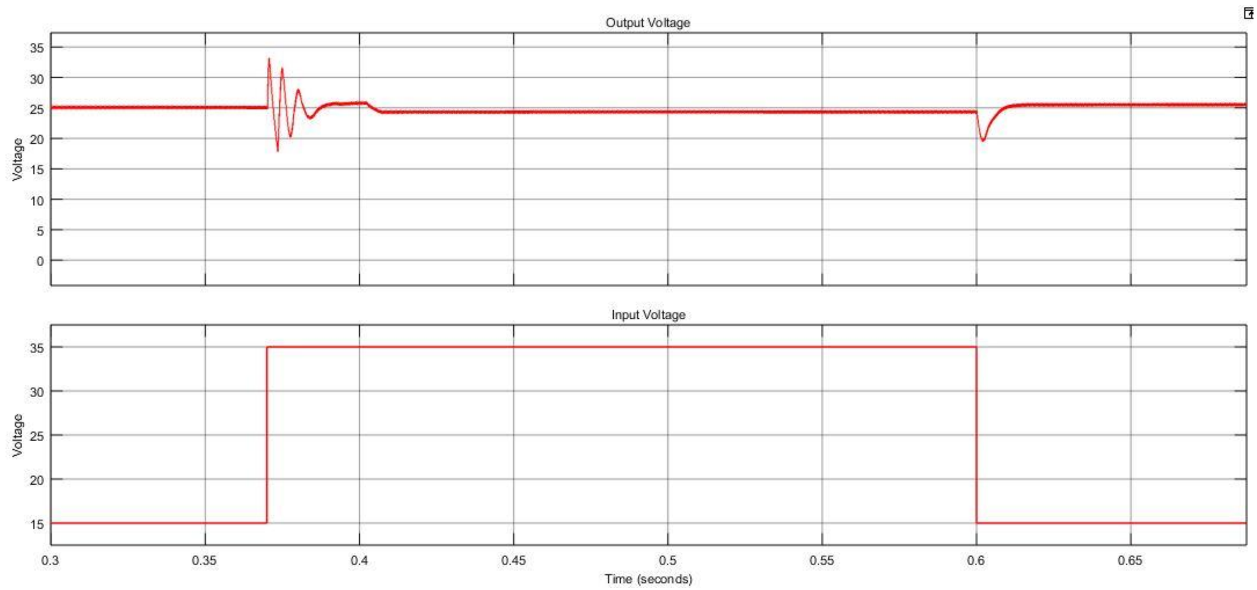

Figure 5.3 Closer View for Output Transition Between Boost-Buck-Boost, V_{oref}=25V

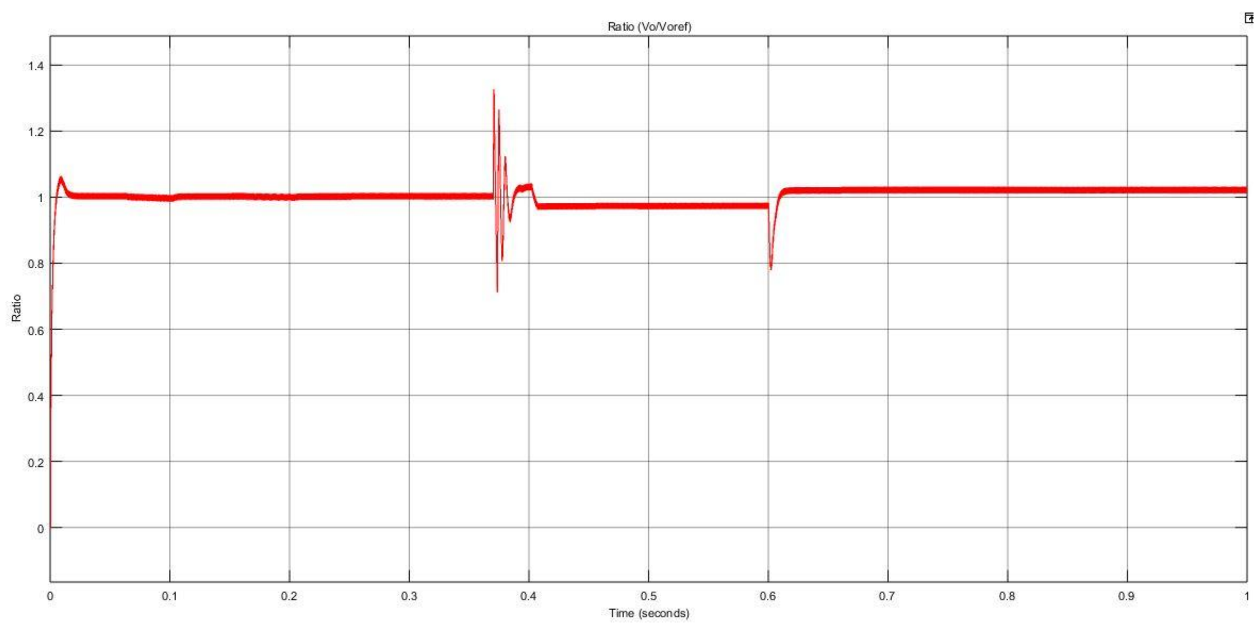

Figure 5.4 The Ratio R, V_{oref}=25V

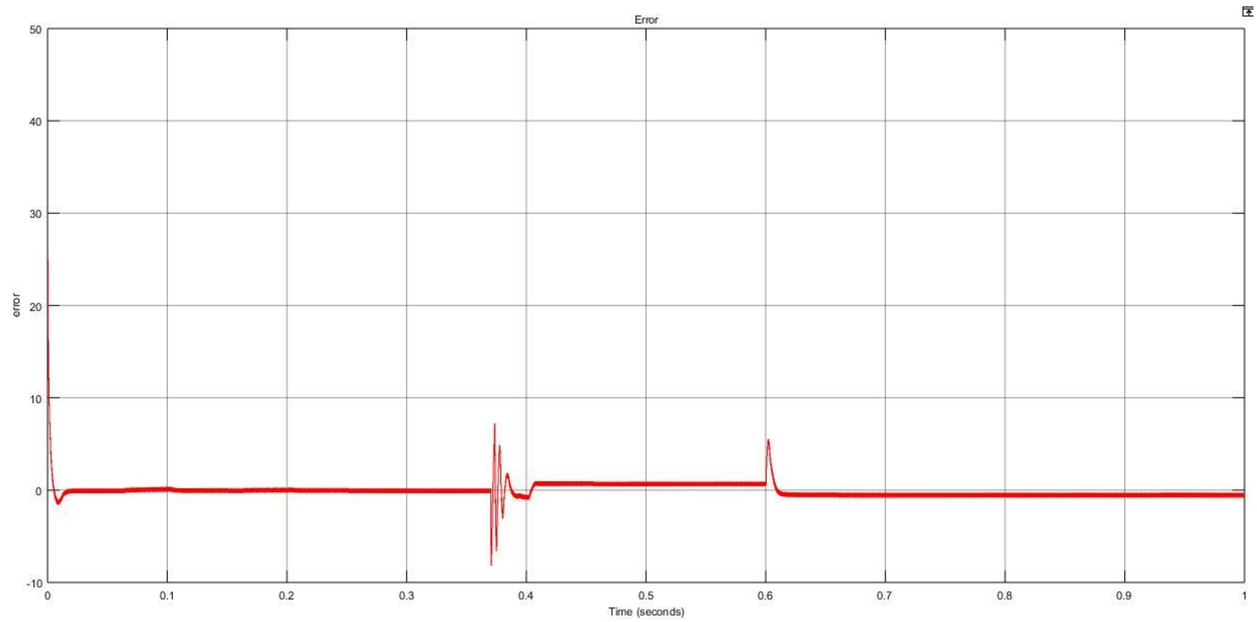

Figure 5.5 The Error (V_{oref}-V_o), V_{oref}=25V

2. Voltage reference 45V

V_{oref}=45V, input voltage lower limit is 35V, and upper limit is 50V

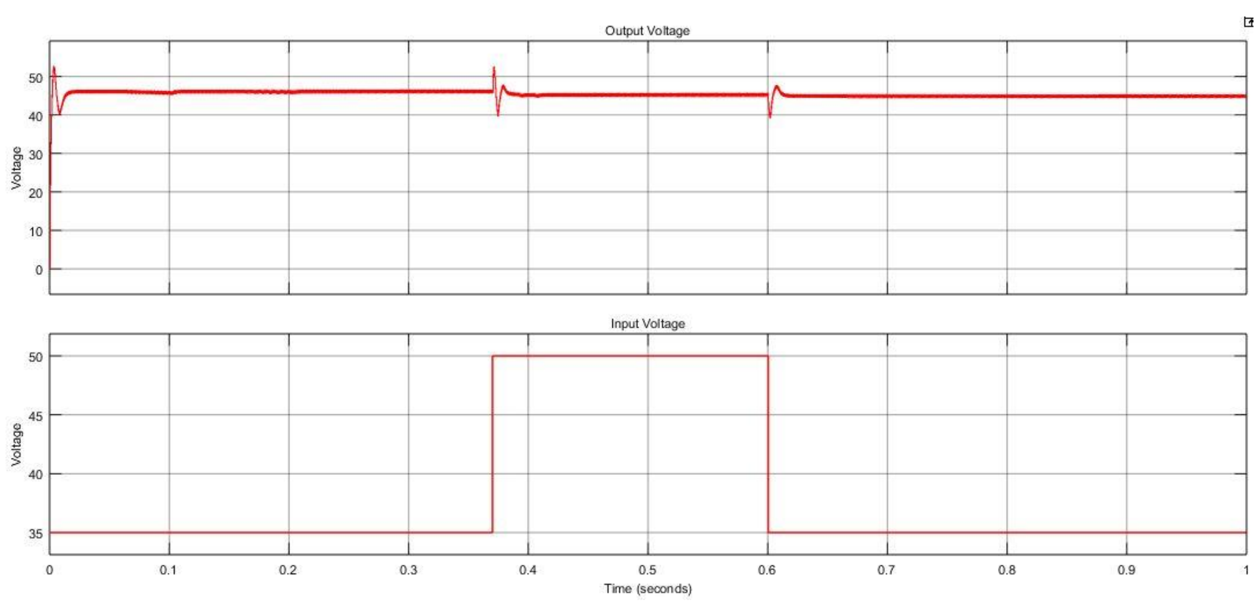

Figure 5.6 Output Voltage, V_{oref}=45V

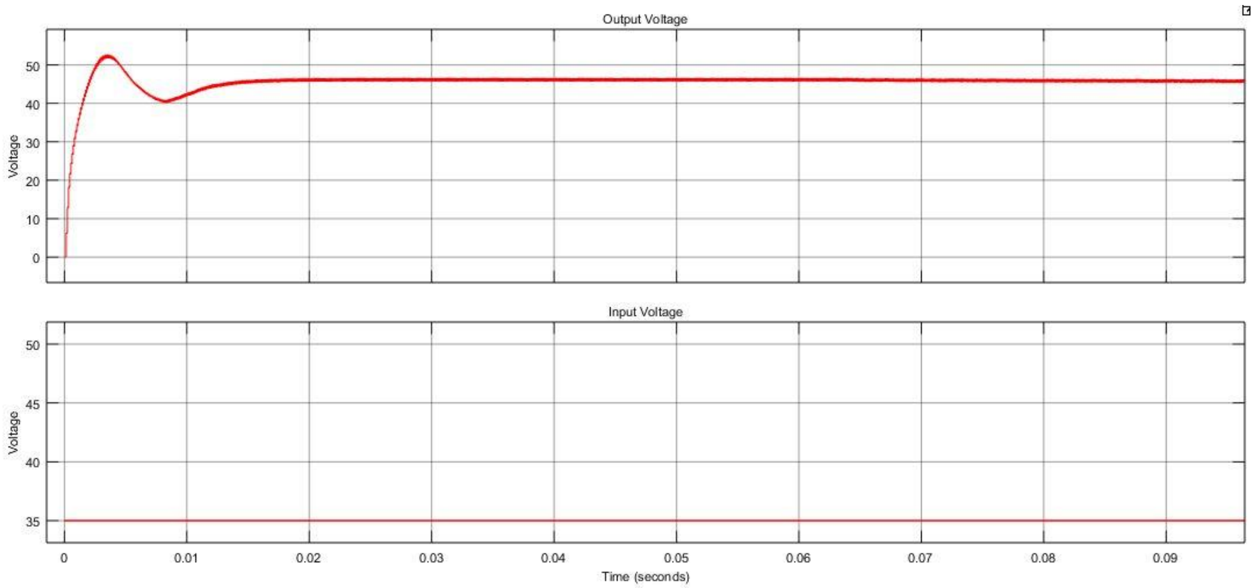

Figure 5.7 Settling Time, V_{oref}=45V

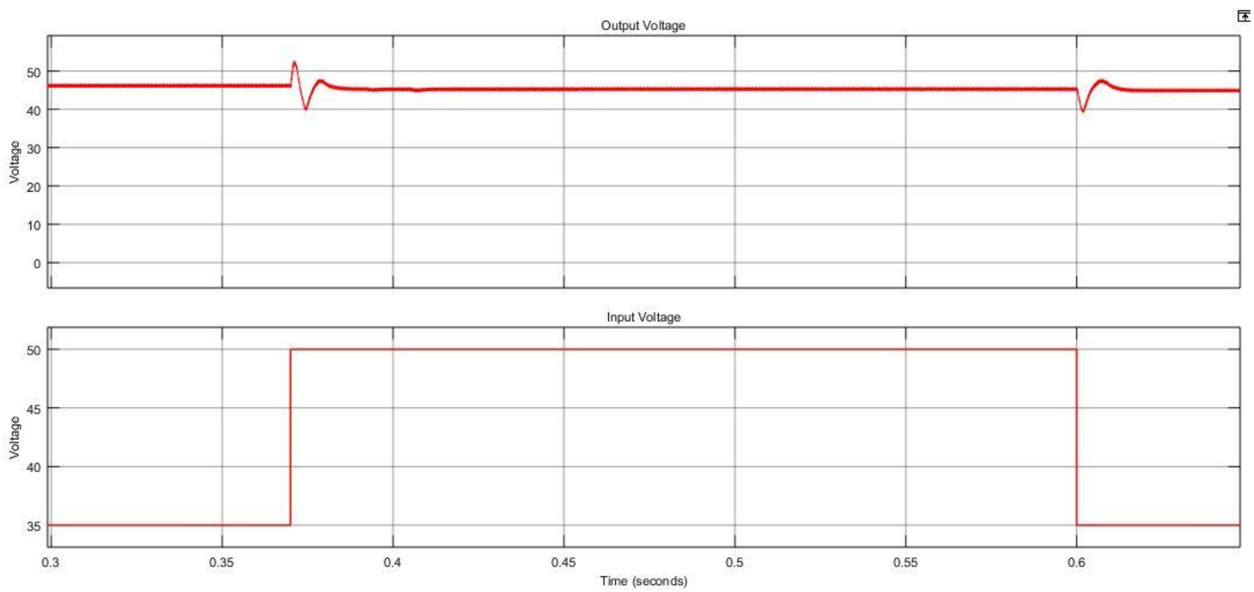

Figure 5.8 Closer View for Output Transition Between Boost-Buck-Boost, V_{oref}=45V

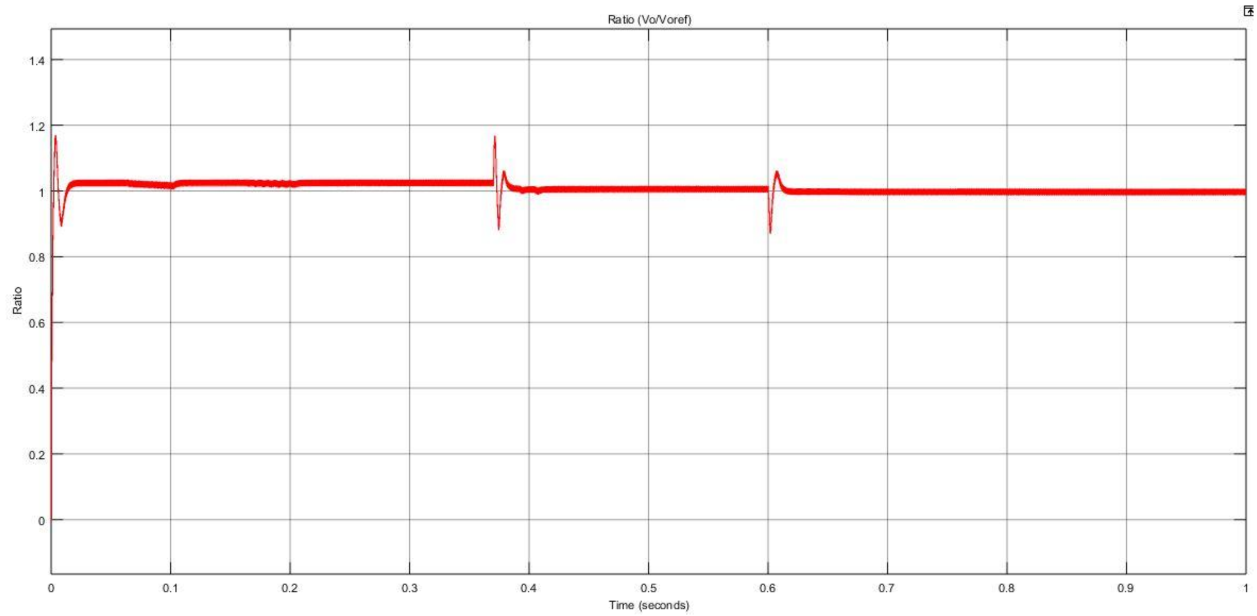

Figure 5.9 The Ratio R, V_{oref}=45V

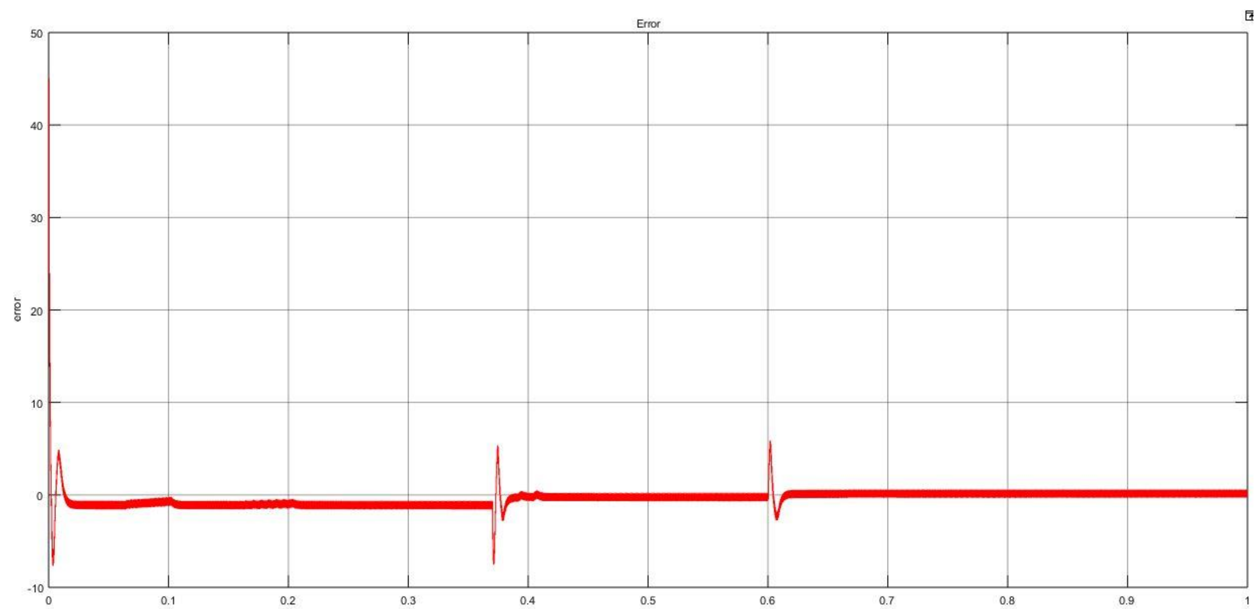

Figure 5.10 The Error (V_{oref}-V_o), V_{oref}=45V

3. Voltage reference 60V

V_{oref}=60V, input voltage lower limit is 50V, and upper limit is 70V

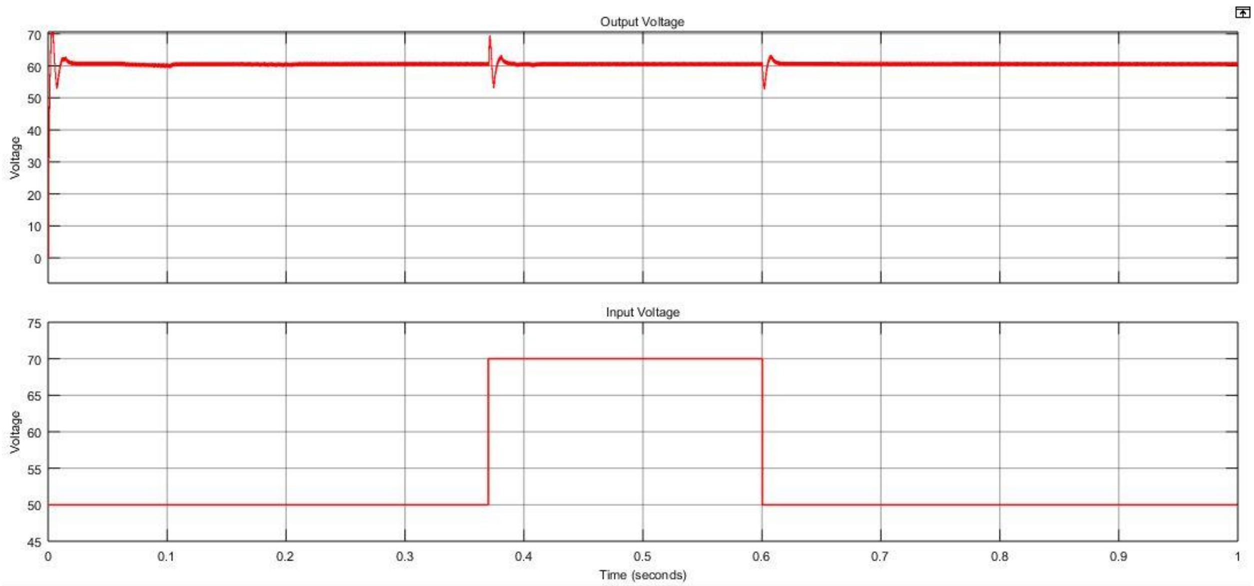

Figure 5.11 Output Voltage, V_{oref}=60V

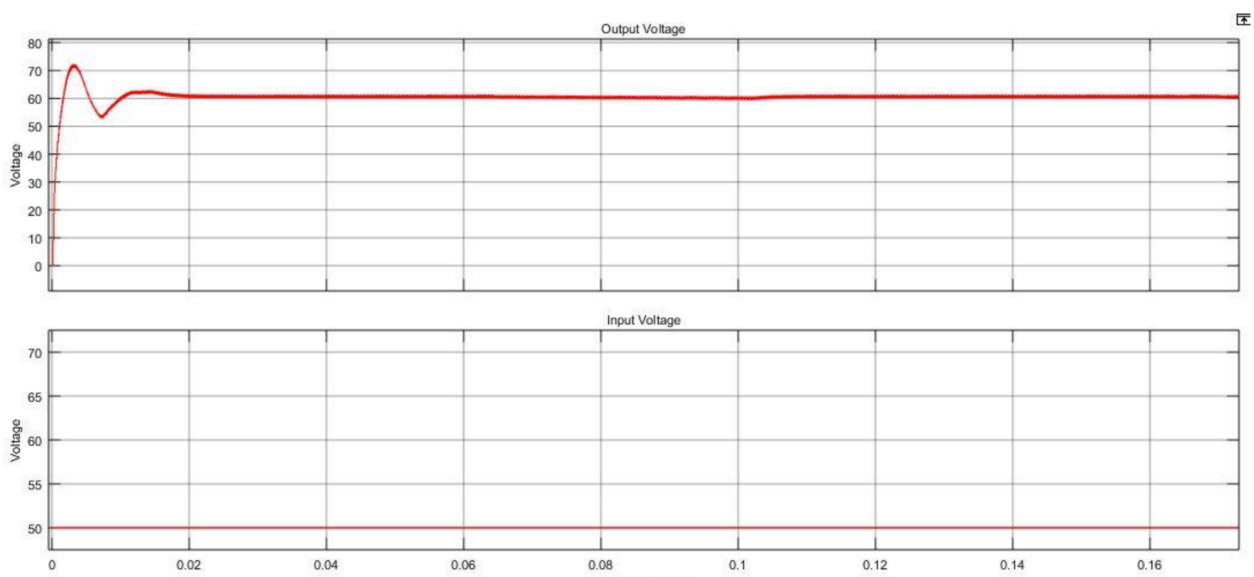

Figure 5.12 Settling Time, V_{oref}=60V

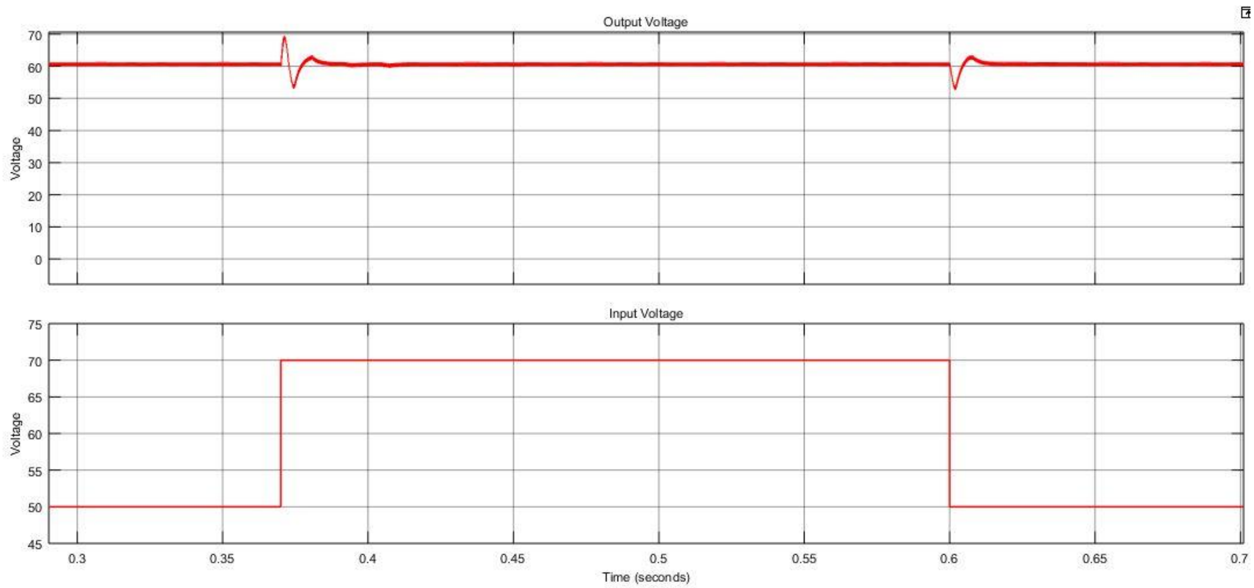

Figure 5.13 Closer View for Output Transition Between Boost-Buck-Boost, V_{oref}=60V

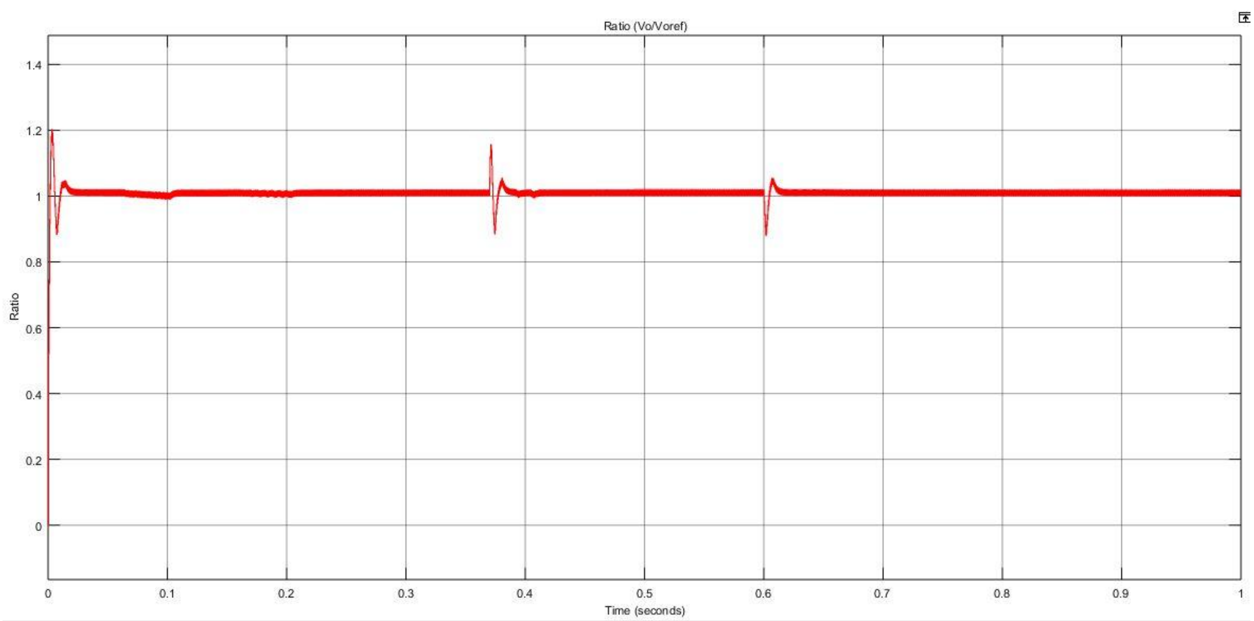

Figure 5.14 The Ratio R, V_{oref}=60V

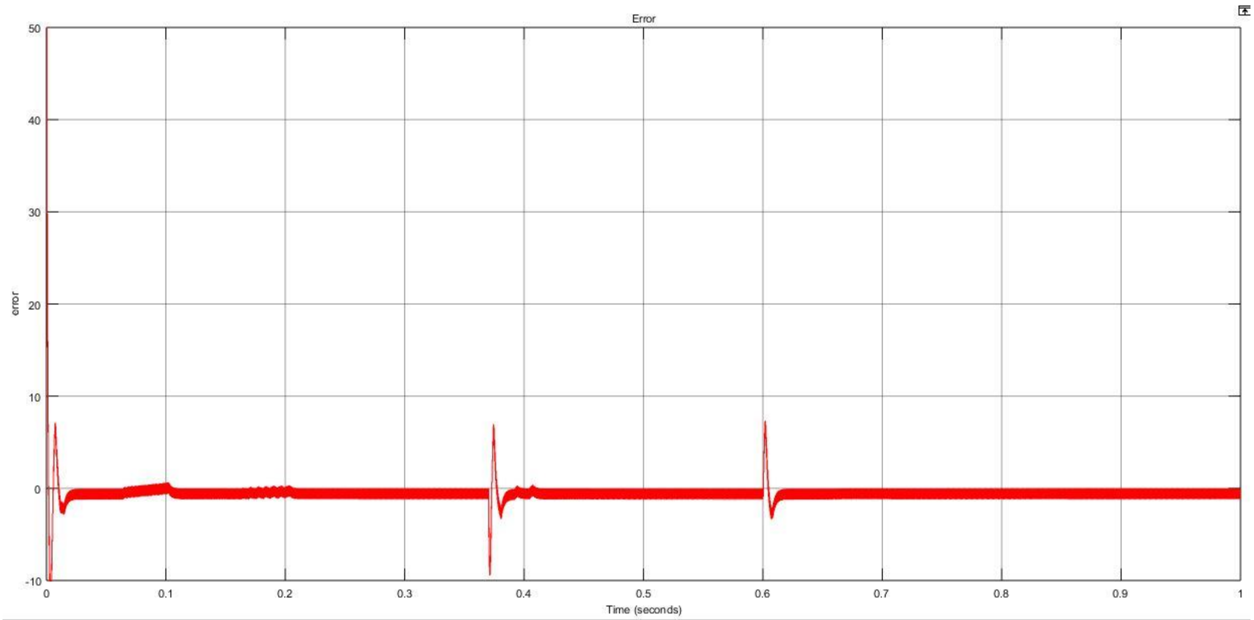

Figure 5.15 The Error (V_{oref}-V_o), V_{oref}=60V

4. Voltage reference 70 V

V_{oref}=70 V, input voltage lower limit is 60 V, and upper limit is 80 V

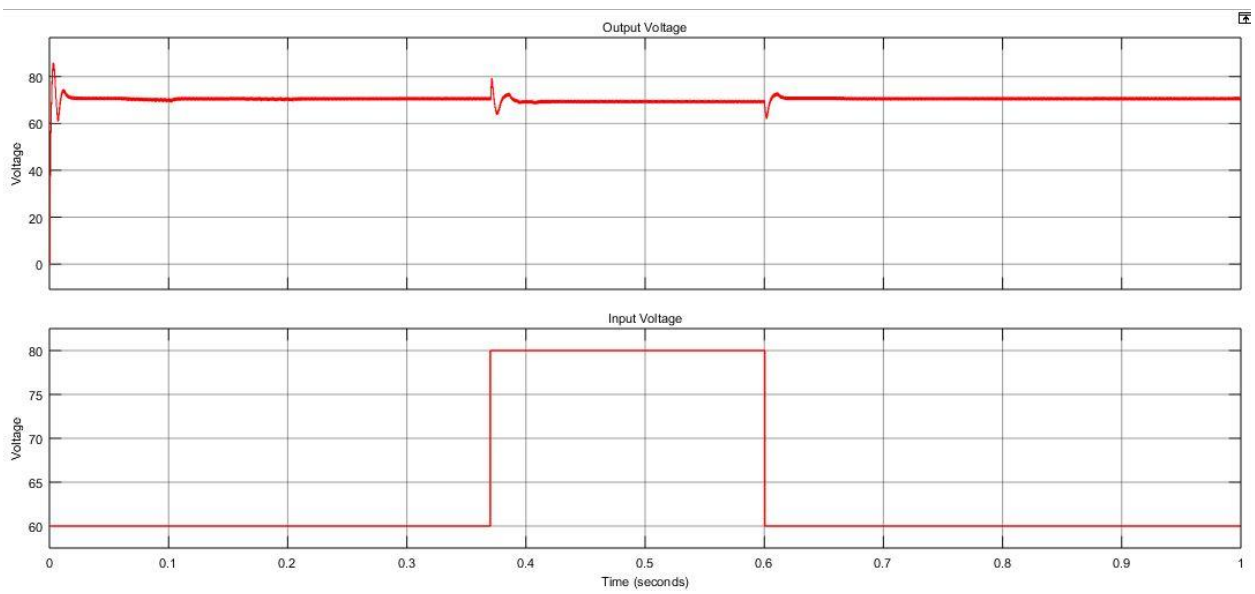

Figure 5.16 Output Voltage, V_{oref}=70 V

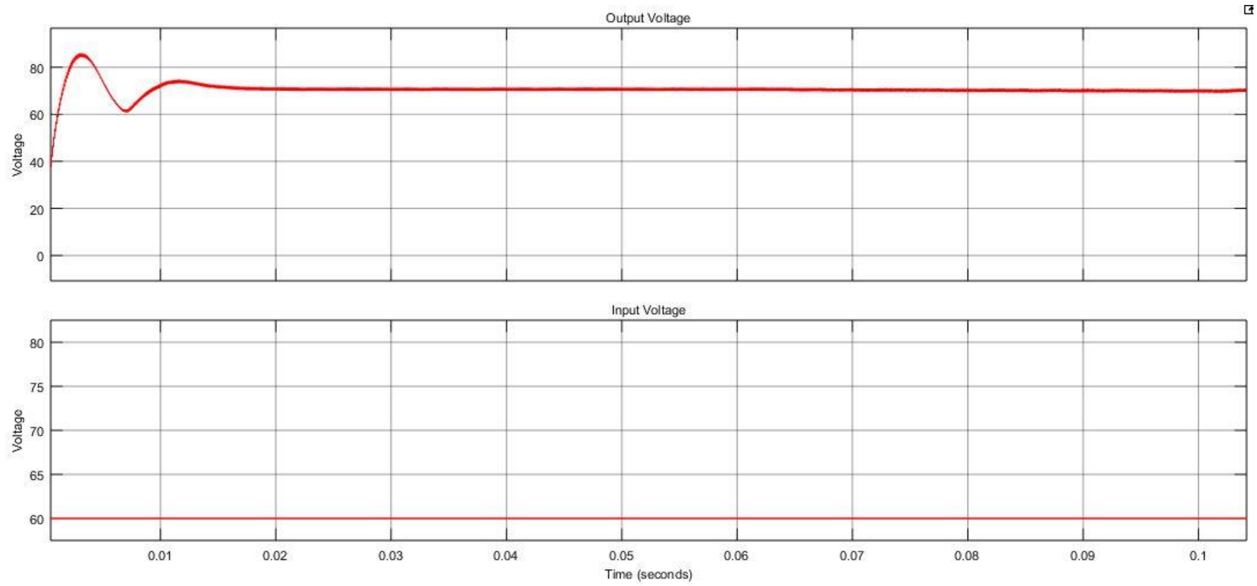

Figure 5.17 Settling Time, V_{oref}=70 V

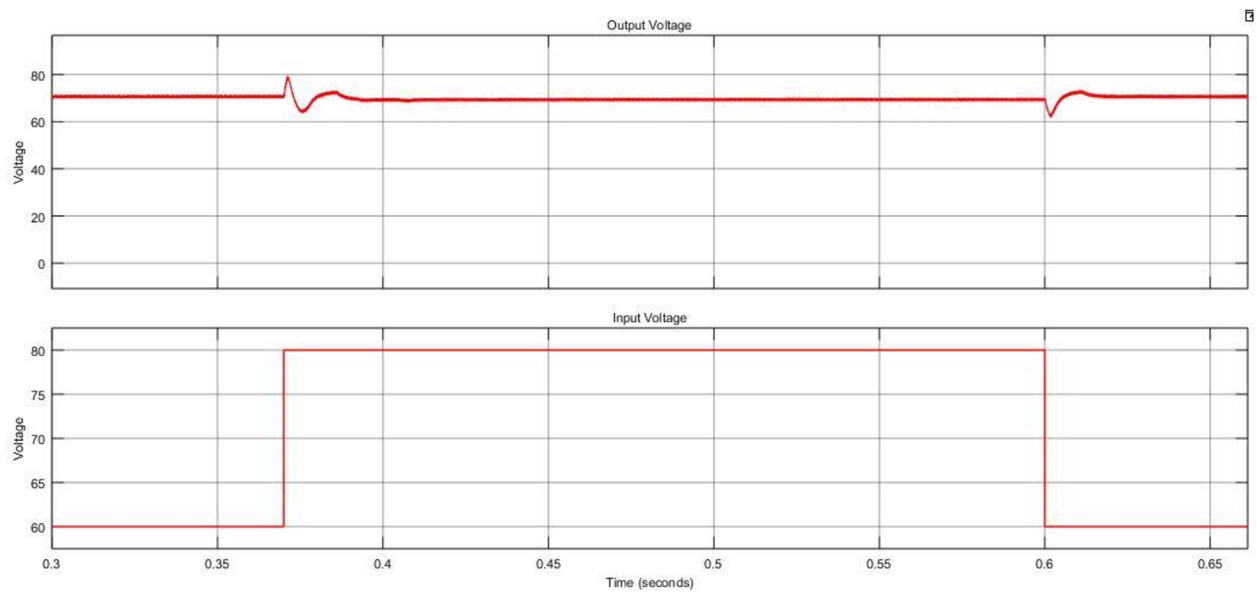

Figure 5.18 Closer View for Output Transition Between Boost-Buck-Boost, V_{oref}=70 V

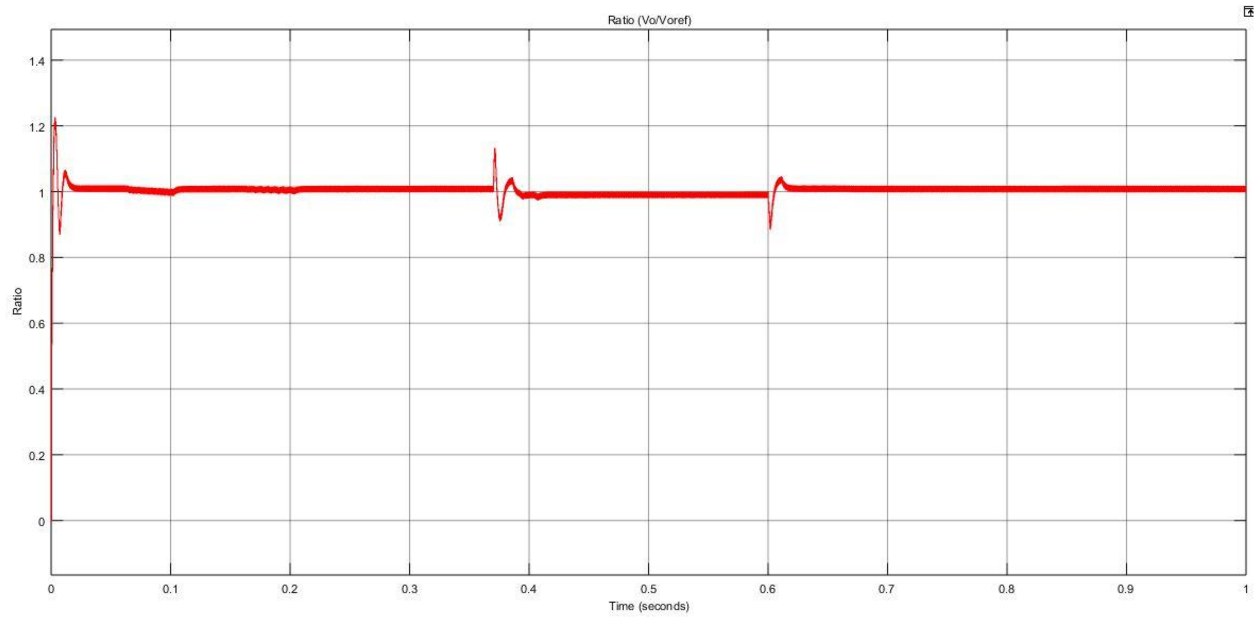

Figure 5.19 The Ratio R, V_{oref}=70 V

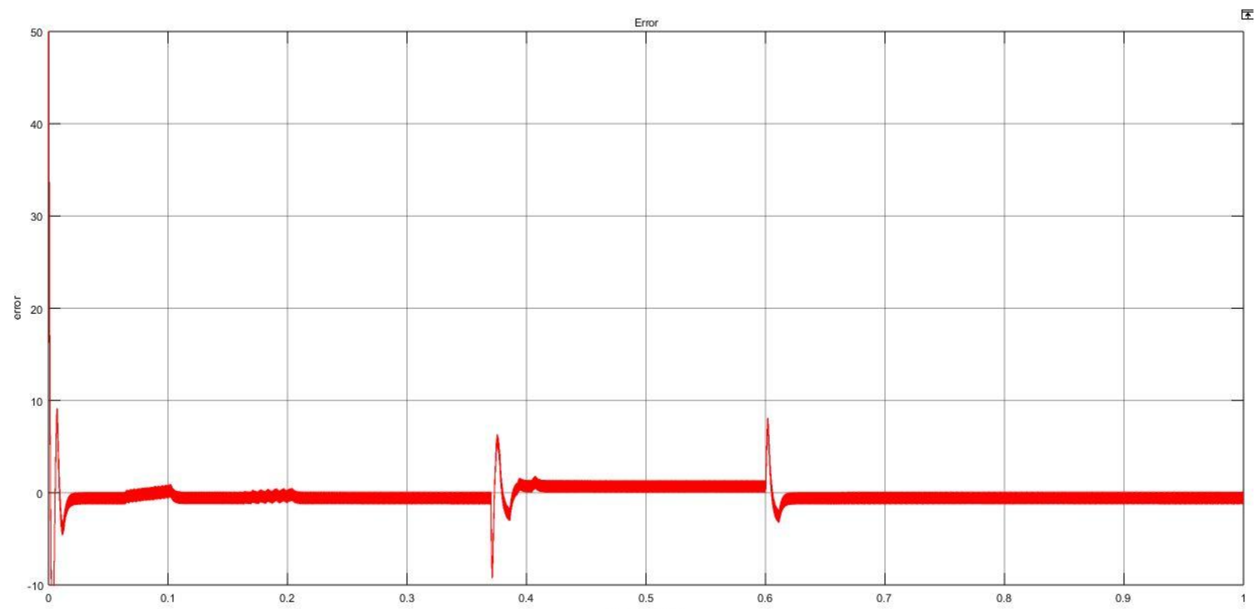

Figure 5.20 The Error (V_{oref}-V_o), V_{oref}=70 V

These examples show the robustness of the design for different output reference voltages and difference between V_{oref} and input voltage within lower or upper limits of 10 V. The design is able to provide a consistent output voltage with very small error between V_{oref} and the V_o. The settling time is very short; it is less than 0.018 second. The transition time between operation modes, that is, from boost to buck or buck to boost is less than 0.02 second.

5.1.1. Increase the Variation in the Input Voltage

In the previous examples of system operation, the difference between V_{oref} and the input voltage lower limit is 10 V which is the same between V_{oref} the input voltage upper limit is 10 V. The design is tested with V_{oref}=60 V but with different upper and lower limits of the input voltages as shown in the waveforms of Figures 5.21 to 5.26. The design shows robust performance to the variation of the input voltage. The circuit fails to maintain the output when the difference between the input voltage and the output reference voltage is 30 V or greater.

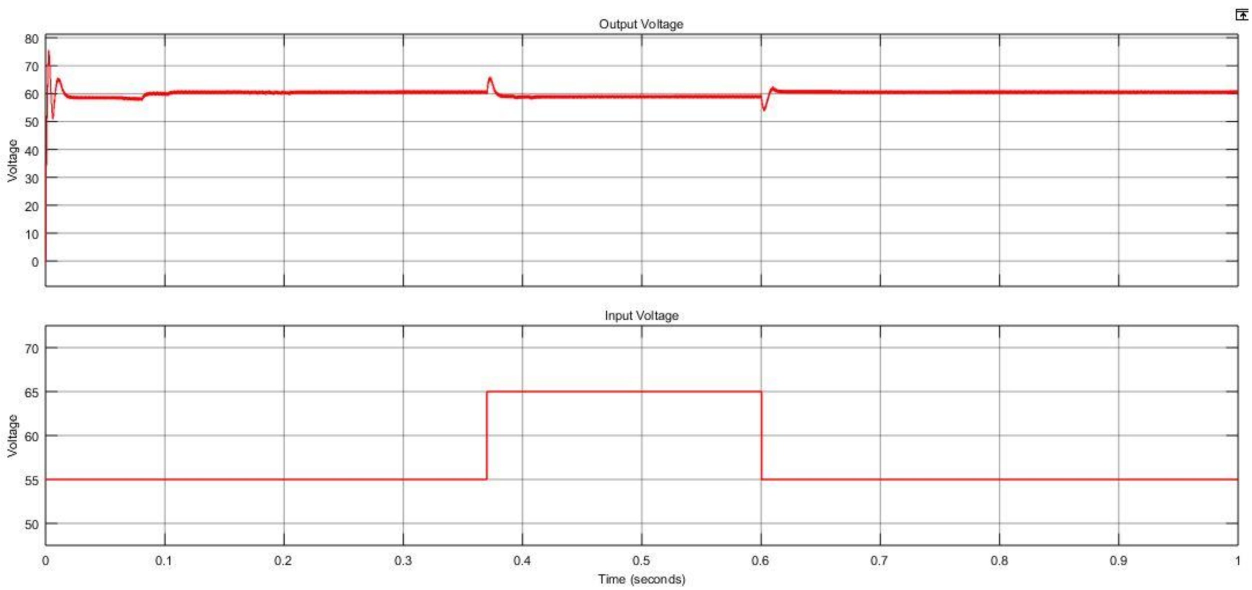

Figure 5.21 V_{oref} is 60 V, V_{in} Lower Limit is 55 V, and V_{in} Upper Limit is 65 V

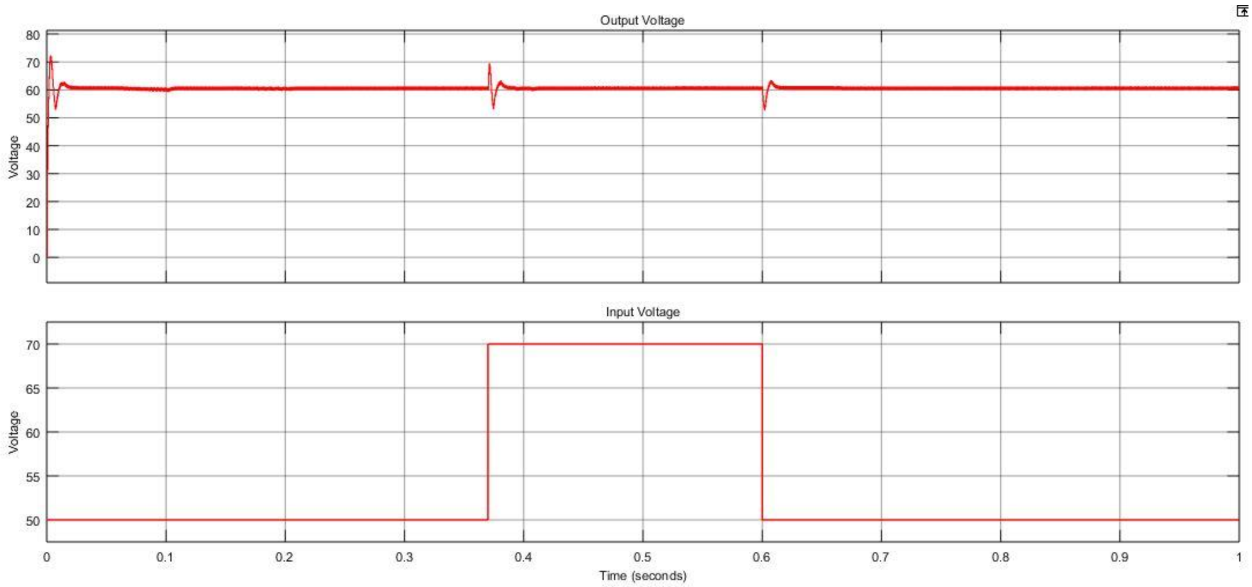

Figure 5.22 V_{oref} is 60 V, V_{in} Lower Limit is 50 V, and V_{in} Upper Limit is 70 V

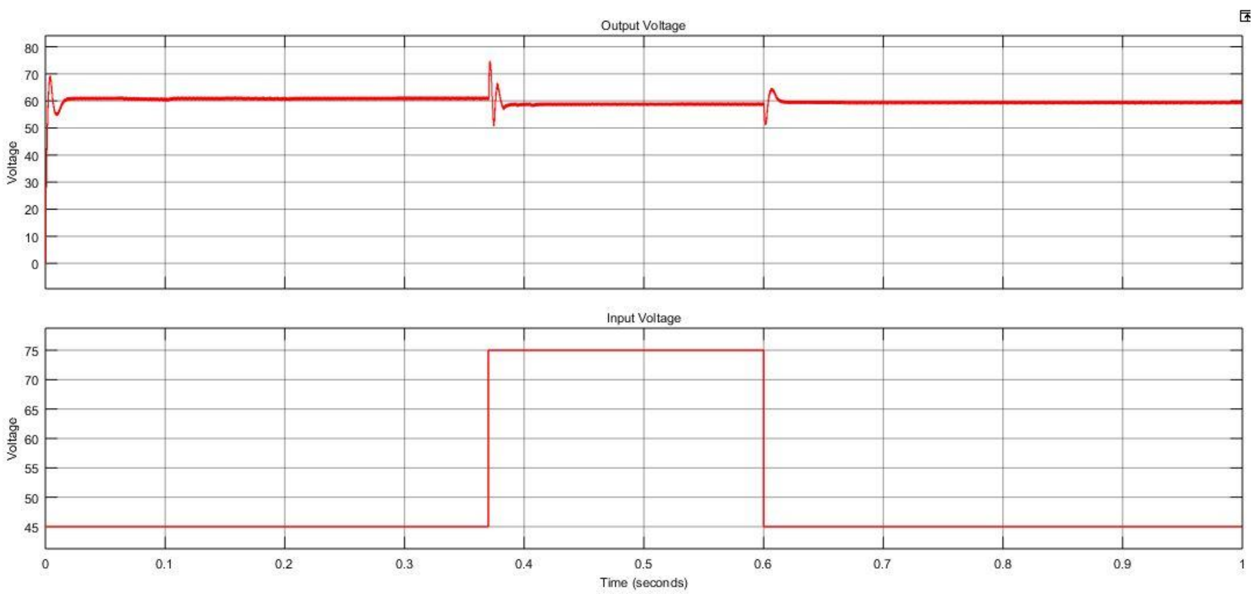

Figure 5.23 V_{oref} is 60 V, V_{in} Lower Limit is 45 V, and V_{in} Upper Limit is 75 V

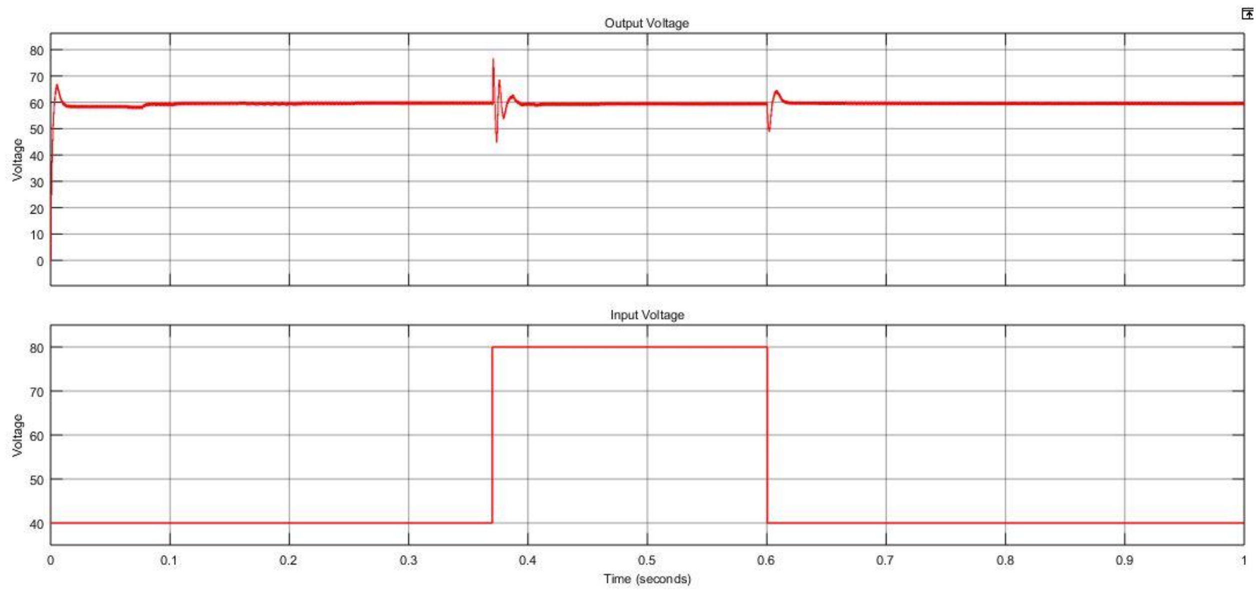

Figure 5.24 V_{oref} is 60 V, V_{in} Lower Limit is 40 V, and V_{in} Upper Limit is 80 V

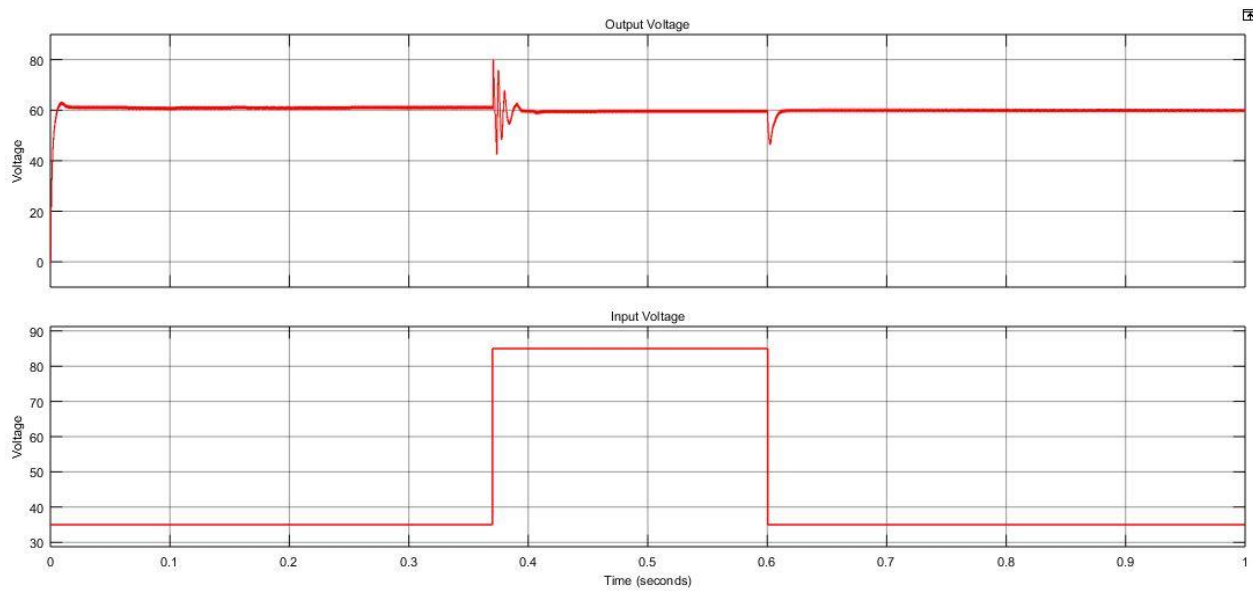

Figure 5.25 V_{oref} is 60 V, V_{in} Lower Limit is 35 V, and V_{in} Upper Limit is 85 V

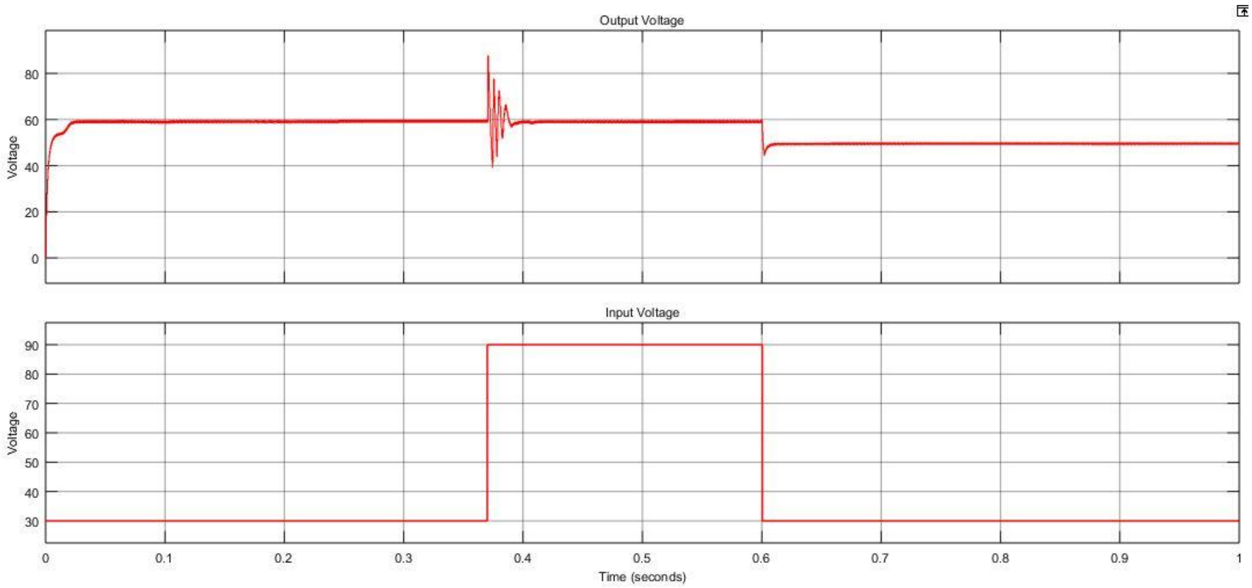

Figure 5.26 V_{oref} is 60 V, V_{in} Lower Limit is 30 V, and V_{in} Upper Limit is 90 V

5.2. Buck-Boost Operational Mode

In this section, Buck-Boost operation mode is considered. The converter operates in Buck mode in the first half and followed by the Boost mode. Figures 5.27 to 5.34 show examples of the output voltage waveforms for the circuit operation with different reference voltages with different input voltage lower and lower limits. For each reference voltage (with different input voltage lower and lower limits), the waveforms for the output voltage and settling are shown.

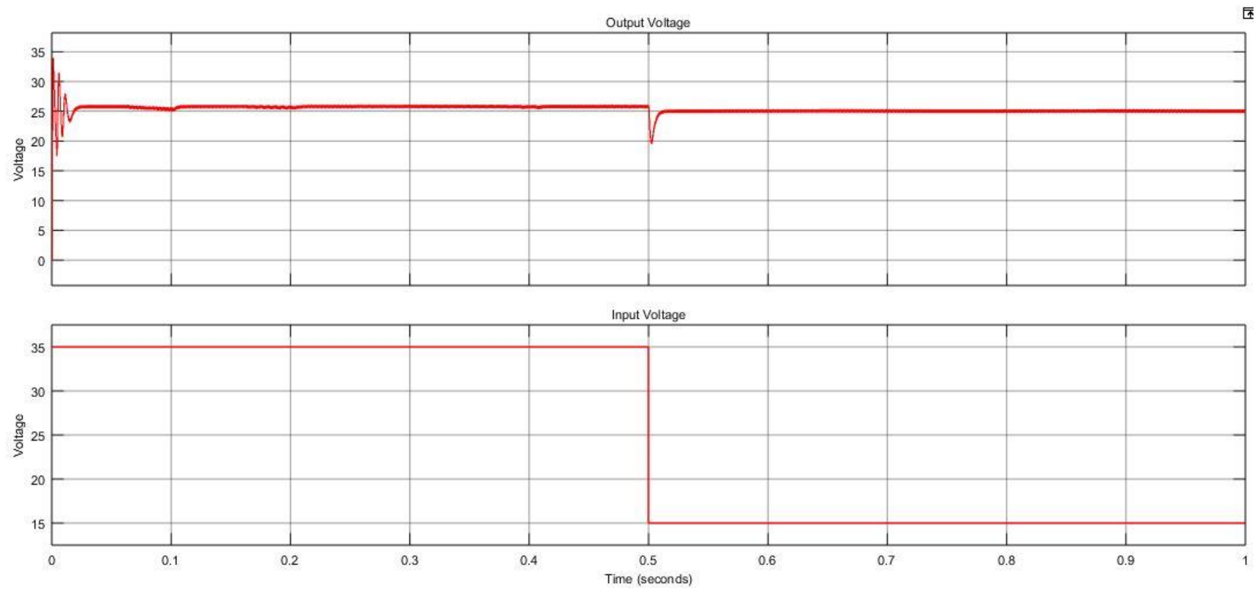

Figure 5.27 V_{oref} is 25 V, V_{in} Lower Limit is 15 V, and V_{in} Upper Limit is 35 V

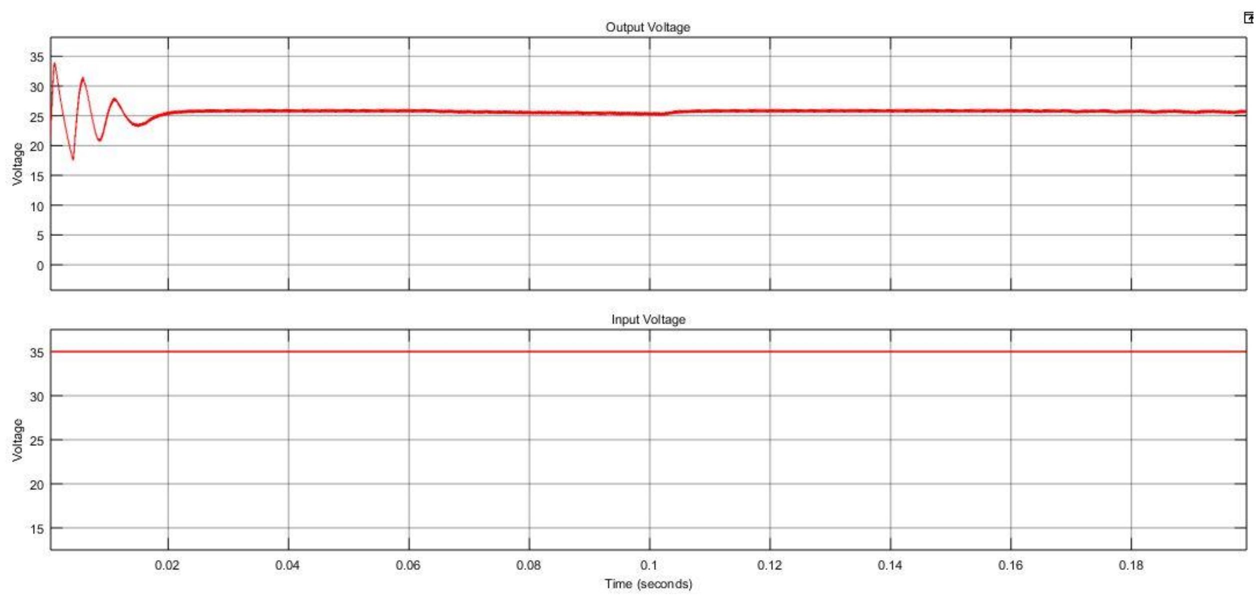

Figure 5.28 Settling Time, V_{oref}=25V

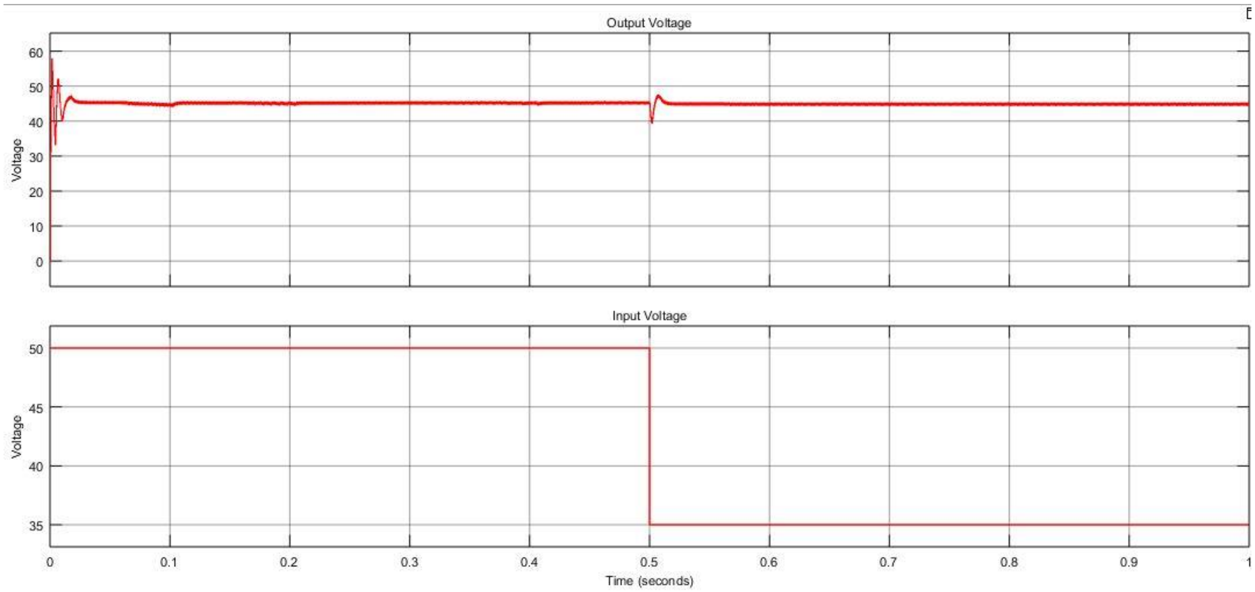

Figure 5.29 V_{oref} is 45 V, V_{in} Lower Limit is 35 V, and V_{in} Upper Limit is 50 V

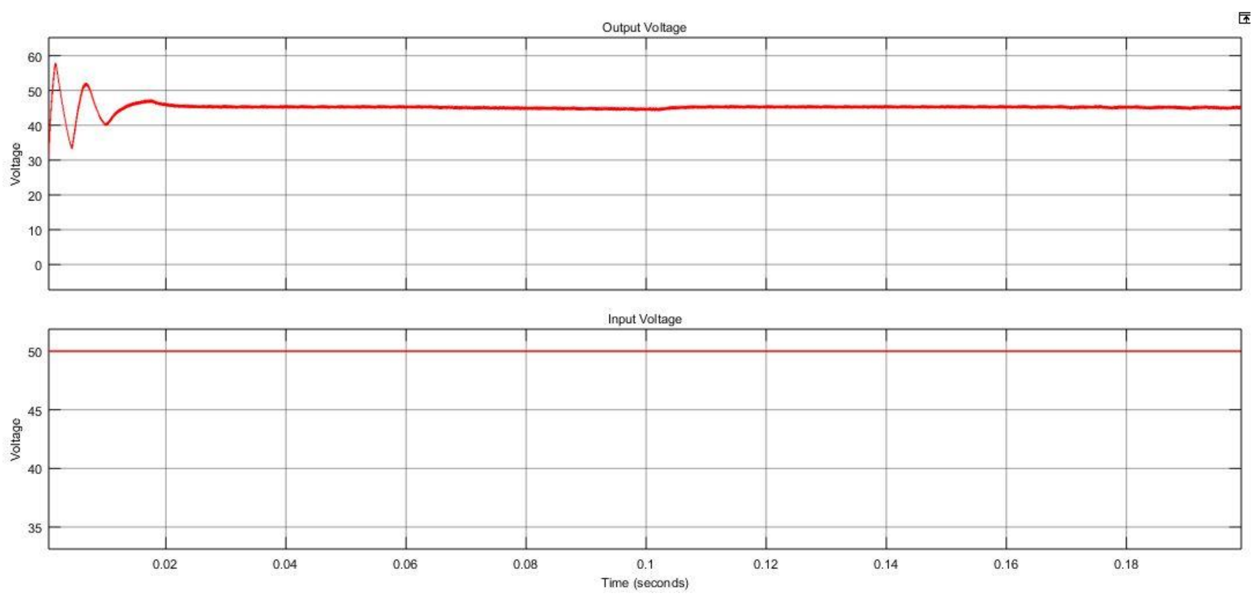

Figure 5.30 Settling Time, V_{oref}=45V

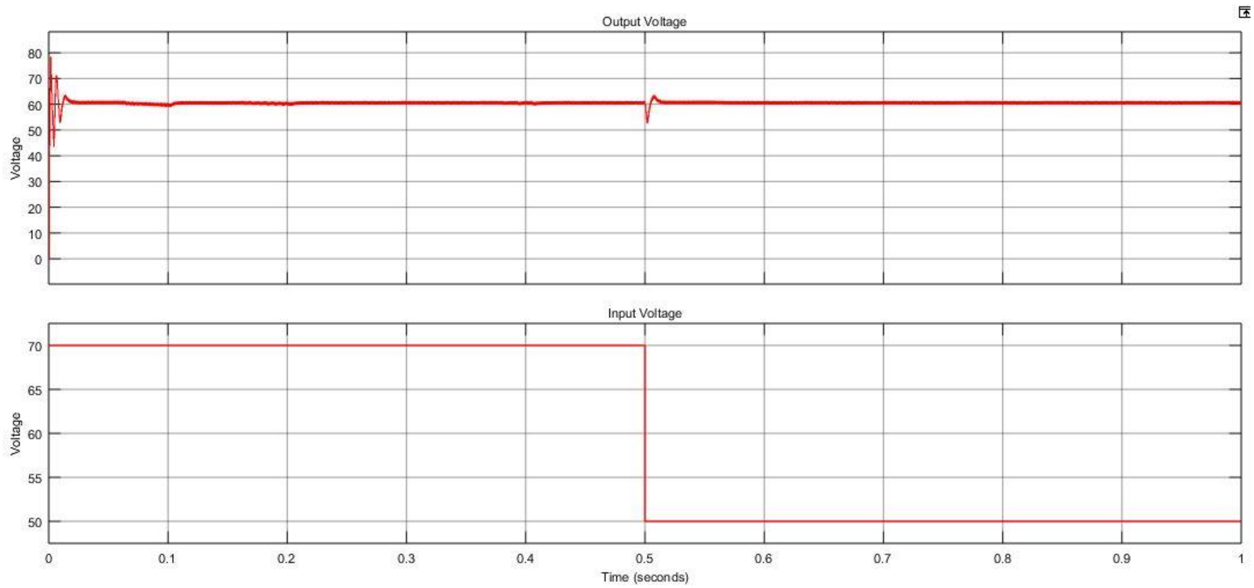

Figure 5.31 V_{oref} is 60 V, V_{in} Lower Limit is 50 V, and V_{in} Upper Limit is 70 V

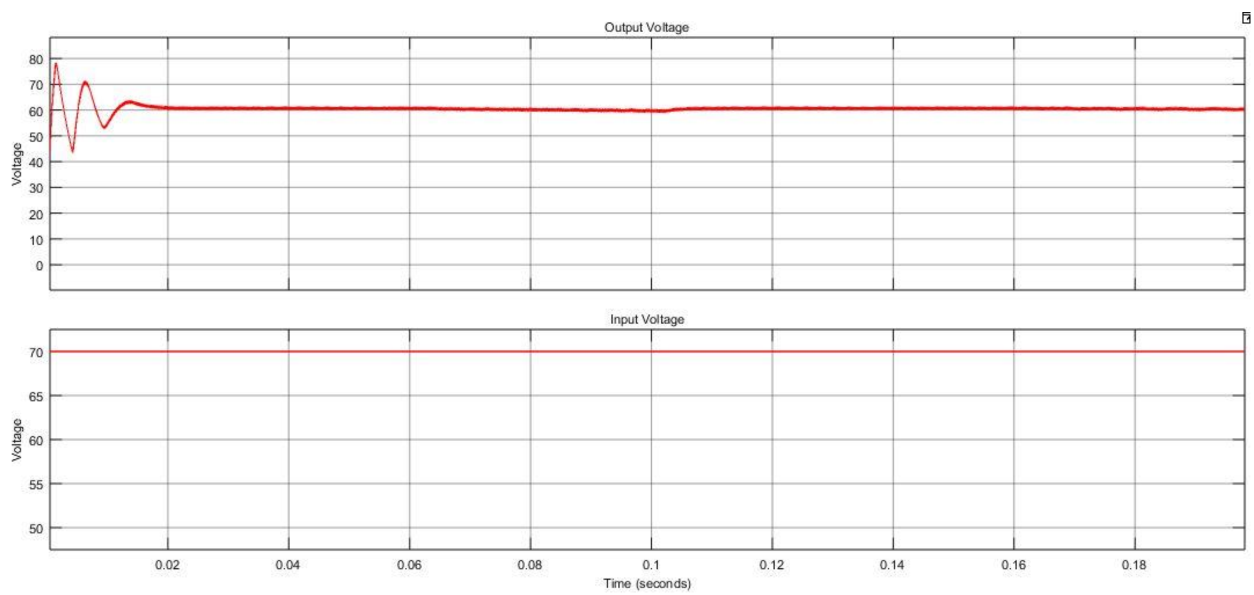

Figure 5.32 Settling Time, V_{oref}=60V

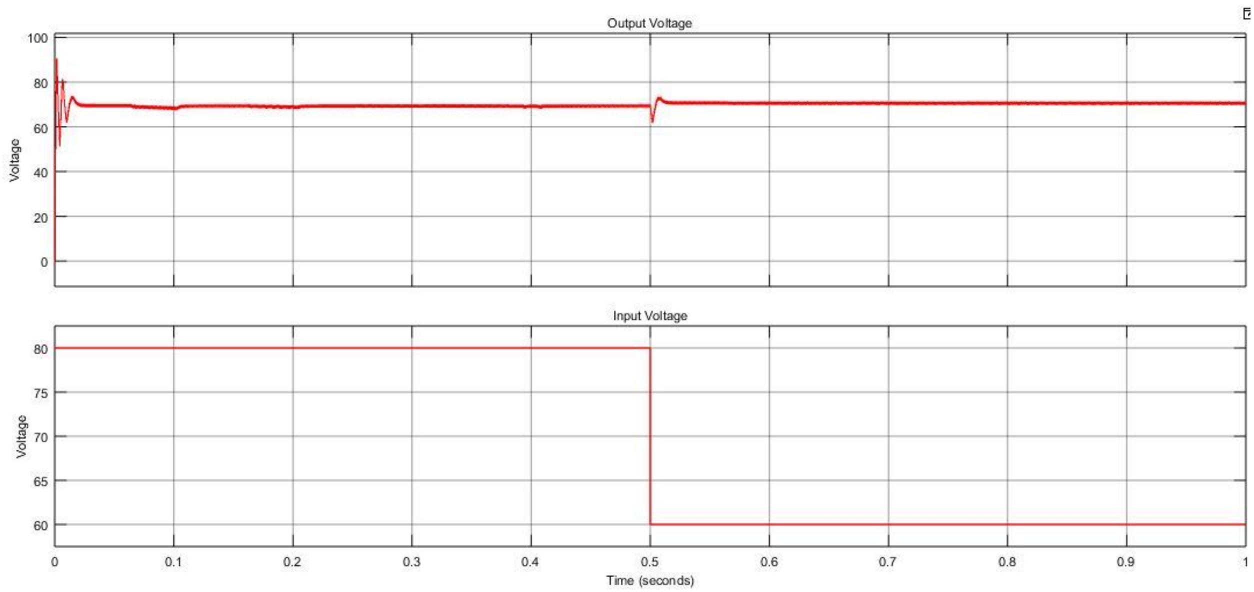

Figure 5.33 V_{oref} is 70 V, V_{in} Lower Limit is 60 V, and V_{in} Upper Limit is 80 V

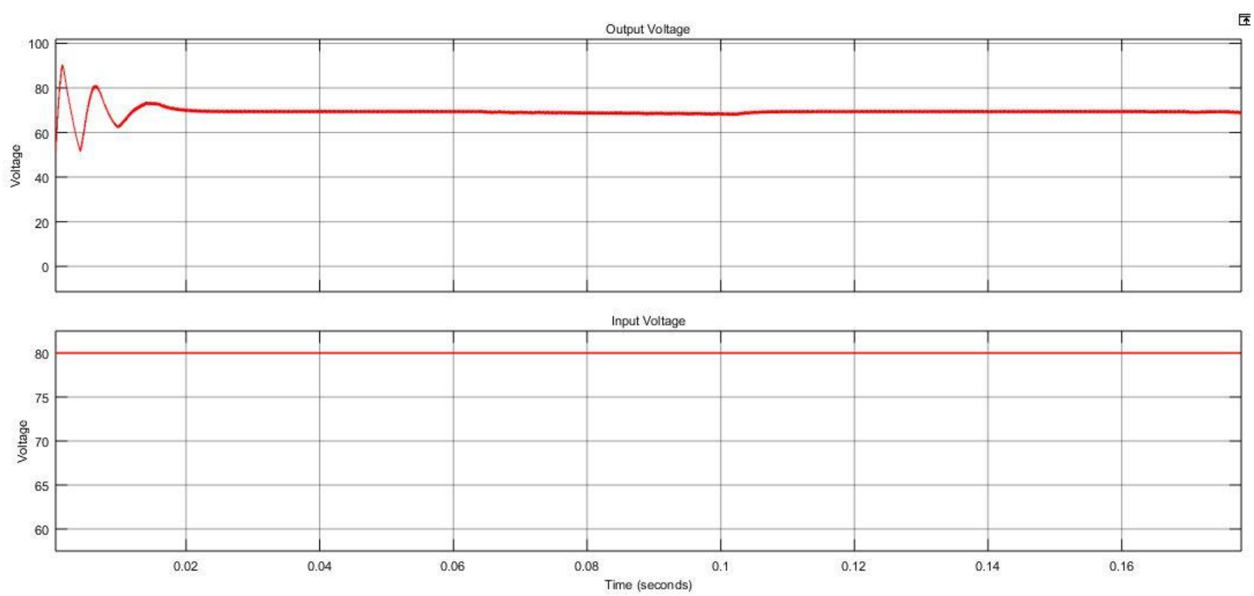

Figure 5.34 Settling Time, V_{oref}=70V

5.3. Sawtooth and PWM Signal Generation

The PWM signal is generated by combining the calculated duty cycle ratio *D* with the Sawtooth signal as shown in Figure 5.35. The Figure 5.36 shows an example of the PWM waveform generated duty cycle ration *D*.

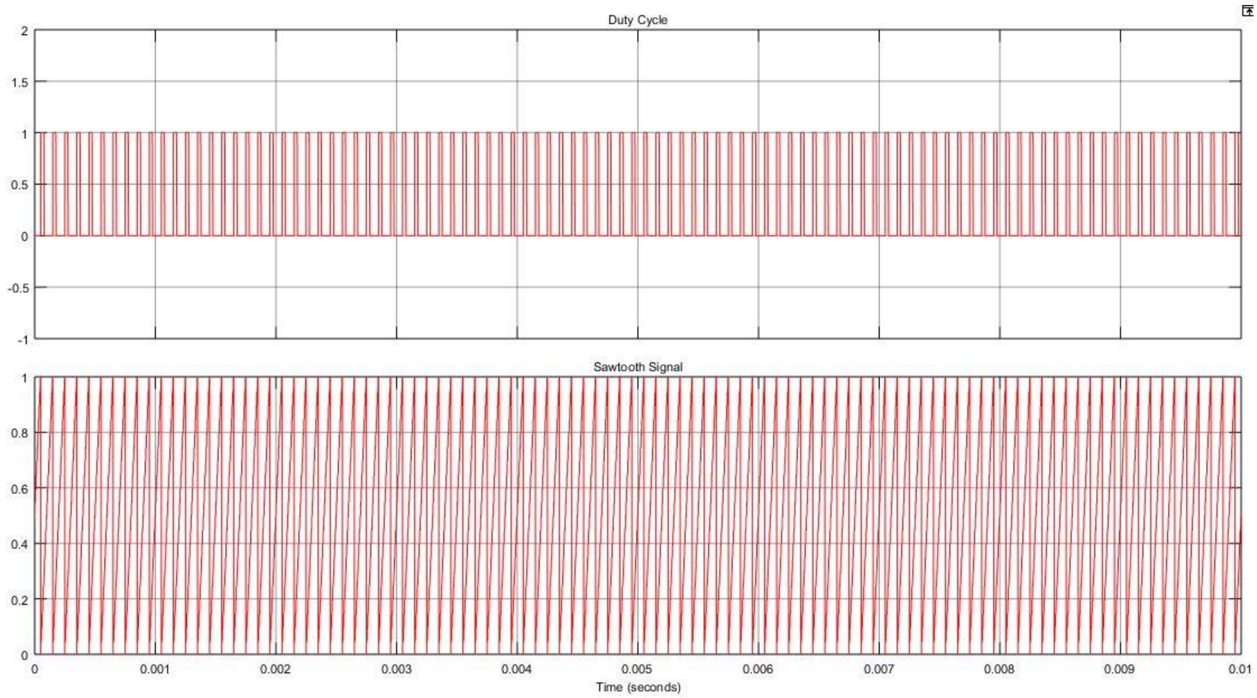

Figure 5.35 Example of the Sawtooth Signal and Generated PWM Signal

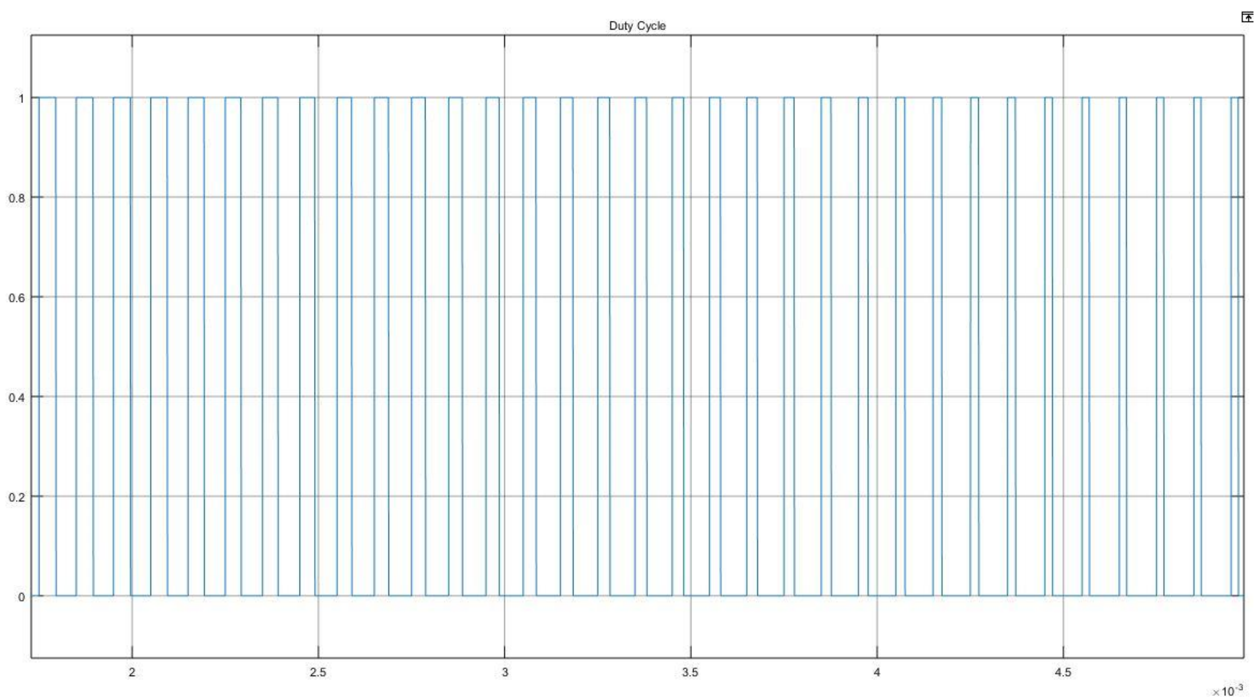

Figure 5.36 Example of the Generated PWM Signal Showing the Change in D

5.4. Selection of the Capacitor and Inductor Values

This section presents the results for different values for capacitors and the inductors use. Figures 5.37 to 5.40 show the waveforms for the output voltage using the capacitor values of 50 μF, 100 μF, 150 μF, and 200 μF. The best capacitor value selected is 150 μF. Figures 5.41 to 5.44 show different inductor values being tested in our design. The inductor was also tuned to select the best value of 50 μH.

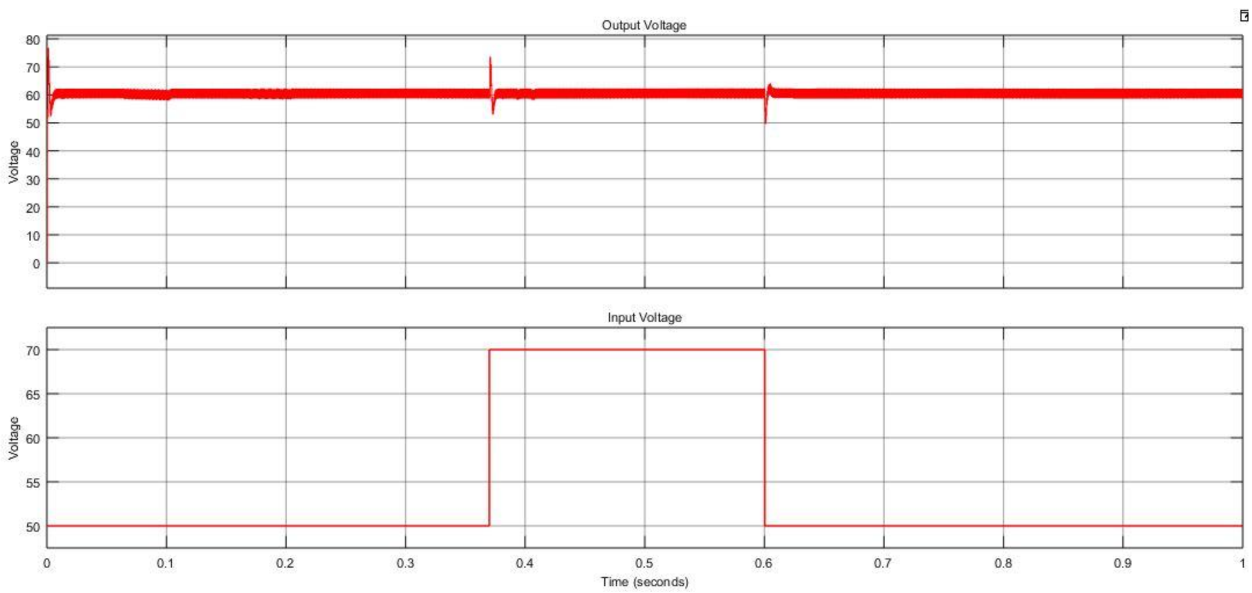

Figure 5.37 Output Voltage When Capacitor Value is 50 μF

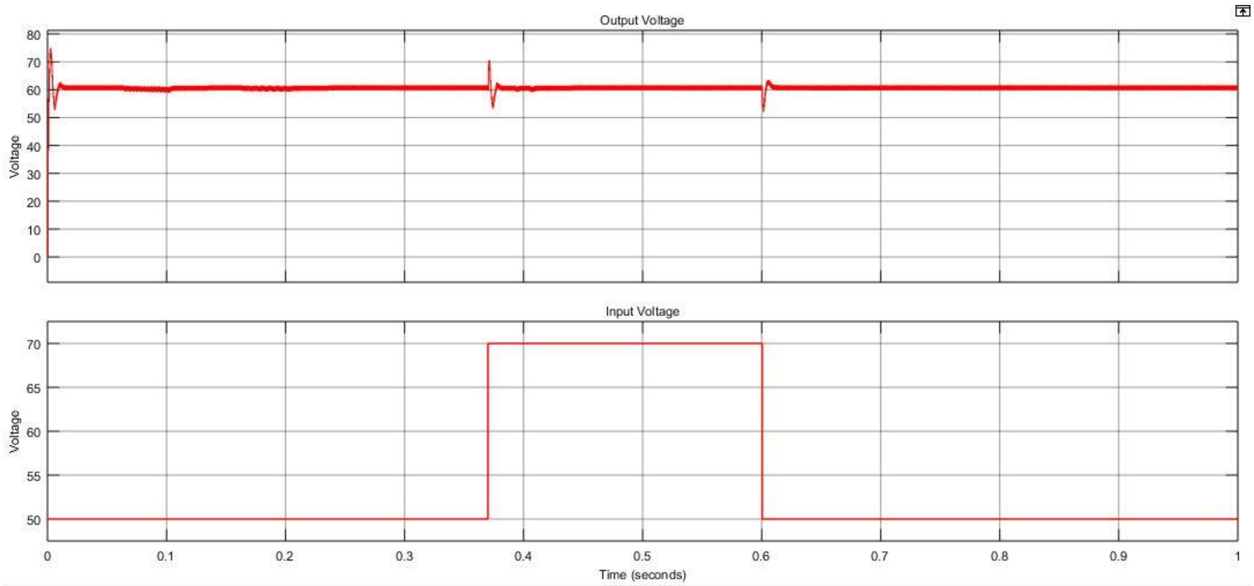

Figure 5.38 Output Voltage When Capacitor Value is 100 µF

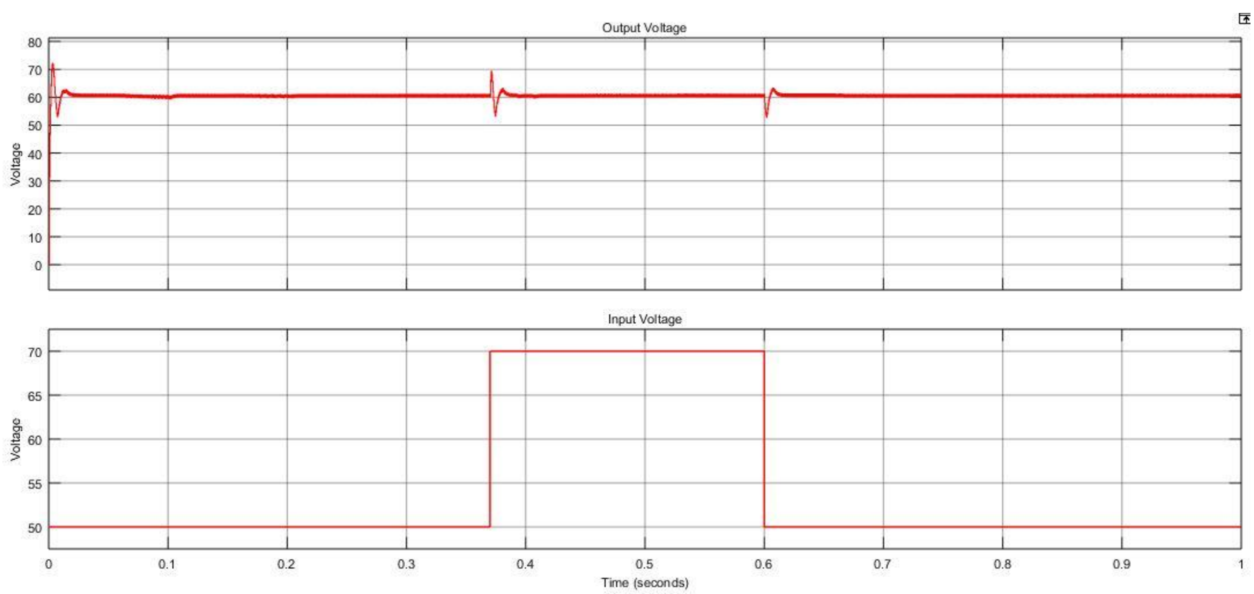

Figure 5.39 Output Voltage When Capacitor Value is 150 µF

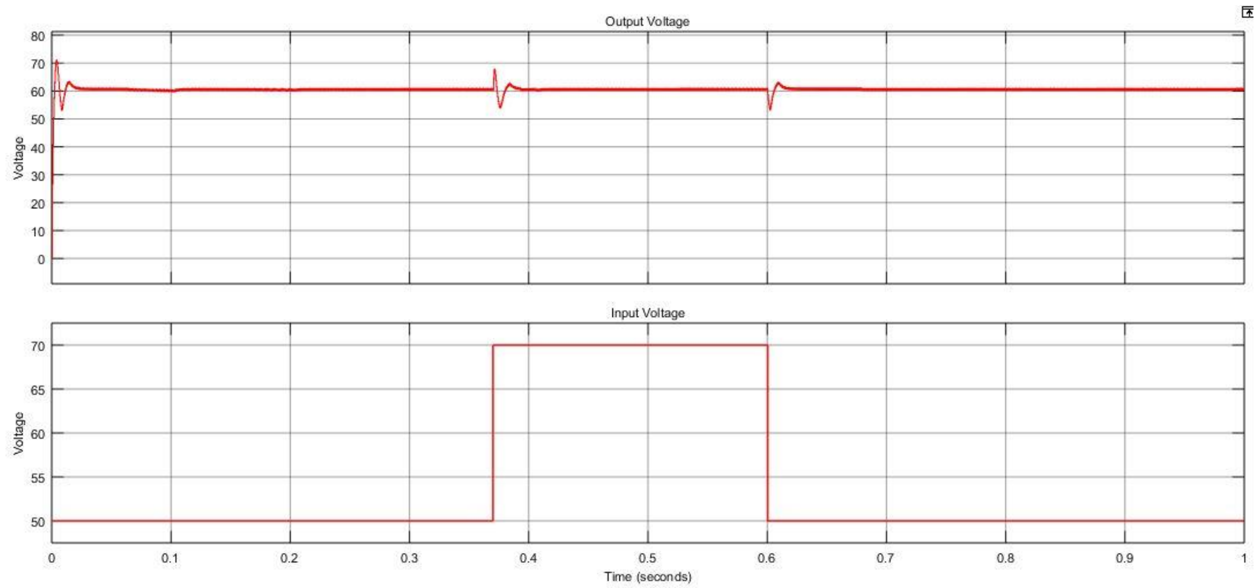

Figure 5.40 Output Voltage When Capacitor Value is 200 µF

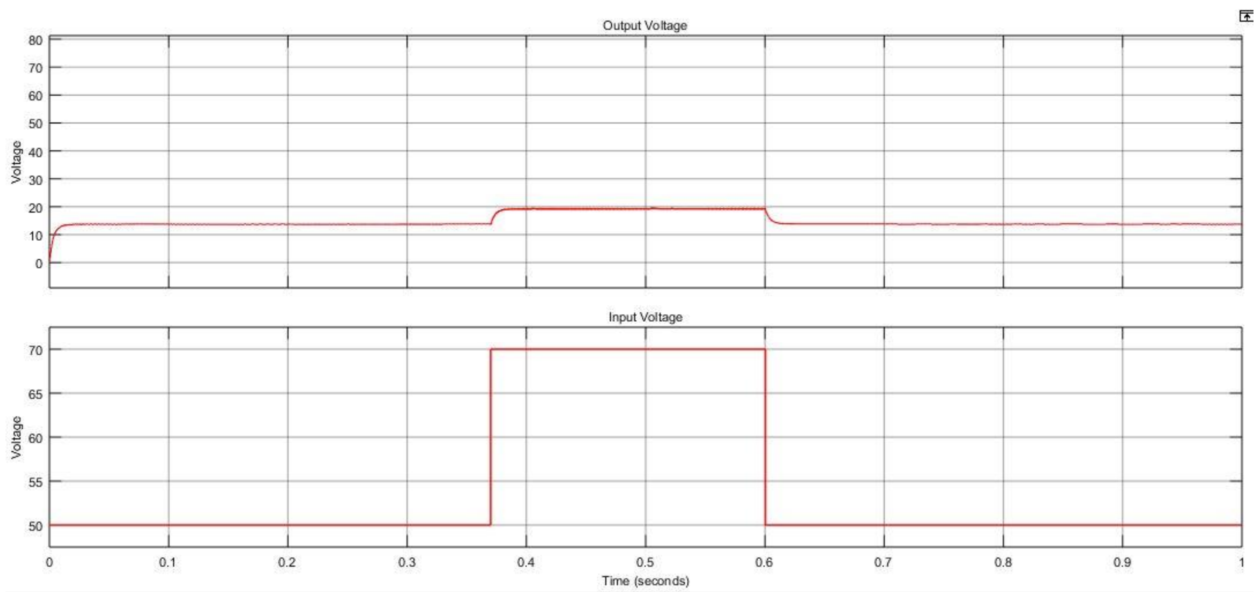

Figure 5.41 Output Voltage When Inductor Value is 0.5 µH

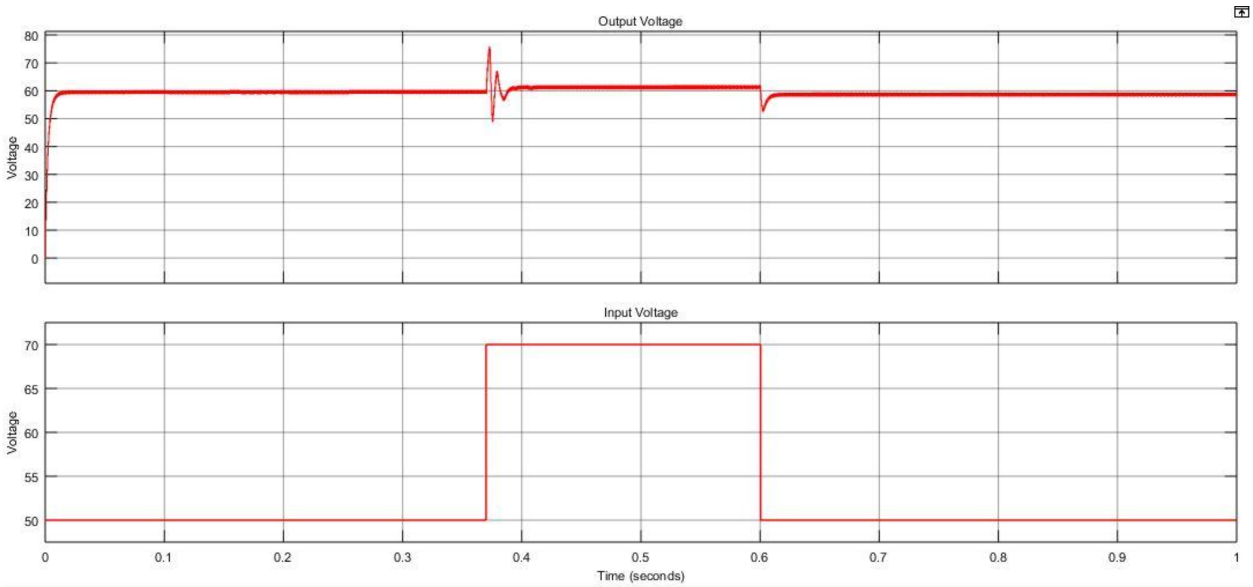

Figure 5.42 Output Voltage When Inductor Value is 5 µH

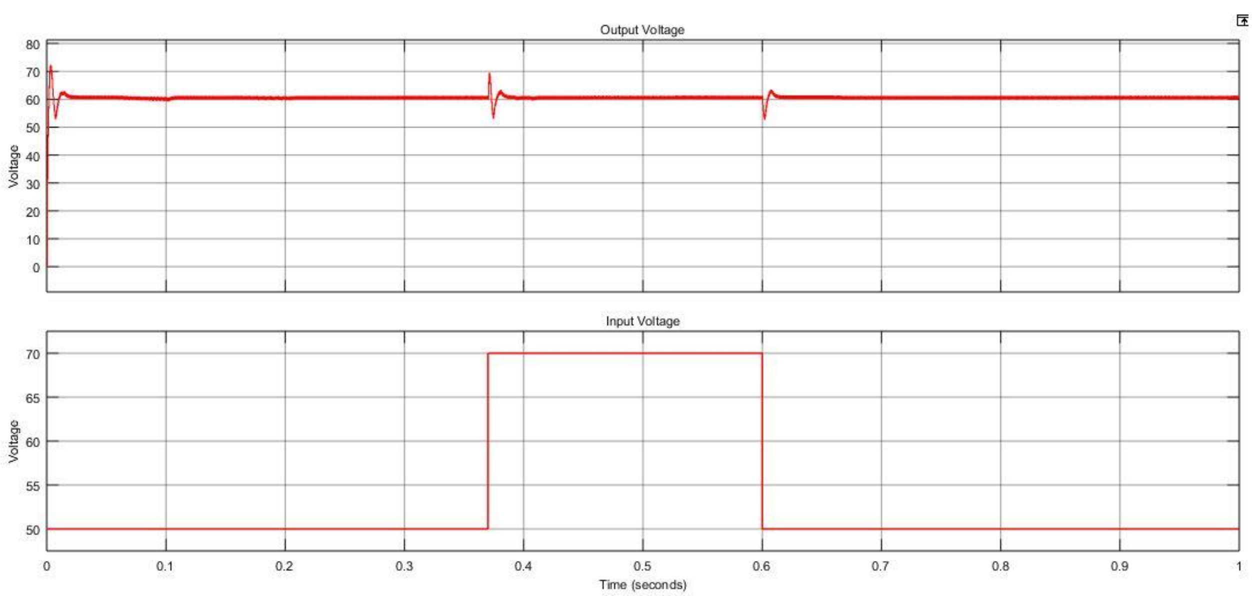

Figure 5.43 Output Voltage When Inductor Value is 50 µH

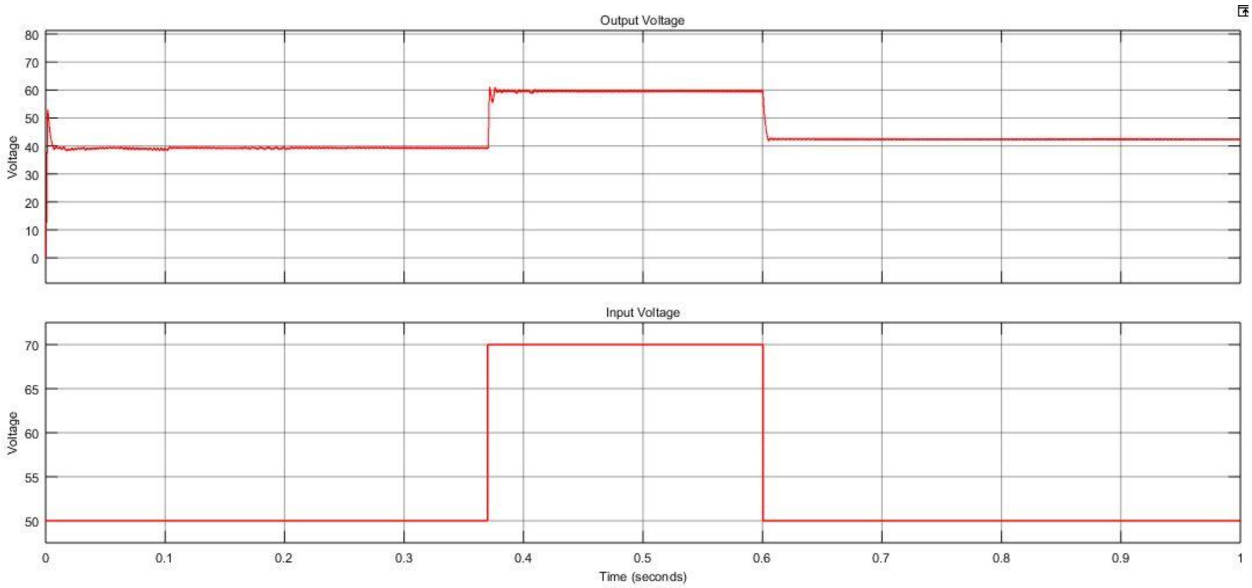

Figure 5.44 Output Voltage When Inductor Value is 500 µH

Figure 5.45 shows the output currents for the Buck-Boost circuit components when the V_{oref} is 60 V, V_{in} lower value is 50 V, and V_{in} upper limit value is 70 V. The value of the capacitor used is 150 µF and for the inductor used is 50 µH.

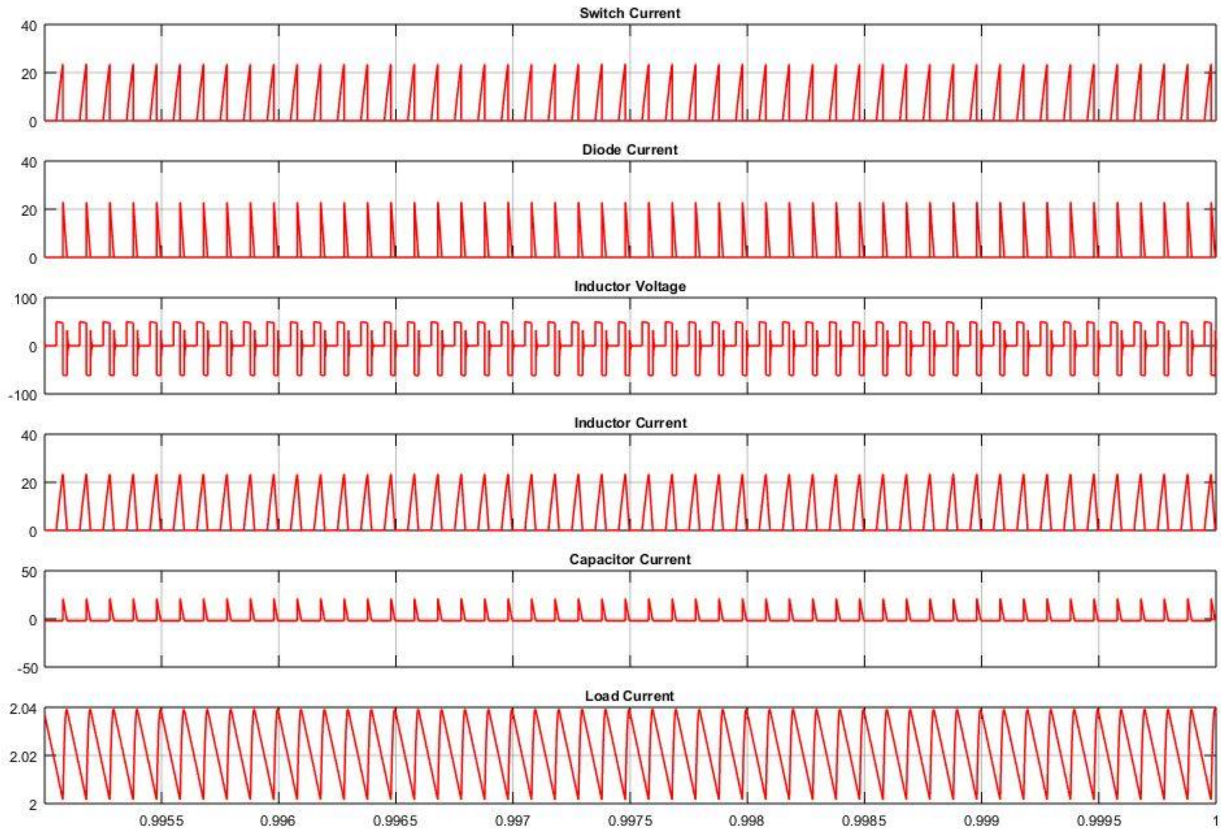

Figure 5.45 Waveforms of Current and Voltage in a Buck–Boost Converter

CHAPTER 6

CONCLUSION AND FUTER WORK

In this thesis, the modeling and performance analysis of the Buck-Boost converter using MATLAB/SIMULINK, have been presented. The parameters for the converter were selected to meet the best performance. The PWM waveform duration was determined from the ratio of the output voltage to the reference output voltage. The PWM was then used to determine the operational modes; Buck or Boost.

The proposed design successfully tracked the output voltage. The design produced robust performance when tested with different input voltage upper and lower limits, and different output reference voltages. The rise time is very short, the settling time is less than 0.018 second, and the settling time for the transition between operation mode is less than 0.02 second. The design is tested for two operational modes; Boost-Buck-Boost, and Buck-Boost.

In future studies, the operational modes concept can be implemented using a microcontroller. The algorithm can also be tested by varying the load connected to Buck-Boost converter, while changing the input voltage. Also, the performance of this controller can be compared with other controllers based the PID, Neural, Fuzzy, or hybrid systems.

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