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Industrial Control Chair

Voltage Control of DC-DC Boost Converter Using Lyapunov Rule Based Model Reference Adaptive Controller

A thesis submitted to the school of Electrical and Computer Engineering of Mekelle University in partial fulfillment of the requirements for the degree of Masters of Science in Control and Instrumentation Engineering

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Declaration

This is to certify that this thesis entitled **Voltage Control of DC-DC Boost Converter Using Lyapunov Rule Based Model Reference Adaptive Controller** submitted in partial fulfillment of the requirements for the award of the degree of M.Sc., in Control and Instrumentation Engineering to the School of Graduate Studies, Mekelle University, through the school of Electrical and Computer Engineering, Industrial Control chair done by **Mr. Mebrahtu Ngusse,** is an authentic work carried out by him under my guidance. The matter embodied in this project work has not been submitted earlier for award of any degree or diploma to the best of my knowledge and belief.

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Abstract

The switched mode DC-DC converters are the simplest power electronic circuits that facilitate the conversion of electrical voltage from one level to another through a switching process efficiently. DC-DC boost converters are utilized for step-up voltage in various applications. The output voltage of boost converter has, oscillation, overshoot, undershoot, and steady-state error. PID controllers have been usually applied to the converters because of their simplicity to obtain the desired voltage. But, PID controller could work well in one operating condition and cannot continuously adapt the changes in the process dynamic. To overcome this problem an advanced controller is required. The proposed Lyapunov Rule Based MRAC is adaptive and non-linear controller designed to overcome the uncertainties and nonlinearities for DC-DC boost Converter under Continuous Conduction Mode (CCM) operating condition. Using MATLAB/Simulink the performance of the proposed Lyapunov rule based MRAC is compared with that of the PID controller based on the dynamic response of the system. Using PID controller, overshoot and settling time have been improved by reducing from 67.5229% to 7.7717% and 0.6985 Sec to 0.277 Sec respectively. In the case of the proposed controller (Lyapunov rule based MRAC), overshoot, settling time, and undershoot have been improved by reducing from 67.5229% to 4.5993%, from 0.6985 Sec to 0.1458 Sec, and from 0.0036% to 0.0% respectively. To test the performance of the DC-DC boost converter, it is assumed that, the input voltage has been decreased and increased from its operating point by 25% and 41.67% respectively. Also the load resistance is assumed to be decreased and increased from its operating load resistance by 25% and 20% respectively. An external disturbance is applied to the system to check how the controller handles to uncertainties and PID controller has shown deviation from the desired value but, the controller MRAC maintained the desired value.

Keywords: MRAC, PID, DC-DC boost converter, CCM, Adaptive control, Lyapunov rule

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List of Symbols

C	Capacitor
C_{min}	Minimum capacitor
D	Average duty cycle
d	Duty cycle
$\hat{d}$	Duty cycle variation
e_{ss}	Steady-state error
f	Switching frequency
i_C	Actual capacitor current
I_L	Average inductor current
i_L	Actual inductor current
$\hat{i}_L$	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
$\hat{i}_S$	Small signal variation of the source current
K_d	Derivative gain
K_i	Integral gain
K_p	Proportional gain
K_u	Ultimate gain
L	Inductor
L_{min}	Minimum inductor
T_u	Ultimate period
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
ΔQ	Change of charge
ΔV_o	Ripple output voltage
y_m	Reference model
θ_1, θ_2	Controller parameters to be updated
γ	Adaptation gain

List of Acronyms

CCM	Continuous conduction mode
DCM	Discontinuous conduction mode
DC	Direct current
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal oxide Semiconductor Field Effect Transistor
MRAC	Model reference adaptive controller
MIT	Massachusetts institute of technology
PI	Proportional Integral
PID	Proportional Integral Derivative
PWM	Pulse width modulation
SMPS	Switched mode power supply

CHAPTER ONE

INTRODUCTION

1.1. Background

Nowadays, the power electronic has changed the life of mankind. It has affected on power generating, transportation and many other industrial procedures [1]. The objective of a power electronics circuit is to match the voltage and current requirements of the load to those of the source. Power electronics circuits convert one type or level of voltage or current waveform to another and are hence called converters. Converters serve as an interface between the source and load. The dc-dc converters are useful when a load requires a specified (often regulated) dc voltage or current but the source is at a different or unregulated dc value [2]. They can be found in almost-every electronic device nowadays, since all semiconductor components are powered by DC sources [3].

The three basic topologies of switching regulators which are used to transfer energy from input to output are boost (voltage step-up), buck (voltage step-down) and buck-boost (voltage step-down-up) converters. The Boost power electronic converter, also known as the step-up converter, is one of the basic topologies of DC-DC converters that step-up the input side voltage while the current steps down from input to output. It is a class of switched mode power supply (SMPS) typically containing at least two semiconductors (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or both in combination. Its main characteristic is that the output voltage is greater than or equal to the input voltage. That is why it can be found in applications where it is necessary to raise and regulate the voltage [4].

DC-DC Boost Converters are nowadays extensively used in the electrical and electronic industries. This simple circuit is the need of almost every electronic circuit, new generation Electric vehicles, medical equipment, textile industry, space systems, renewable energy systems, etc. [5].

DC-DC boost converters can be operated either in continuous conduction mode (CCM) or in discontinuous conduction mode (DCM) based on the continuity of inductor current flow. A dc-dc boost converter is said to be operating in CCM, if inductor current never reaches to zero and is said to be operating in DCM, if inductor current reaches zero and remains there for certain period of time [6].

DC-DC boost converter requires controller to manage the desired value. Adaptive controls are widely used by researchers to solve dynamic problems and some of them use PID as its control structure. Conventional PID controllers are effective in linear systems, but it is not suitable for non-linear systems and higher-order systems. The fixed parameter in PID controller is not quite robust or not able to adapt and therefore the adaptive controller techniques is required to improve system response [7].

Adaptive control is one of the most widely used control strategies to design advanced control systems for better performance and accuracy. Adaptive control is thus, a controller that can modify its behavior in response to changes in the dynamics of the process and the character of the disturbance [8].

Model reference adaptive control is one of the main approaches of adaptive control schemes. The desired performance is expressed as a reference model. The adjustment mechanism changes the parameters of the converter by minimizing the error between the system output and the reference model. Hence, the lyapunov rule based model reference adaptive controller is intended to track output voltage of the boost converter to the reference by minimizing the error with guaranteed stability [8].

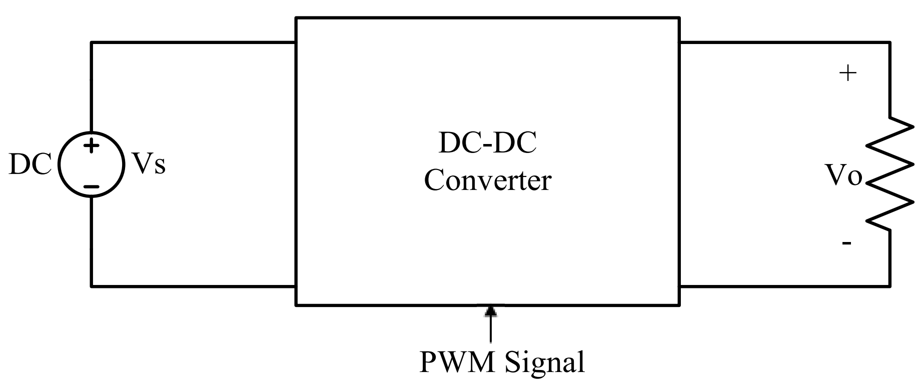


Figure 1. 1:Block diagram of DC-DC converter [9]

An electric power converter, DC-DC converter or more commonly known as a switched mode DC-DC converter as shown in Figure 1.1, either steps up or steps down the source voltage, Vs according to the requirement of the load connected, by making adjustments in the duty cycle applied to the switching device [9]

1.2. Statement of the Problem

The DC-DC boost converters consist of power semiconductor devices that are operated as electronic switches. The control of the DC-DC boost converter is a challenging task due to the inherently nonlinear characteristic of the switching operation. The output voltage of boost converter has, oscillation, overshoot, and undershoot. Not only this, but also it is unable to give the desired voltage under input voltage and load variations, which results in steady-state error. The switching converters should be insensitive to load disturbances and fluctuations of the voltage sources. The nonlinearity of a DC-DC boost converter can have a range of adverse effects on devices such as communication systems that rely on precise voltage regulation. The voltage deviations might cause operational errors, system resets, or failure of components. Consequently, this converter needs a controller with a high degree of dynamic response. Proportional-Integral-Differential (PID) controllers have been usually applied to the converters because of their simplicity to obtain the desired voltage. However, applications of PID controllers are not reliable and satisfactory in the case of non-linear systems. It is difficult to account for the variation of system parameters and also it produces an overshoot and undershoot, which in turn influence the voltage regulation of boost converter. Therefore, the Lyapunov rule based MRAC, which is an adaptive controller, has been designed for the boost converter to improve the converter performance by reducing the overshoot, oscillation, undershoot, and it gives the desired output voltage under the variation of the input voltage and load resistance.

1.3. Objectives

1.3.1. General objective

The general objective of this thesis is to design lyapunov rule based model reference adaptive controller (MRAC) for voltage control of a DC-DC boost Converter in order to improve performance responses.

1.3.2. Specific objectives

The specific objectives of this thesis are:

- To improve the performance values of the DC-DC boost converter
- To adapt the small signal model of DC-DC boost converter using state space averaging
- To linearize the small signal model of DC-DC boost converter
- To adapt the mathematical model of DC-DC boost converter.
- To analyze and compare the dynamic performance of conventional PID with Lyapunov rule based MRAC for DC-DC boost converter and simulate using MATLAB/Simulink

1.4. Scope of the Thesis

This thesis is focused on voltage control of the DC-DC boost converter using lyapunov rule based MRAC. The entire system is simulated using MATLAB/Simulink, by considering on the converter's operation in continuous conduction mode (CCM), and ideal conditions. Finally, the performance analysis of the lyapunov rule based MRAC is to be studied in terms of time domain specifications.

1.5. Significance of the Thesis

The boost converter is a DC-DC voltage level amplifier. The output voltage of the DC-DC boost converter has the potential to contribute in a significant way in electric vehicles, industry, communication, renewable energy systems, and household appliances.

1.6. Methodology

This section explains the methodology to be employed in this thesis. The first task to meet the general objective stated above is to review related works done on DC-DC boost converter. It has been reviewed what have been done before this thesis about DC-DC boost converter and analyzed their good feature and drawbacks.

The second step is to study and modeling of the DC-DC boost converter system mathematically. The mathematical model developed contains some nonlinear terms since the system is nonlinear, therefore assuming the system acts linear for some range of operation it will be linearized around its equilibrium point by using small signal linearization technique of the DC-DC boost converter.

The next task is designing of the proposed controller which is MRAC based on Lyapunov adaptation rule and then the response of the system is simulated using MATLAB/Simulink. The other thing is, the output response performance of the proposed controller is compared with the output response performance of conventional PID controller by varying the input voltage and load resistance. Finally, the performance of the proposed controller tested through simulation and the result shows the validity of the designed system and the conclusion is drawn from the simulation result.

1.7. Thesis Layout

The thesis is organized as follow:
Chapter one briefs the overall background of the study. The main part of study such as statement of the problem, thesis objective, thesis significances, thesis scope, and methodology used to accomplish this thesis, and thesis report layout is presented well in this chapter.

Chapter two covers the literature review of previous study and general information about boost converter and theoretical review on PID control, Adaptive control system are also described in this chapter.

Chapter three presents the system model and controller design. The methodology used to derive the mathematical model of open loop boost converter, and used to design PID controller and MRAC based on Lyapunov adaptation rule is described well in this chapter

Chapter four presents the overall results of the boost converter without controller and with controller in different cases. Also the effectiveness of PID controller and MRAC are compared.
In Chapter five conclusion and recommendation for future works are discussed.

CHAPTER TWO

LITERATURE REVIEW

2.1. Related Work

DC-DC converters are widely used in switch-mode power supplies. Since, the switching transistor dissipates less power when serving as a switch, SMPS have high efficiency. These switch mode DC-DC converters have received an increasing deal of interest in many areas due to their wide applications. The basics of the DC-DC converters have been reviewed, and the same has been extended to the control mechanism. The switching converters should be insensitive to load disturbances and fluctuations of the voltage sources. Therefore analysis, control and stabilization of switching converters are the main factors that need to be considered. Many control methods are used for controlling of switch mode DC-DC converters. The following papers are reviewed so far related to the voltage control of DC-DC boost converter.

M.F. Adnan et al.in [9] proposed Design and Simulation of a DC - DC Boost Converter with PID Controller for Enhanced Performance. In this paper proper voltage regulation of Boost converter is achieved employing PID controller, tuned using trial and error method to find appropriate values for the proportional, integral and derivative gains, thereby improving converter performance. Incorporating a PID controller with the converter improves the dynamic response and try to reduce the steady-state error and attain the final value. However, it is observed that the output voltage fluctuates with variation of input voltage by a large amount. Moreover the converter exhibits significant increase in undershoot, settling time and oscillation as the input voltage varies.

M. Kumar et al.in [10] have proposed design of a model reference adaptive controller (MRAC) for DC-DC Boost Converter for Variations in Solar Outputs using modified MIT Rule in an Islanded Micro grid. In this paper, a design perspective of a dc-dc boost converter is proposed, which stabilizes the output voltage variations with the help of a modification in the MIT rule. A set of inputs are considered and applied to the converter to validate the accuracy of the proposed model with the help of adaptation gain. The modified MIT rule based controller follows the reference model in a precise way. But MIT rule based controllers are very sensitive towards variations in input and can cause instability into the system. So, MIT rule is not stability guaranteed.

C.S. Sachin et al.in [11] have proposed Design and Simulation for Sliding Mode Control in DC-DC Boost Converter. In this paper the boost converter is modeled and PWM based sliding mode controller is designed to overcome deficiency present in conventional PWM controllers by giving a good regulation at any operating condition. The sliding mode control is robust to load variations and provide consistent performance. But due to the chattering effect of the sliding mode controller the system has significant overshoot and oscillation.

K. V. Khunte et al. in [12] proposed Output Voltage Control of DC-DC Boost Converter Using Model Predictive Control Approach. This article contains an approach to control the output voltage of dc-dc boost converter using model predictive control algorithm. The proposed control algorithm has any merits such as fast response time, very little deviation from reference value despite change in other parameters of model. The proposed strategy is very easy to understand and gives a systematic approach for designing a controller. There is no requirement of tedious work of tuning the gains every time to get expected results, once set the model is capable of working over the wide range of values. But in this paper the output voltage has an oscillatory nature and results to stability problem. MPC have computational complexity.

K. Vishnu et al. in [13] proposed Boost converter with fuzzy logic, pi controller and sliding mode control for a variable source input. This paper discusses types of feedback control used in variable source fed Boost converter. Disadvantages of PI controllers are for a nonlinear system it is not reliable, when overshoot in output voltage reduces at that time system shows longer rise time, more effect on dynamic response and output voltage regulation. The sliding mode controller is a non-linear based controller. The advantages of sliding mode controller are for large line and load variations it provide good stability, fast dynamic response, simple ,easy for implementation, high robustness. Disadvantages of sliding mode controller are converters suffer from changes in switching frequency, and there is high oscillation due to chattering effect. Advantages of Fuzzy Logic Controller is, it provides a strong performance under variation in parameter and load disturbances. But, still the output has overshoot, oscillation and has high computational time that results to computational complexity.

T. Kobaku et al. in [14] proposed Quantitative Feedback Design Based Robust PID Control of Voltage Mode Controlled DC-DC Boost Converter. The article presents a comprehensive study and design of robust PID controller for DC-DC boost converter using Quantitative feedback theory (QFT). In this work, a computationally simple robust PID controller is designed using QFT to control the output voltage of a DC-DC boost converter under voltage mode control. The proposed robust PID controller exhibits improvement in the output voltage response in the presence of uncertainty and external disturbances. The simulation results clearly show that the proposed robust PID controller performs better than the conventional PID controller for various disturbances. It provides a quick corrective action than the conventional PID and thereby achieving significant improvements such as fast settling time and reduced over/undershoot, respectively. However, there is an oscillation on the system response that could result the system to be unstable.

M. Shadoul et al.in [15] proposed DC- DC Boost Converter Controller Design for PV Applications. In the proposed paper the method used to design the controller is root locus method and the controller for the boost converter in this paper is PI controller. The controller and the model are tested in the MATLAB/SIMULINK for source and load disturbances. The simulation results show that the closed-loop performance with PI controller is improved compared with closed loop controller with-out controller and minimize any steady state error. But PI controller effectively handles for linear systems and it does not give better performance for nonlinear systems. So, this leads to instability, oscillation and poor performance in controlling the system.

To improve the drawbacks in the reviewed literature, a controller with a high degree of dynamic response is required. Adaptive control is thus, a controller that can modify its behavior in response to changes in the dynamics of the process. So, the proposed Lyapunov rule based MRAC is designed to handle systems with uncertainties or variations by adapting the controller parameters based on the difference between the desired system model and the actual system behavior. The reference model is to be tracked by the plant by minimizing the error. The control unit is to be adjusted by the parameter adjustment mechanism of the controller under parameter uncertainties so as to provide the desired response.

2.2. DC-DC Converter

Mainly, the DC-DC converters are the simplest power electronic devices that consists of the power

Semi-conducting devices which are operated as electronic switches and classified as switched-mode DC-DC converters or normally referred as Switched mode power supply. These converters are electronic devices that are used to change DC electrical power efficiently from one voltage level to another. They are an electronic circuit which converts a DC signal from one voltage level to another level by storing the input energy and realizing that energy to the output at different voltage level.

The DC-DC converters use an inductor and a capacitor as energy storage elements so that energy can be transferred from input to the output. DC- DC converters are widely used in switched-mode power supplies (SMPS) and have a wide range of uses today and are becoming increasingly more important in everyday use. To achieve the output voltage constant, feedback control loop is used to automatically adjust the duty cycle regardless of input voltage variation and load changes. There are different types of DC-DC converters. The most commonly known are:

- Boost converter
- Buck converter
- Buck-boost converter

2.3. Boost Converter

The DC-DC boost converter (DBC) is the simplest converter topology for effectively reproducing increased output voltage for a given input voltage .Boost converter is used to convert unregulated DC input voltage to a controlled DC output voltage with a desired voltage level. It is sometimes called a step-up DC-DC converter.

Boost converters are considered indirect energy transfer converters. The converter transfers energy by use of an energy storing phase and an energy discharging phase .When the switch is open the energy is stored in the inductor while the output capacitor delivers power to the load. When the switch is closed, the inductor transfers energy to the capacitor to recharge the capacitor [16].

In power electronics, boost converters are widely used to power devices. There are many types of voltage supplies, such as batteries, fuel cells, generators, that can provide a constant voltage or can be obtained directly from an AC source through a rectifier. However, the load may require a voltage that is higher than that which can be supplied. The boost converter is responsible for taking this lower input voltage and converting it to the higher voltage required.

Boost converters do not generate power; rather, they use an inductor and a switch to store energy and release it at levels greater than that provided by the input [17] .The topology gets its name from producing an output voltage that is higher in magnitude than the input voltage. The circuit diagram of boost converter is as shown below by figure 2.1.

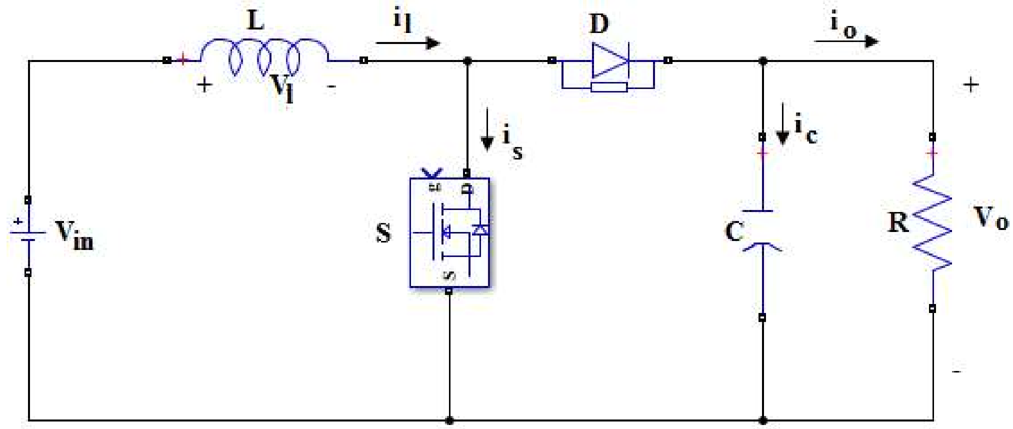


Figure 2. 1:Boost converter topology [18]

The waveforms of boost converter for continuous conduction mode of operation are shown in the Figure 2.2 below.

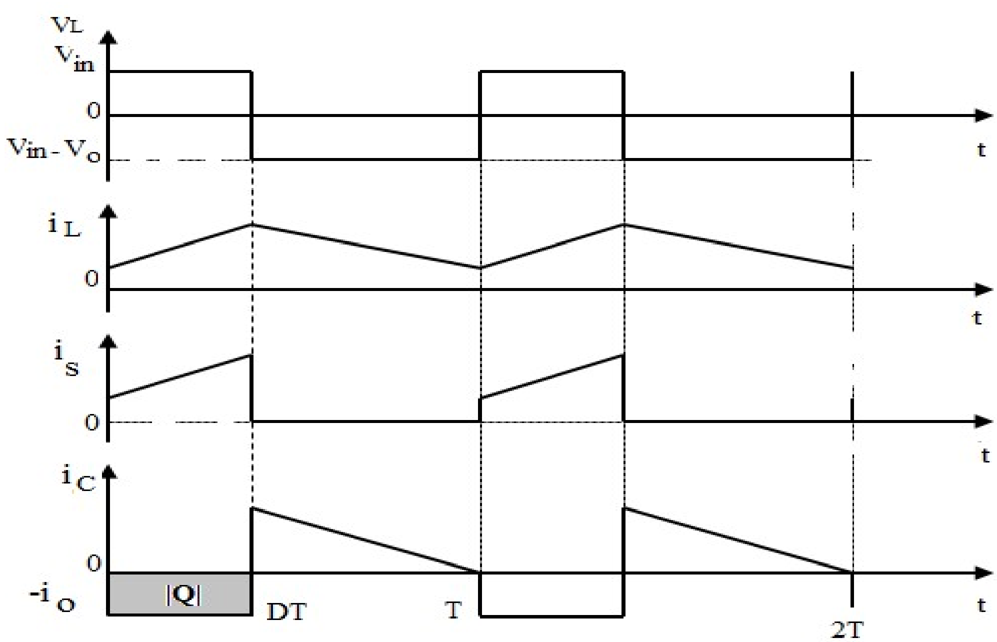


Figure 2. 2:Waveforms of boost converter [18]

2.3.1. Boost Converter Formula

Based on the boost converter analysis for the switch closed and open and using Kirchhoff's voltage law and current law it is possible to calculate the following.

Calculation for Duty Ratio

For calculation of the duty ratio, first of all assume that the converter is in steady-state. The following assumptions are to be made for the calculation of the duty ratio.

- The circuit exists in steady-state condition
- Components are ideal hence parasites are neglected.
- The circuit occurs to be in continuous conduction mode. Current through inductor is continuous.
- Capacitor is very large, the voltage at the load is constant
- Switching period is T and Duty Cycle is D. The switch is open for time (1-D) T and closed for time interval DT.

2.3.1.1. Boost Converter Analysis for the Switch Closed (ON)

From Figure 2.1 as shown in the above, when the switch (MOSFET) is closed (ON) for time duration t_{on} the switch conducts the inductor current and the diode becomes reverse biased. This results in a positive voltage across the inductor. T is the switching period, and the switch is closed for time DT and open for$(1-\mathrm{D})\mathrm{T}$, where D is the steady-state duty cycle. "ON" mode state:

$$V_{in} - L\frac{di_L}{dt} = 0 \tag{2.1}$$

$$\frac{V_C}{R} + C\frac{dV_C}{dt} = 0 \tag{2.2}$$

Rearranging Equation (2.1) gives,

$$L\frac{di_L}{dt} = V_{in} \tag{2.3}$$

Equation (2.3) can be written as,

$$\frac{\Delta i_L}{\Delta t} = \frac{V_{in}}{L} \tag{2.4}$$

Since, the duration of time when the switch ON is given as $\Delta t = DT$, Equation (2.4) is given as,

$$\Delta i_{L(closed)} = \left(\frac{V_{in}}{L}\right) DT \tag{2.5}$$

Equation (2.5) is the expression for the inductor current when **s**witch is closed. Where, D = duty ratio.

2.3.1.2. Boost Converter Analysis for the Switch Open (OFF)

From Figure 2.1 as shown in the above, when the switch (MOSFET) is turned off, because of the inductive energy stored, inductor current continues to flow. During this time diode is forward biased and the current flows through it. Now the voltage across the inductor can be defined by.

$$V_L = V_{in} - V_o = L\frac{di_L}{dt} \tag{2.6}$$

Equation (2.6) can be written as,

$$\frac{\Delta i_L}{\Delta t} = \frac{V_{in}-V_o}{L} \tag{2.7}$$

Since the duration of time when the switch becomes OFF is given as, $\Delta t = (1-D)T$ Equation (2.7) is given as,

$$\Delta i_{L(open)} = (\frac{V_{in}-V_o}{L})(1-D)T \tag{2.8}$$

We already know that at steady state the current through the inductor over a time period T is zero. From that assumption, we can derive:

$$\Delta i_{L(closed)} + \Delta i_{L(open)} = 0 \tag{2.9}$$

Substituting Equation (2.5) and (2.8) into Equation (2.9) and simplifying it gives,

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \tag{2.10}$$

Equation (2.10) shows the relation of the Duty ratio to the input, output voltages of the circuit. From this equation, it is evident that increasing in the duty ratio will result in a larger output than the supply voltage and the output voltage cannot be lower than the supply voltage. In other ways, since in steady-state operation waveform must repeat from one time period to the next, the integral of the inductor voltage V_L over one time period must be zero.

$$\int_0^T V_L\, dt = \int_0^{t_{on}} V_L\, dt + \int_{t_{on}}^T V_L\, dt = 0 \tag{2.11}$$

Where T is switching period i.e.$(T = t_{on} + t_{off})$ and integrating over switching period gives,

$$(V_{in})t_{on} + (V_{in} - V_O)(T - t_{on}) \tag{2.12}$$

If equation (2.12) is simplified,

$$\frac{V_o}{V_{in}} = \frac{T}{T-t_{on}} = \frac{1}{1-D} \tag{2.13}$$

Calculation for Inductor

Assuming no power losses in the converter, the average power supplied by the input is equal to the average power absorbed by the load. From the law of energy conservation:-

$$P_O = P_{in} \tag{2.14}$$

But, equation (2.14) can be written as,

$$V_O I_O = V_{in} I_L = \frac{{V_O}^2}{R}$$

$$V_{in} I_L = \frac{{V_O}^2}{R}$$

$$V_{in} I_L = \frac{\left[\frac{V_{in}}{(1-D)}\right]^2}{R} \tag{2.15}$$

From the above expression, the expression of I_L is obtained as such:

$$I_L = \frac{V_{in}}{R(1-D)^2} \tag{2.16}$$

The maximum and minimum inductor currents can be derived by using the average values of inductor currents as:

$$I_{Lmax} = I_L + \frac{\Delta i_L}{2} \tag{2.17}$$

$$I_{Lmax} = \frac{V_{in}}{R(1-D)^2} + \frac{V_{in}DT}{2L} \tag{2.18}$$

$$I_{Lmin} = I_L - \frac{\Delta i_L}{2} \tag{2.19}$$

$$I_{Lmin} = \frac{V_{in}}{R(1-D)^2} - \frac{V_{in}DT}{2L} \tag{2.20}$$

For continuous conduction mode, the inductor current must remain positive. Therefore, to determine the boundary between continuous conduction mode and discontinuous conduction mode the minimum inductor current is set to zero.

$$I_{Lmin} = \frac{V_{in}}{R(1-D)^2} - \frac{V_{in}DT}{2L} = 0 \tag{2.21}$$

Rearranging and solving equation (2.21), the minimum inductor for continuous current is given as:

$$L_{min} = \frac{D(1-D)^2 R}{2f} \tag{2.22}$$

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

So, the value of the inductor that determines the boundary between the CCM and DCM operation is the one given in equation (2.22). Thus for boost converter to operate in CCM, the value of inductor should be greater than the minimum value of inductor.

The ripple inductor current is given as the difference between the maximum and minimum value of the inductor current.

$$\Delta i_L = I_{Lmax} - I_{Lmin} \tag{2.23}$$

Substituting for I_{Lmin} and I_{Lmax} from Equation (2.20) and (2.18) respectively into Equation (2.23) and simplifying gives,

$$\Delta i_L = \frac{V_{in}}{L} DT \tag{2.24}$$

Calculation for Capacitor: The output capacitor is assumed to be very large in order to yield constant output voltage. For a given capacitor value the ripple in the output voltage (ΔV) can be calculated by considering the waveform shown in Figure 2.2 above for continuous conduction mode of operation. The filter capacitor must provide the output DC current to the load when the diode is off. The maximum increase of the charge (ΔQ) which is stored in filter capacitor C is equal to shaded rectangular area.

$$|\Delta Q| = i_O DT \tag{2.25}$$

$i_O = \frac{V_O}{R}$ And substitute to equation (2.25), then

$$|\Delta Q| = \frac{V_O DT}{R} = C\Delta V$$

Then, the minimum value of the filter capacitance that results in the voltage ripple ΔV is given by:

$$C_{min} = \frac{V_o D}{\Delta V_o R f} \tag{2.26}$$

Thus for boost converter to operate in CCM, to limit the peak-to-peak value of the ripple voltage below a certain value and to minimize the voltage overshoot, the filter capacitance value should be greater than the minimum capacitance.

2.4. Purpose of Different Components in the Boost Converter

A boost converter consists of several key components:

- Inductor
- Switch
- Diode
- Capacitor

Inductor: The inductor, which stores and releases energy throughout the switching cycles, is an essential part of the boost converter. It is a passive electronic component typically consisting of a coil of wire wound around a core. The inductor stores energy in its magnetic field and helps regulating the output voltage by controlling the current flow. It stores energy when the transistor is ON and releases it when the transistor is OFF. It resists changes in current flow and helps in smoothing the output voltage fluctuations.

Switch: The switch, often a transistor such as a MOSFET, controls the flow of current in the converter circuit. By alternatively connecting and disconnecting the inductor to the load, the switch (usually a MOSFET or IGBT) plays a crucial role in managing the energy transfer between the input and output. While the switch is on, energy from the input source is stored in the inductor. The inductor's magnetic field stores this energy, causing the current through the inductor to increase. When the switch turns off, the magnetic field collapses inducing a voltage across the inductor in the opposite direction. By controlling the duty cycle of the switch, the boost converter regulates the output voltage. The longer the switch remains on, the more energy is stored in the inductor, resulting in a higher output voltage. Here transistors chosen for use in switching power supplies must have fast switching time and should be able to withstand the voltage spikes produced by the inductor. Since the characteristics of the MOSFET are fast switching and voltage driven, they have been chosen for the power switching in this designing requirement [20].So, the switch in DC-DC boost converter controls the energy transfer between the input source, the inductor, and the output load, allowing for the generation of a higher output voltage than the input voltage.

Operating frequency: The operating frequency of a DC-DC boost converter refers to the frequency at which the converter switches ON and OFF to regulate the output voltage. The operating frequency plays a crucial role in determining the efficiency and performance of the converter. A higher operating frequency typically results in high-quality, smaller size, light weight, increased reliability, reduced cost and efficient power supplies [21].The reason for this is to reduce even further the overall size of the power converter.

Diode: The diode is a solid state device that is connected in parallel with the inductor to allow the flow of current when the transistor is turned off. It allows current to flow in one direction while blocking it in the opposite direction. During the switch-off time, the diode only permits current to flow in one direction in the circuit toward the output. When the switch is open, it stops the current from returning to the input side. It provides a path for the inductor current to continue flowing in the same direction, preventing the output capacitor from discharging back into the inductor during the ON state.

Capacitor: A capacitor is a passive two terminal electronic component that stores electrical energy in an electric field. Capacitors are essential components in DC-DC boost converters providing energy storage, reducing ripple, improving efficiency, regulating, and reducing noise. Capacitor provides the filtering action by providing a path for the harmonic currents away from the load. Output capacitance (across the load) is required to minimize the voltage overshoot and ripple present at the output of a step-up converter. The capacitor is large enough so that its voltage does not have any noticeable change during the time the switch is off.

2.5. Operation Modes of Boost Converter

Basically there are two modes of operation for DC-DC boost converter based on the continuity of inductor current flow [22]. These are:

- Discontinuous conduction mode (DCM) and
- Continuous conduction mode (CCM)

2.5.1. Discontinuous Conduction Mode (DCM)

In DCM, the current through the inductor falls to zero during a portion of the switching cycle. This means that the inductor current flows discontinuously, either during the ON or OFF time of the switching cycle, depending on the operating condition i.e. inductor is completely discharged at the end of the switching cycle [22].

In DCM, a switching cycle is composed of three intervals. The first two are the same as in CCM, where energy is stored in the inductor during the ON time of the switch, and transferred to the load during the OFF time of the switch. In DCM, however, all of the energy in the inductor transfers to the load during this second interval. The third interval begins when the energy in the inductor is depleted, and terminates at the end of the switching period the next time the switch turns on. During this third interval (the idle period in Figure 2.5 given below), the voltage across the inductor decays to zero, the voltage across the switch decays to the input voltage, and the input-to-output voltage differential is across the rectifier. There is essentially no current flowing in the power stage during this interval [22].

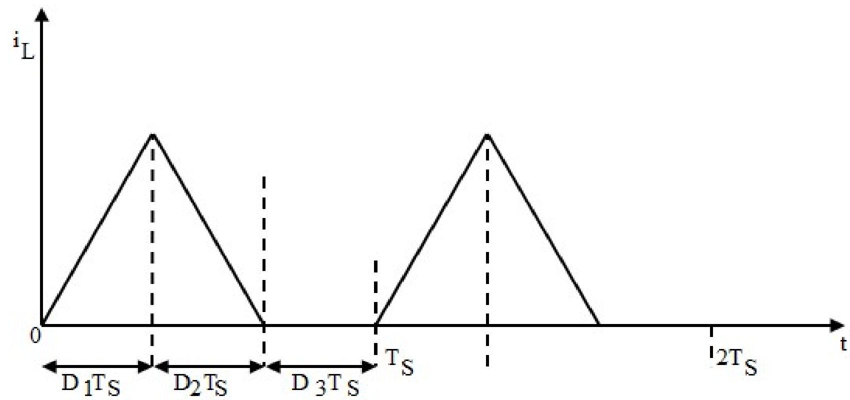


Figure 2. 3: Wave form of inductor current in DCM [17]

2.5.2. Continuous Conduction Mode (CCM)

In continuous conduction mode, the current through the inductor never falls to zero during the entire switching cycle. This means that the inductor current flows continuously, both during the ON and OFF times of the switching cycle i.e. inductor partially discharges before the start of the switching cycle [22].

In CCM, power transfer is a two-step process. When the switch is ON, stored energy builds in the inductor. When the switch is OFF, energy transfers to the output through the diode. During the ON time of the switch, if we assume zero losses for the moment, the voltage across the inductor is approximately the input voltage; and the voltage across the rectifier is the capacitor, or output voltage. When the switch turns OFF, the energy stored in the inductor releases into the output through the rectifier. The voltage across the inductor is approximately the input-to-output voltage difference, and the voltage across the switch becomes approximately the output voltage.

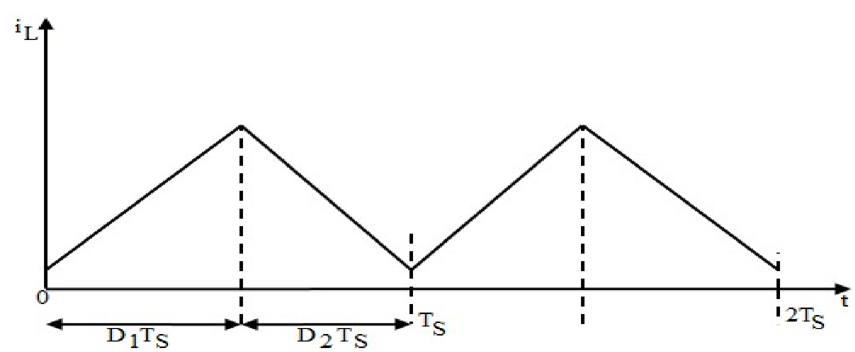


Figure 2. 4: Wave form of inductor current in CCM [17]

2.6. PID Controller

A PID (Proportional-Integral-Derivative) controller is a control loop feedback mechanism widely used in industrial control systems. A PID controller is a type of feedback control system that calculates an error value as the difference between a desired set point and a measured process variable. It then applies a proportional, integral, and derivative term to the error value to generate a control output that adjusts the process to the desired set point [23].

The PID controller algorithm involves three separate parameters; the Proportional, the Integral and Derivative terms. The Proportional value provides immediate correct action based on the current error, the Integral term determines the reaction based on the sum of recent errors over time to remove any steady state errors, and the Derivative term anticipates future errors based on the rate of change of error. By "tuning" the three constants in the PID controller algorithm the PID can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation [23].

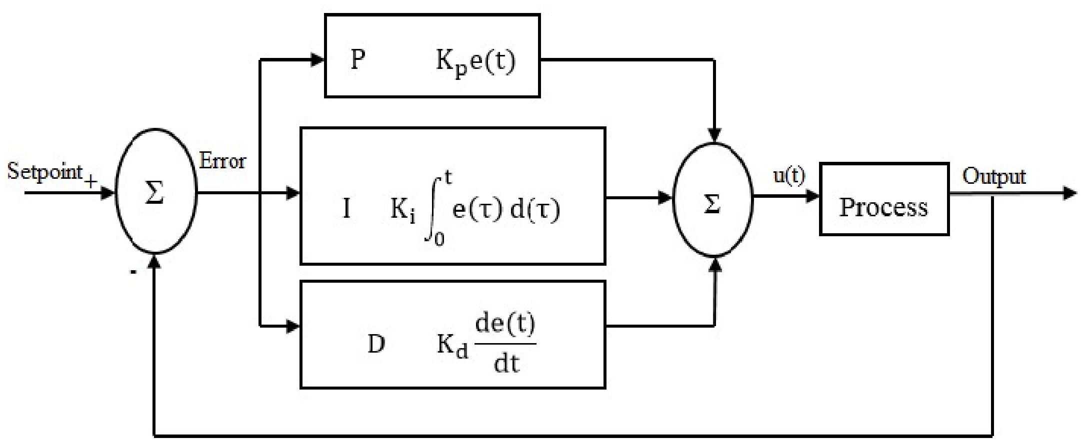


Figure 2. 5: Block diagram of a PID controller [23]

The output of PID controller becomes the sum of the three signals. Multiplying the error signal by a constant proportional gain K_p, plus multiplying the error signal by a constant derivative gain K_d , and plus multiplying the error signal by a constant integral gain K_i gives the output of PID controller. The output of PID controller is given by u (t) from Figure 2.7.Then taking Laplace transform, and solving for transfer function, gives ideal PID transfer function given by U(S). It is given as,

$$u(t) = Kpe(t) + Kd\frac{de(t)}{dt} + Ki\int e(t)dt \tag{2.27}$$

Taking Laplace transform, the transfer function of PID controller becomes

$$G_C(S) = K_P + \frac{Ki}{S} + K_D S \tag{2.28}$$

Conventional PID controllers have been extensively used in industry, due to their effectiveness for linear systems, ease to understand and simple to implement. But they are not effective and have difficulties in the presence of non-linearity.

2.7. Adaptive control

In every language, “to adapt” means to change a behavior to conform to new circumstances. Intuitively, adaptive control is thus, a controller that can modify its behavior in response to changes in the dynamics of the process and the character of the disturbance. Adaptive controller is a controller with adjustable parameters and a mechanism for adjusting the parameters. The controller becomes non-linear because of the parameter adjustment mechanism. It has however, a very special structure. An adaptive control system can be thought of as having two loops. One loop is a normal feedback with the process and controller. The other loop is the parameter adjustment loop. A block diagram of adaptive system is shown in Figure 2.8. The parameter adjustment loop is often slower than the normal feedback loop [8] .

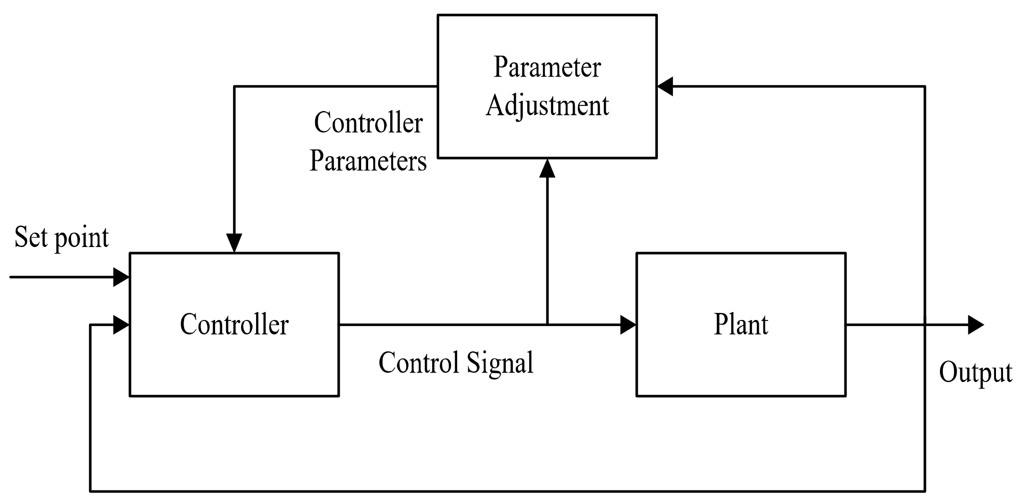


Figure 2. 6 : Block diagram of Adaptive system [8]

Adaptive systems have useful properties, which can be used to design control systems with improved performance. There are four schemes of adaptive systems such as; gain scheduling, model reference adaptive control, self-tuning regulators, and stochastic adaptive control [8]. In this thesis the model reference adaptive control is used as a controller to control the DC-DC boost converter.

CHAPTER THREE

SYSTEM MODELING AND CONTROLLER DESIGN

3.1. Introduction

This chapter deals with the mathematical model of DC-DC boost converter and controller design of the system.

3.2. Mathematical Model of DC-DC Boost Converter

The mathematical model of DC-DC boost converter in state space form is obtained by application of basic laws governing the operation of the system. The dynamics of this converter operating in continuous conduction mode can be easily obtained by applying Kirchhoff's voltage and current laws. The following assumptions are taken into consideration:

- The switches (diode and MOSFET) are treated as being ideal.
- The losses in the inductive and the capacitive elements are neglected.
- The switch is closed for time DT and open for time (1-D) T, where D is duty ratio and T is switching period.
- The converter operates at steady state.
- The inductor current is continuous (i.e. always positive).
- The capacitor is very large i.e. in order to limit the peak-to-peak value of the ripple voltage below a certain value and to minimize voltage overshoot; it must be greater than the minimum capacitance required for Continuous conduction mode.
- The inductor value must be greater than the minimum inductor to insure continuous conduction mode and to prevent higher conduction loss in switch, inductor and parasitic resistances.

A basic boost converter topology is given in Figure 3.1 below.

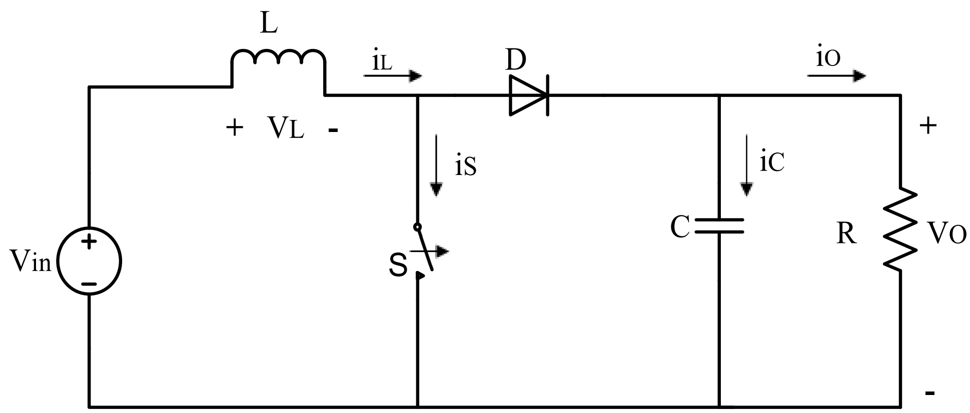


Figure 3. 1: Boost converter circuit diagram [24]

When the switch is closed, the diode is reverse biased and the equivalent circuit diagram is shown in Figure 3.2 below.

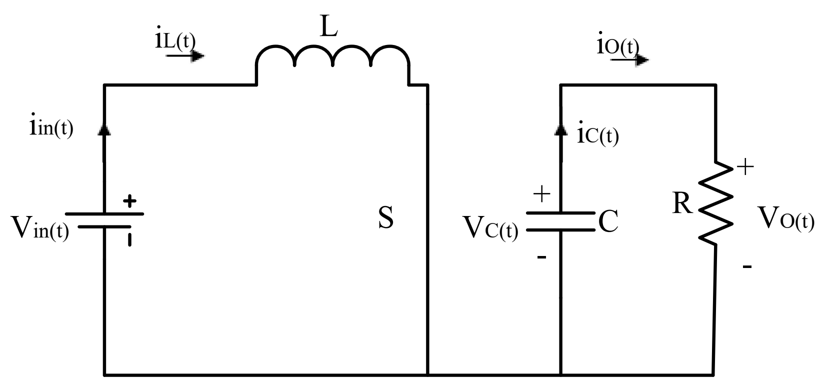


Figure 3. 2: The equivalent circuit of boost converter during closed switch

When the switch is closed, the differential equations related to the states are given as:

$$\left.\begin{aligned} L\frac{di_L(t)}{dt} &= v_{in}(t) \\ C\frac{dv_C(t)}{dt} &= \frac{-v_C(t)}{R} \end{aligned}\right\} \tag{3.1}$$

Defining the state vector as $x = [i_L \; v_c]^T$, $i_S(t) = i_L(t)$ and the output voltage $v_O(t) = v_C(t)$ the above equation can be written in the following form.

$$\left.\begin{aligned} &\left.\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dv_C(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_{in}(t) \right\} \\ &\left.\begin{bmatrix} v_o(t) \\ i_S(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} v_{in}(t) \right\} \end{aligned}\right\} \tag{3.2}$$

This can be written as:

$$\left.\begin{aligned}\frac{dx(t)}{dt} &= A_1x(t) + B_1u(t)\\ y(t) &= C_1x(t) + D_1u(t)\end{aligned}\right\} \quad (3.3)$$

Where, $A_1 = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix}$, $B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}$, $C_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ and $D_1 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$

The variables x(t), u(t)and $y(t)$ are the state variables consisting of output voltage and inductor current, input voltage to the converter and output voltage and source current respectively. During the open state of the switch, the diode is forward biased (in conducting state) and the energy stored in the inductor is released to the output RC circuit through the diode. The equivalent circuit is as shown in figure 3.3 below and the voltage and current equations are as follows;

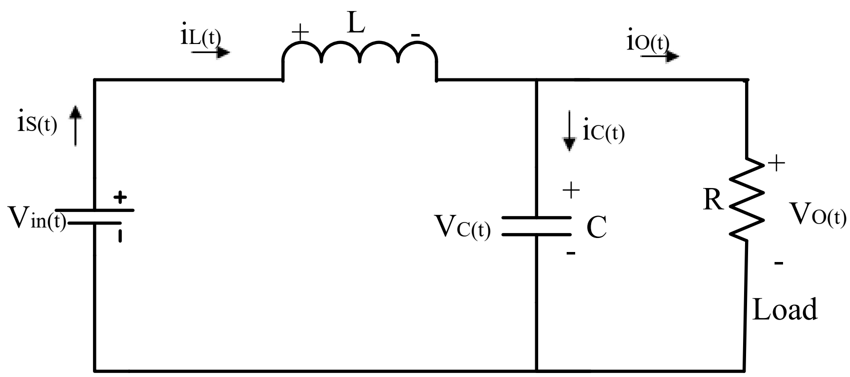


Figure 3. 3 : The equivalent circuit of boost converter during open switch

$$\left.\begin{aligned} v_{in}(t) - v_C(t) - L\frac{di_L(t)}{dt} &= 0 \\ i_L(t) - \frac{V_C(t)}{R} - C\frac{dV_C(t)}{dt} &= 0 \end{aligned}\right\} \quad (3.4)$$

The state equations for the differential equations given in (3.4) can be written as follow,

$$\left.\begin{aligned} L\frac{di_L(t)}{dt} &= -v_C(t) + v_{in}(t) \\ C\frac{dV_C(t)}{dt} &= -\frac{V_C(t)}{R} + i_L(t) \\ v_O(t) &= v_C(t) \\ i_S(t) &= i_L(t) \end{aligned}\right\} \quad (3.5)$$

Then the state equation matrices are given as,

$$\left.\begin{aligned} \begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dV_C(t)}{dt} \end{bmatrix} &= \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_{in}(t) \\ \begin{bmatrix} v_o(t) \\ i_S(t) \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} v_{in}(t) \end{aligned}\right\} \quad (3.6)$$

This can be written as:

$$\left.\begin{aligned}\frac{dx(t)}{dt} &= A_2x(t) + B_2u(t)\\ y(t) &= C_2x(t) + D_2u(t)\end{aligned}\right\} \tag{3.7}$$

Where, $A_2 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}$, $B_2 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}$, $C_2 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ and $D_1 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$

3.3. State Space Average Model of Boost Converter

To get a DC-DC converter model across one switching period, a state space averaging approach is utilized. To put it another way, the state space descriptions of the two modes must be replaced with a single state-space description that approximates the behavior of the circuit across the whole time T using the duty cycle as a weighting factor. The combined state equations in to a single averaged state space equation is given as follow:

$$\left.\begin{aligned}\frac{dx(t)}{dt} &= Ax(t) + Bu(t)\\ y(t) &= Cx(t) + Du(t)\end{aligned}\right\} \tag{3.8}$$

Where,

$A = dA_1 + (1-d)A_2, B = B_1 + (1-d)B_2, C = C_1 + (1-d)C_2, D = D_1 + (1-d)D_2$

$x(t) = \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix}, u(t) = v_{in}(t), y(t) = \begin{bmatrix} v_O(t) \\ i_S(t) \end{bmatrix}$ And d = duty cycle.

$$\left.\begin{aligned}\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dV_C(t)}{dt} \end{bmatrix} &= \left[d\begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} + (1-d)\begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \right] \begin{bmatrix} i_L(t) \\ v_O(t) \end{bmatrix} + \left[d\begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} + (1-d)\begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \right] v_{in}(t) \\ \begin{bmatrix} v_O(t) \\ i_S(t) \end{bmatrix} &= \left[d\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} + (1-d)\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \right] \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix}\end{aligned}\right\} \tag{3.9}$$

By rearranging and simplifying the above matrices given in equation (3.9) the state space average model of the converter is given as;

$$\left.\begin{aligned}\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dV_C(t)}{dt} \end{bmatrix} &= \begin{bmatrix} 0 & -\frac{(1-d)}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_{in}(t) \\ \begin{bmatrix} v_O(t) \\ i_S(t) \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix}\end{aligned}\right\} \tag{3.10}$$

3.4. Small Signal Model of Boost converter

Since switching converters are nonlinear systems, it is desirable to construct linearized ac small signal model of the power electronic converter around its DC steady-state operating point. This is accomplished by perturbing and linearizing the state space averaged model around precise operating point. Now by considering small perturbations of the operating point, the variables associated with the average model can be written as.

$$i_L = I_L + \hat{i}_L,\ v_C = V_C + \hat{v}_C, v_{in} = V_{in} + \hat{v}_{in},\ v_O = V_O + \hat{v}_O, d = D + \hat{d}, i_S = I_S + \hat{i}_S$$

Where the quantity $\hat{i}_L, \hat{v}_C, \hat{v}_{in}, \hat{v}_O, \hat{d}$ and $\hat{i}_S$ are small ac variations about the equilibrium point. By substituting these state variables in the state space averaged model of the DC-DC boost converter given in equation (3.10) gives,

$$\left.\begin{aligned} \begin{bmatrix} \frac{d(I_L+\hat{i}_L)}{dt} \\ \frac{d(V_C+\hat{v}_C)}{dt} \end{bmatrix} &= \begin{bmatrix} 0 & -\frac{(1-(D+\hat{d}))}{L} \\ \frac{1-(D+\hat{d})}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} I_L + \hat{i}_L \\ V_C + \hat{v}_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} [V_{in} + \hat{v}_{in}] \\ \begin{bmatrix} V_O + \hat{v}_O \\ I_S + \hat{i}_S \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} I_L + \hat{i}_L \\ V_C + \hat{v}_C \end{bmatrix} \end{aligned}\right\} \tag{3.11}$$

Equation (3.11) consists of three terms which are steady-state (dc) terms, linear ac terms and nonlinear ac terms.

$$\left.\begin{aligned} \begin{bmatrix} \frac{dI_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} &= \begin{bmatrix} 0 & -\frac{(1-D)}{L} \\ \frac{1-D}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & \frac{V_C}{L} \\ 0 & -\frac{I_L}{C} \end{bmatrix} \begin{bmatrix} V_{in} \\ d \end{bmatrix} \\ \begin{bmatrix} V_O \\ I_S \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix} \end{aligned}\right\} \text{The steady state (dc) term}$$

$$\left.\begin{bmatrix} \frac{d\hat{i}_L}{dt} \\ \frac{d\hat{v}_C}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{\hat{d}}{L} \\ \frac{-\hat{d}}{C} & 0 \end{bmatrix} \begin{bmatrix} \hat{i}_L \\ \hat{v}_C \end{bmatrix}\right\} \quad \text{Non-linear ac term}$$

To develop the small signal ac model of the converter it is considered the dc term as constant and letting it to be zero and by neglecting the nonlinear second order ac terms the linearized ac model of the DC-DC boost converter is given as follow.

$$\left.\begin{aligned} \begin{bmatrix} \frac{d\hat{i}_L}{dt} \\ \frac{d\hat{v}_C}{dt} \end{bmatrix} &= \begin{bmatrix} 0 & -\frac{(1-D)}{L} \\ \frac{1-D}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} \hat{i}_L \\ \hat{v}_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & \frac{V_C}{L} \\ 0 & -\frac{I_L}{C} \end{bmatrix} \begin{bmatrix} \hat{v}_{in} \\ \hat{d} \end{bmatrix} \\ \begin{bmatrix} \hat{v}_O \\ \hat{i}_S \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \hat{i}_L \\ \hat{v}_C \end{bmatrix} \end{aligned}\right\} \tag{3.12}$$

From equation (3.12) we have the following terms such as;

$$\left.\begin{aligned} \frac{d\hat{i}_L}{dt} &= -\frac{(1-D)}{L}\hat{v}_C + \frac{\hat{v}_{in}}{L} + \frac{V_C\hat{d}}{L} \\ \frac{d\hat{v}_C}{dt} &= \frac{(1-D)}{L}\hat{i}_C - \frac{\hat{v}_C}{RC} - \frac{I_L\hat{d}}{C} \\ \hat{v}_O &= \hat{v}_C \\ \hat{i}_S &= \hat{i}_L \end{aligned}\right\} \tag{3.13}$$

Taking Laplace transform of equation (3.13) we have the following;

$$S\hat{i}_L(S) = -\frac{(1-D)}{L}\hat{v}_C(S) + \frac{\hat{v}_{in}(S)}{L} + \frac{V_C(S)\hat{d}(S)}{L} \tag{3.14}$$

$$S\hat{v}_C(S) = \frac{(1-D)}{C}\hat{i}_L(S) - \frac{\hat{v}_C(S)}{RC} - \frac{I_L(S)\hat{d}(S)}{C} \tag{3.15}$$

Now let's drive the transfer function that relates $\hat{d}(s)$ and $\hat{v}_O(s)$ from equations (3.14) and (3.15). From equation (3.14) $\hat{i}_L(S)$ is solved and it is given that $\hat{v}_C(s) = \hat{v}_O(s)$, Then

$$\hat{i}_L(S) = -\frac{(1-D)}{SL}\hat{v}_O(S) + \frac{\hat{v}_{in}(S)}{SL} + \frac{V_O(S)\hat{d}(S)}{SL} \tag{3.16}$$

Equation (3.16) is substituted into equation (3.15).

$$S\hat{v}_O(S) = \frac{(1-D)}{C}\left(-\frac{(1-D)}{SL}\hat{v}_O(S) + \frac{\hat{v}_{in}(S)}{SL} + \frac{V_O(S)\hat{d}(S)}{SL}\right) - \frac{\hat{v}_O(S)}{RC} - \frac{I_L(S)\hat{d}(S)}{C} \,|\, \hat{v}_{in}(s) = 0$$

$$S\hat{v}_O(S) = \frac{(1-D)}{C}\left(-\frac{(1-D)}{SL}\hat{v}_O(S) + \frac{V_O(S)\hat{d}(S)}{SL}\right) - \frac{\hat{v}_O(S)}{RC} - \frac{I_L(S)\hat{d}(S)}{C}$$

$$S\hat{v}_O(S) = -\frac{(1-D)^2}{SCL}\hat{v}_O(S) + \frac{(1-D)V_O(S)\hat{d}(S)}{SLC} - \frac{\hat{v}_O(S)}{RC} - \frac{I_L(S)\hat{d}(S)}{C}$$

Collecting the same terms together and taking common, then

$$S\hat{v}_O(S) + \frac{(1-D)^2}{SCL}\hat{v}_O(S) + \frac{\hat{v}_O(S)}{RC} = \frac{(1-D)V_O(S)\hat{d}(S)}{SLC} - \frac{I_L(S)\hat{d}(S)}{C}$$

$$\hat{v}_O(S)\left(S + \frac{(1-D)^2}{SCL} + \frac{1}{RC}\right) = \hat{d}(S)\left(\frac{(1-D)V_O(S)}{SLC} - \frac{I_L(S)}{C}\right) \tag{3.17}$$

Rearranging equation (3.17) the transfer function that relates the duty ratio and the output voltage of the boost converter is given as;

$$\frac{\hat{v}_O(S)}{\hat{d}(S)} = \frac{V_O}{1-D}\left[\frac{-\frac{1}{RC}S + \frac{(1-D)^2}{LC}}{S^2 + \frac{1}{RC}S + \frac{(1-D)^2}{LC}}\right] \tag{3.18}$$

3.5. Design of PID Controller for Boost converter

A PID controller is a closed feedback loop controlling mechanism that can control a plant based on the measurement of the process variable. It corrects error by continuously calculating the difference between the desired set-point and the actual value of the process variable. The controller then adjusts the control output based on the error in order to minimize it and bring the process variable closer to the set-point. Its calculation involves three separate parameters; the Proportional, the Integral and Derivative values. The weighted sum of these three actions is used to adjust the process via a control element. By "tuning" the three constants in the PID controller, it can provide control action designed for specific requirements. The overall block diagram of the PID controlling mechanism of DC-DC boost converter system is shown in the Figure 3.4 below.

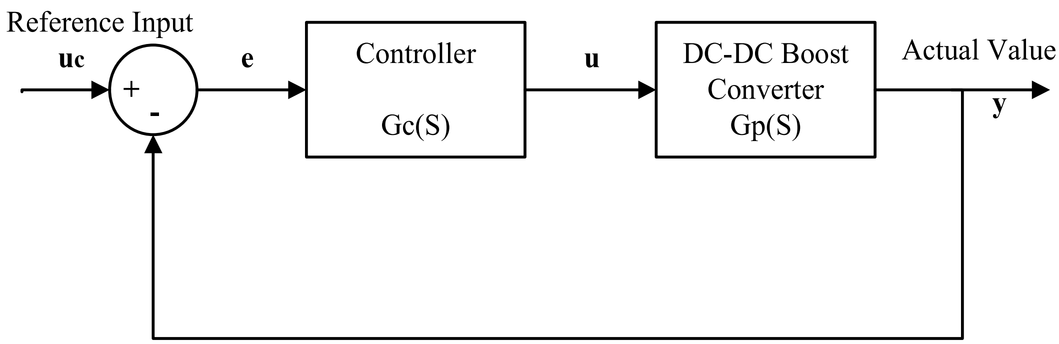


Figure 3. 4 : Over all structure of the controller and plant

Zeigler Nicholas Method: - The Zeigler and Nicholas method is a well-known tuning method for PID controllers. So, here in order to design the PID controller parameters the Zeigler Nicholas tuning method is used. This Zeigler Nicholas tuning method is used to get the values of K_p, K_i and, K_d appropriately by using oscillation. From PID controller the control unit $u(t)$ is given by

$$u(t) = K_p e(t) + \frac{K_p}{T_i}\int_0^t e(t)d(t) + K_p T_d \frac{de(t)}{dt} \tag{3.19}$$

From equation (3.19) the parameters K_i and K_d are then,

$$K_i = \frac{K_p}{T_i} \text{ And } K_d = K_p T_d \tag{3.20}$$

After finding out the ultimate gain (K_u), then ultimate frequency (ω_u) is calculated. The ultimate period (T_u) is given by:

$$T_u = \frac{2\pi}{\omega_u} \tag{3.21}$$

Table 3. 1: Zeigler Nicholas tuning chart

Type of controller	K_p	T_i	T_d
P	$0.5K_u$	∞	0
PI	$0.4K_u$	$0.4T_u$	0
PID	$0.6K_u$	$0.5T_u$	$0.125T_u$

K_u & T_u are the ultimate gain and period respectively. They are the gain and the period where sustained oscillation occurs. The open loop transfer function which relates duty ratio to output voltage of the DC-DC boost converter is given in equation (3.18). The parameters of this transfer function are substituted from Table 3.3. Then, from the characteristic equation the values of K_u and T_u are calculated as Ku $= 5.21 * 10^{-3}$ and Tu $= 0.131$.

Table 3. 2: Calculated controller parameters for the given values of Ku and Tu

Type of controller	K_p	$K_i = \frac{K_p}{T_i}$	$K_d = K_p T_d$
P	0.002605	0	0
PI	0.002084	0.0524	0
PID	0.003125	0.04771	$5.1172*10^{-5}$

Parameters of Boost converter

In order to test the performance of boost converter the selected parameter of the converter is given in the Table 3.3 below.

Table 3. 3 : Parameter values of boost converter [25]

No	Description	Parameter	Value	Unit
1	Input voltage	V_{in}	12	V
2	Reference voltage	V_{ref}	48	V
3	Switching frequency	F	75	kHz
4	Duty cycle	D	0.75	-
5	Load resistance	R	200	Ω
6	Inductance	L	75	mH
7	Capacitance	C	720	μF

3.6. Simulink Model of DC-DC Boost Converter Using PID Controller

The MATLAB/Simulink model of the DC-DC boost converter with PID controller is given below in Figure 3.5.

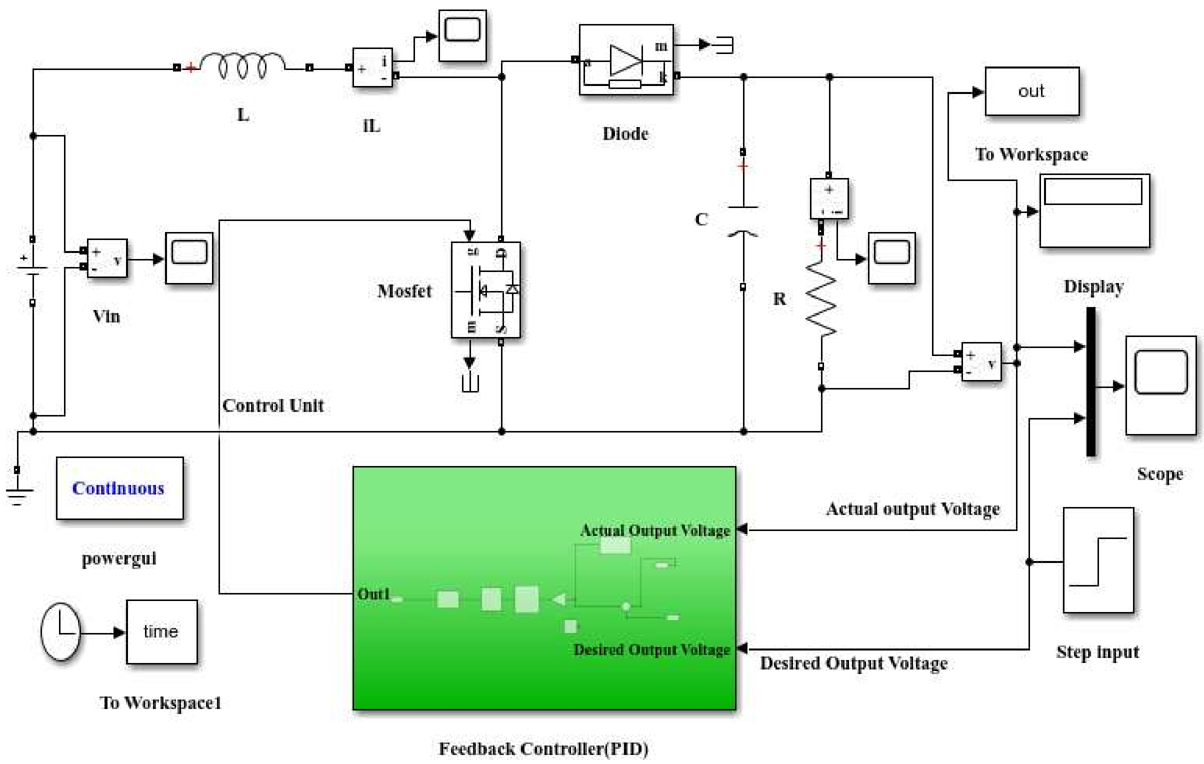


Figure 3. 5: MATLAB/Simulink model of boost converter with PID controller

3.7. Design of MRAC for Boost converter

Model Reference Adaptive Control (MRAC) systems aim to create a closed loop controller with parameters that can be updated to changes of system response. It is a type of Adaptive control technique that uses a reference model to adjust the parameters in real-time in order to achieve a desired performance. The model is selected in such a way that it gives the ideal response of the process which is the desired one. The controller continuously compares the output of the system (plant) with the reference model and updates its parameters based on the error between the two that acts as input to the adaptation mechanism. The parameters of the controller are adjusted automatically by the adaptation mechanism so as to match the performance of the plant with that of the model. The parameter adjustment mechanism can be using MIT rule or Lyapunov stability method. Lyapunov based MRAC uses Lyapunov theory to ensure that the adaptive control system remains stable and converges to the desired reference model and the system is stability guaranteed. But MIT rule based MRAC does not provide the same stability guarantee as lyapunov based MRAC [8].

MRAC has two loops: an inner loop or normal feedback loop that is an ordinary control loop consisting of the plant and controller, and an outer or adaptation loop that adjusts the parameters of the controller in such a way as to drive the error between the model output and plant output to zero. The parameter adjustment loop is often slower than the normal feedback loop. The structure of MRAC consists of four main parts: the controller, the plant, the reference model and the adjustment mechanism as shown in figure 3.4.

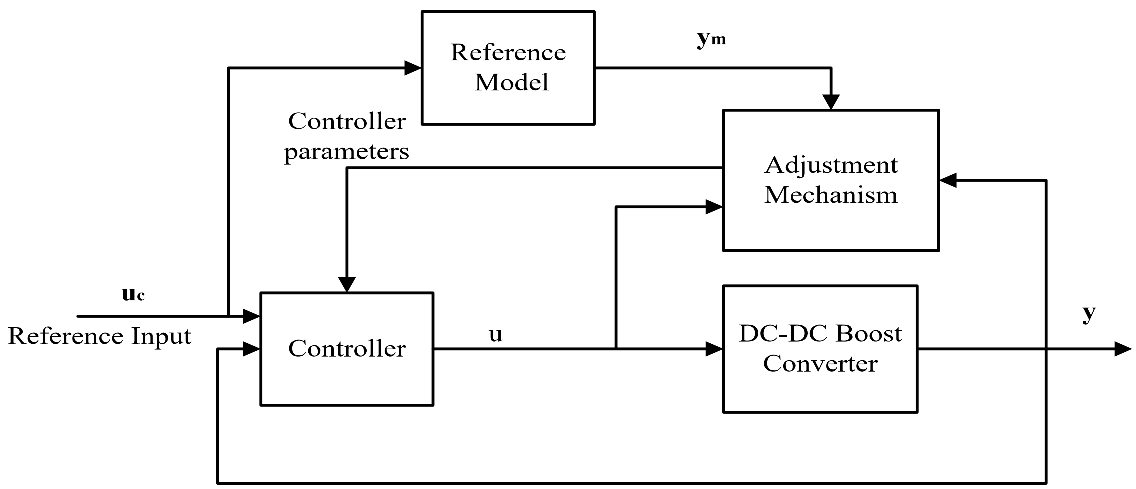


Figure 3. 6 : Block diagram of Model Reference Adaptive controller (MRAC)

Controller: The controller is an essential part of the system that is responsible for adjusting the system parameters to make the actual system or plant behavior match the reference model.

Reference Model: The reference model is a mathematical model that represents the desired behavior of the system. It is used to specify the ideal response of the adaptive control system to external command. It should reflect the performance specifications in control tasks. Using MRAC one can choose a reference model that respond quickly to a step input with a short settling time, and then build such a desired controller.

Adaptation Mechanism: The adaptation mechanism is used to adjust the parameters in the control law. Adaptation law searches for the parameters such that the response of the plant which should be same as the reference model. It is a set of algorithms that continuously update the controller parameters based on the error between the actual system output and the reference system output.

3.7.1. Lyapunov Stability Method

The Lyapunov stability theory can be used to describe the algorithms for adjusting parameters in

Model Reference Adaptive control system. This method attempts to find the Lyapunov function and an adaptation mechanism in such a way that the error between plant and model goes to zero. Also this method ensures stability of the control parameters of the system. When designing MRAC using Lyapunov rule, it is chosen: the reference model, the controller, and the tuning gains for the adjustment mechanism. The reference model is usually assumed as a first order system with a differential equation to derive the control structure. The reference model is given by [8]

$$\frac{dy_m}{dt} = -a_m y_m + b_m u_c \tag{3.22}$$

The process to be controlled is described as a first order model

$$\frac{dy}{dt} = -ay + bu \tag{3.23}$$

For the control law, a combination of feed forward and feedback are chosen as

$$u = \theta_1 u_c - \theta_2 y \tag{3.24}$$

And the error can be

$$e = y - y_m \tag{3.25}$$

Where;

y_m - is the reference model output

y-is the plant output voltage

θ_1 and θ_2 – the parameters of the controller to be updated

u_c – is the reference input

e- is the difference between actual plant output and reference model output.

u- is the controller output signal

It is required to make the error goes to zero as much as possible, and it is natural to drive a differential equation for the error as follows [8]:

$$\dot{e} = \dot{y} - \dot{y}_m$$

$$\dot{e} = -ay + bu - (-a_m y_m + b_m u_c)$$

$$\dot{e} = -ay + bu + a_m y_m - b_m u_c \tag{3.26}$$

Substitute u from equation (3.24) in to equation (3.26)

$$\dot{e} = -ay + b(\theta_1 u_c - \theta_2 y) + a_m y_m - b_m u_c$$

$$\dot{e} = -ay - b\theta_2 y + a_m y_m + (b\theta_1 - b_m)u_c$$

$$\dot{e} = -a_m e - (b\theta_2 + a - a_m)y + (b\theta_1 - b_m)u_c \tag{3.27}$$

From the error dynamics it is clear that error turns zero if,

$$\theta_1 = \frac{b_m}{b} \tag{3.28}$$

$$\theta_2 = \frac{(a_m - a)}{b} \tag{3.29}$$

To ascertain Lyapunov rule in the parameter adjustment mechanism, derive the parameters θ_1 and θ_2 to their desired values. A quadratic function is chosen as a Lyapunov function that is described by V (e, θ1, θ2). A positive definite Lyapunov function (V) is chosen, in such a way that derivative of it, along the solution is negative semi definite, and then the system turns stable. If derivative is negative definite, then system is asymptotically stable.

$$V(e, \theta_1, \theta_2) = \frac{1}{2}\left[e^2 + \frac{1}{b\gamma}(b\theta_2 + a - a_m)^2 + \frac{1}{b\gamma}(b\theta_1 - b_m)^2\right] \tag{3.30}$$

this function should be positive semi definite and is zero when error is zero.

The Lyapunov function is zero when e is zero and the controller parameters are equal to the correct values. The total derivation of V yields.

$$\dot{V} = e\frac{de}{dt} + \frac{1}{\gamma}(b\theta_2 + a - a_m)\frac{d\theta_2}{dt} + \frac{1}{\gamma}(b\theta_1 - b_m)\frac{d\theta_1}{dt} \tag{3.31}$$

From equation (3.24) and equation (3.28)

$$\dot{V} = -a_m e^2 + \frac{1}{\gamma}(b\theta_2 + a - a_m)\left(\frac{d\theta_2}{dt} - \gamma y e\right) + \frac{1}{\gamma}(b\theta_1 - b_m)\left(\frac{d\theta_1}{dt} + \gamma u_c e\right) \tag{3.32}$$

Since $\dot{V}$ is negative, then equation (3.32) is a Lyapunov function. Then the parameters are updated as

$$\frac{d\theta_1}{dt} = -\gamma u_c e$$

$$\theta_1 = \frac{-\gamma u_c e}{s} \tag{3.33}$$

$$\frac{d\theta_2}{dt} = \gamma y e$$

$$\theta_2 = \frac{\gamma y e}{s}$$

Where γ is the adaptation gain

The derivative $\dot{V} = -a_m e^2$ is thus a negative semi definite. This implies that $V(t) \le V(0)$ and hence, θ_1 and θ_2 must be bounded. As a result the output of the system $y = e + y_m$ is also bounded. There is no guarantee that an adaptive controller based on the MIT rule will give stable closed loop system. So, the Lyapunov stability based method avoids the instability problems present in the gradient or MIT approach [8].

In this thesis, underdamped second order system is chosen as reference model G_m, with damping ratio 0.7 and natural frequency 41 rad/sec whose transfer function is given by

$$G_m = \frac{1681}{S^2+57.4S+1681} \tag{3.34}$$

Here, the damping ratio 0.7 and natural frequency 41 rad/sec are chosen by trial and error method. The selection of underdamped second order system with damping ratio 0.7 and natural frequency 41 rad/sec is to obtain the desired value with fast response and minimum overshoot. This combination provides a good trade-off between fast response and moderate overshoot, ensuring the system is stable and performs well.

3.7.2. Simulink Model of MRAC for DC-DC Boost converter

The MATLAB/Simulink model of DC-DC boost converter with MRAC is given below in Figure 3.7.

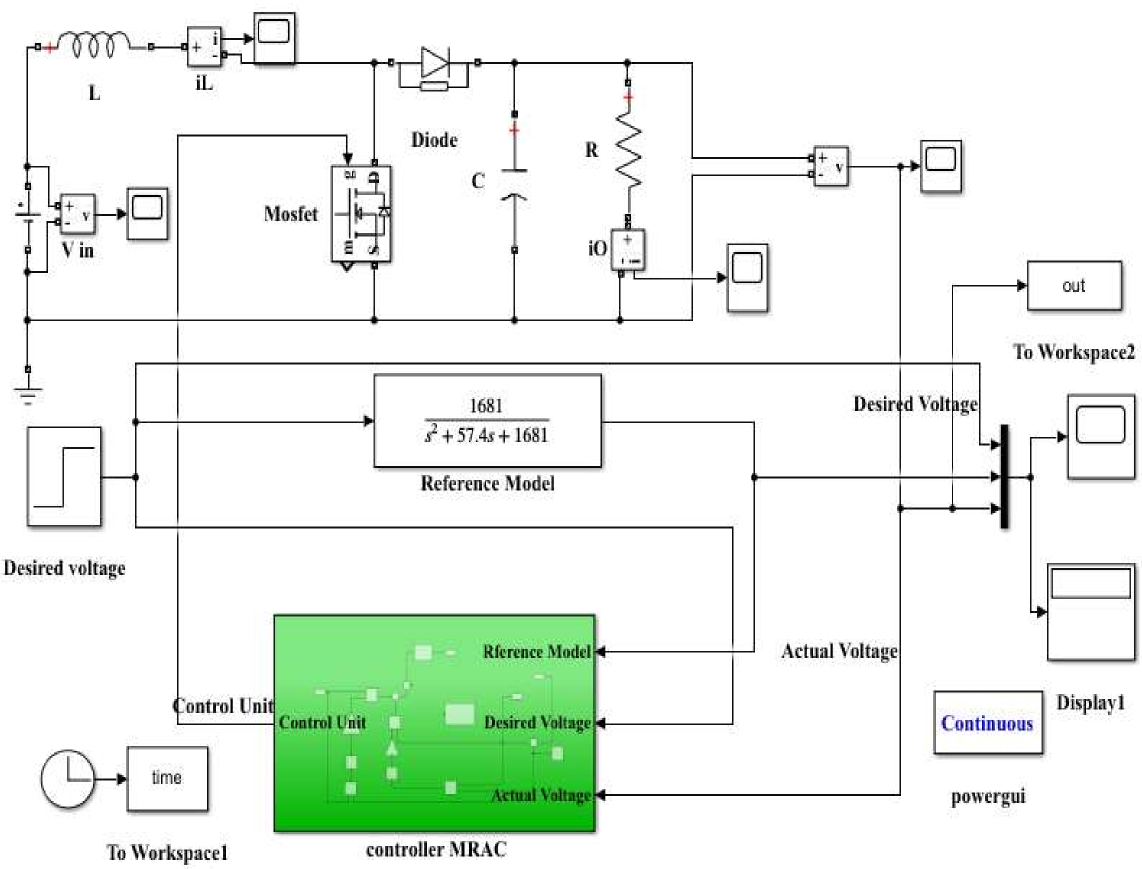


Figure 3. 7 : Simulink model of DC-DC boost converter using MRAC

CHAPTER FOUR

SIMULATION RESULTS AND DISCUSSIONS

In this chapter simulation results of the system are discussed. First, simulation results of the open loop system are carried out. The next step is the response of the closed-loop system presented using the PID controller. Finally, the response of the closed-loop system using the proposed controller MRAC is discussed and compared with the results of the PID controller which is used as a benchmark.

4.1. Open Loop Performance of Boost Converter

The open loop performance of Boost converter is investigated using MATLAB/Simulink model given in Figure 4.1. The parameters used to carry out the simulation studies are provided in Table 3.3 as shown above.

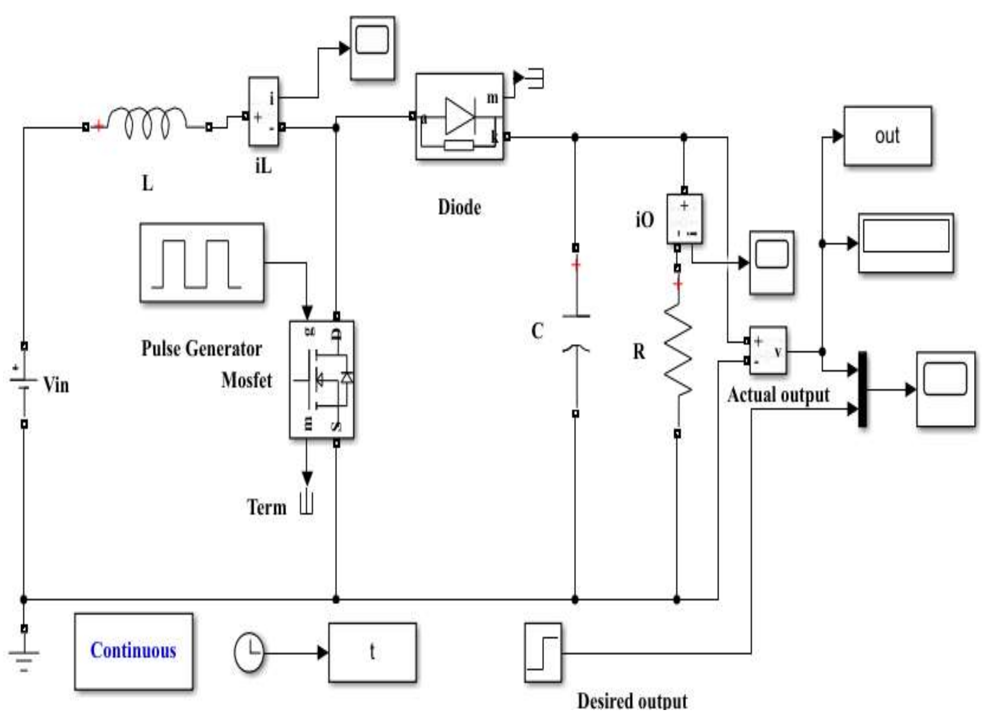


Figure 4. 1 : MATLAB/Simulink model of open loop boost converter

The open loop output voltage response obtained using MATLAB/Simulink is shown in Figure 4.2. It is observed that the overshoot, undershoot, rising time, and settling time of output voltage are respectively given as 67.5229 %, 0.0036%, 0.0330 seconds, and 0.6985second. From the simulation result it is also observed the output voltage deviation which results steady-state error.

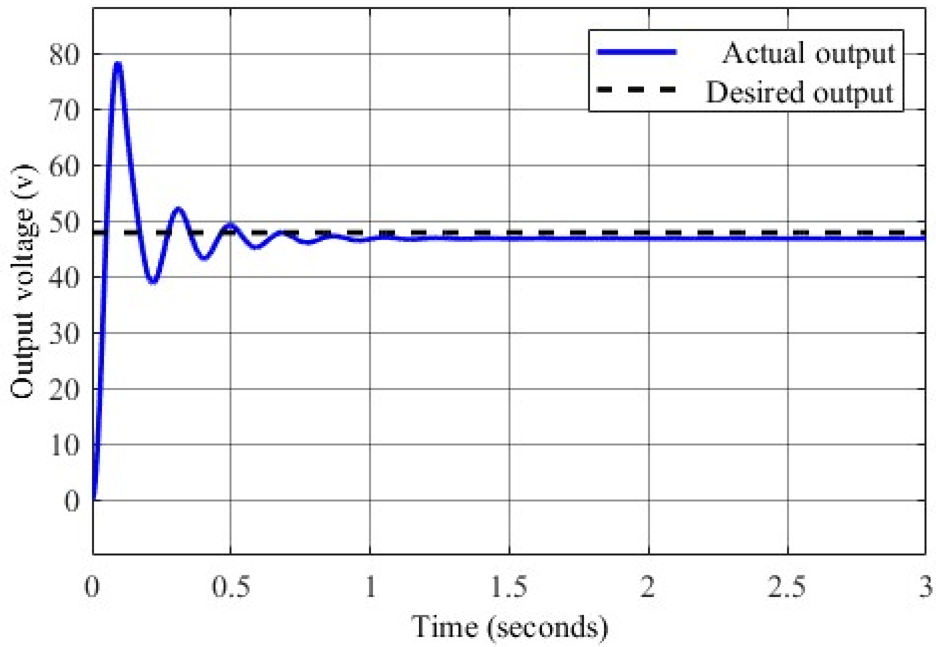


Figure 4. 2 : Simulation result of open loop boost converter

The performance of open loop boost converter is given in Table 4.1 as follows

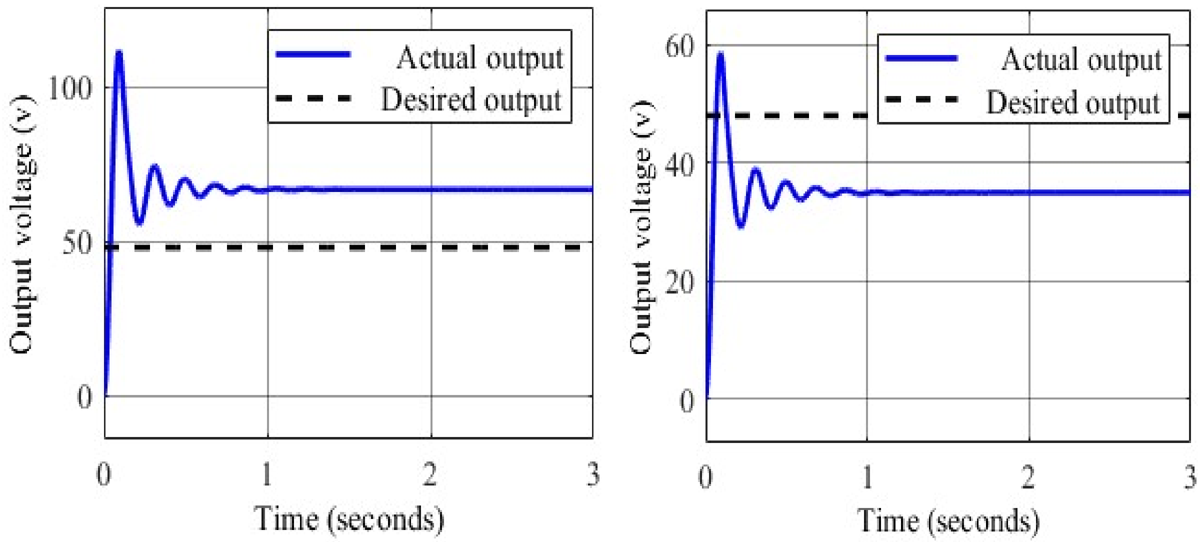
Table 4. 1: performance of Open loop Boost converter

Rise Time	Settling Time	Overshoot	Undershoot	e_{ss}
0.033 Sec	0.6985 Sec	67.5229%	0.0036%	1.111V

4.2. Disturbance of Input voltage and Load resistance in open loop boost converter

To test the open loop performance of the DC-DC boost converter under input voltage variation, the input voltage is increased from nominal input voltage (12V) to 17V and decreased from 12V to 9V as shown in figure 4.3 (a) and (b) respectively. It is clearly seen that the actual voltage is not able to reach the desired voltage and results in steady-state error besides the high overshoot. Increasing the input voltage from 12V to 17V increases the overshoot and steady-state error.

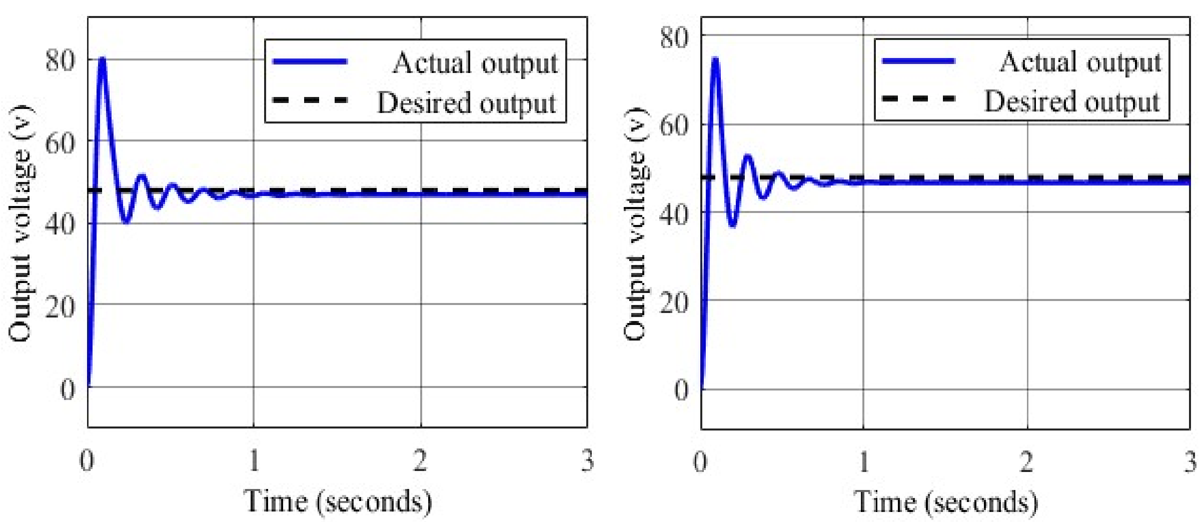
Decreasing the input voltage from 12V to 9V causes an increase in the steady-state error and cannot reach the desired output voltage.



(a) I/p voltage change from 12V to 17V (b) I/p voltage change from 12V to 9V

Figure 4. 3 : Simulation result for input voltage variation

To see the effect of load resistance variation, the load resistance is increased from nominal load resistance (200 Ω) to 240 Ω and it is decreased from 200 Ω to 150 Ω as shown in Figure 4.4 (a) and (b) below. The variation of the load resistance has almost no change in the output voltage compared to the voltage measured from the nominal load resistance.



(a) Load resistance change from 200 Ω to 240 Ω (b) Load resistance change from 200 Ω to 150 Ω

Figure 4. 4 : Simulation results under load resistance variation

From the open loop response, it is clear that the high overshoot, oscillation, and steady-state error of the output voltage are not required thereby there is the need for a closed-loop system with a controller to control the value at the desired value and settle the output voltage in a fast time response and to minimize the overshoot.

4.3. Performance of Boost Converter Using PID Controller

The performance of the DC-DC boost converter is demonstrated in this section with the PID controller using MATLAB/Simulink for the parameters of the boost converter that are given in Table 3.3 above. Here, the PID controller is used as a benchmark to compare the performance of MRAC with the performance of a PID controller.

The simulation result of the DC-DC boost converter with the PID controller is given in Figure 4.5 below. Its performance response is stated in time domain specifications in Table 4.2 below.

Table 4. 2: Performance of DC-DC Boost converter Using PID controller

Rise Time	Settling Time	Overshoot	Undershoot	e_{ss}
0.0171 Sec	0.2770 Sec	7.7717 %	0.0047 %	0.0V

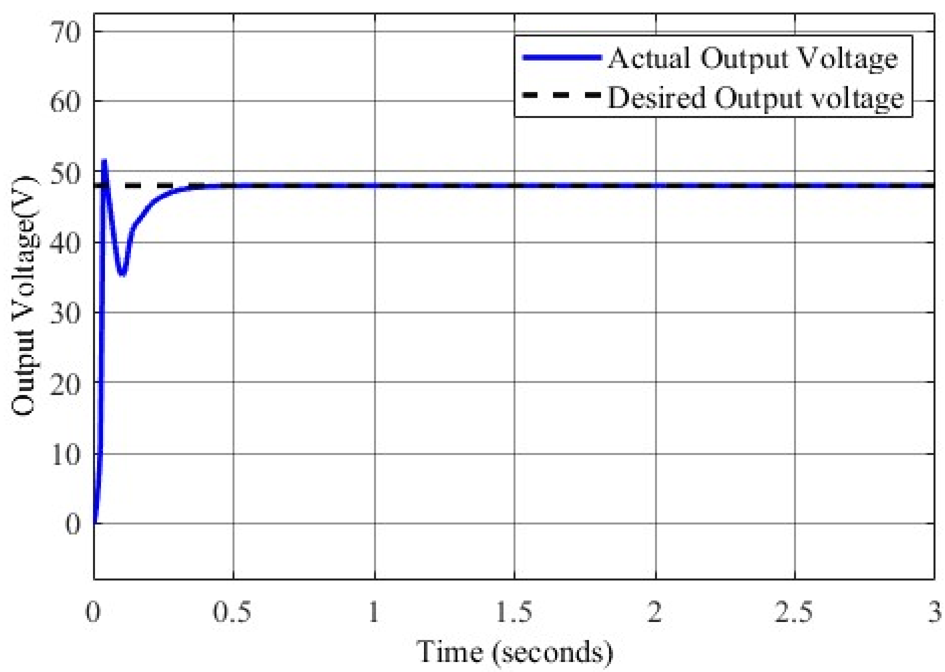


Figure 4. 5 : Simulation result of DC-DC Boost converter using PID controller

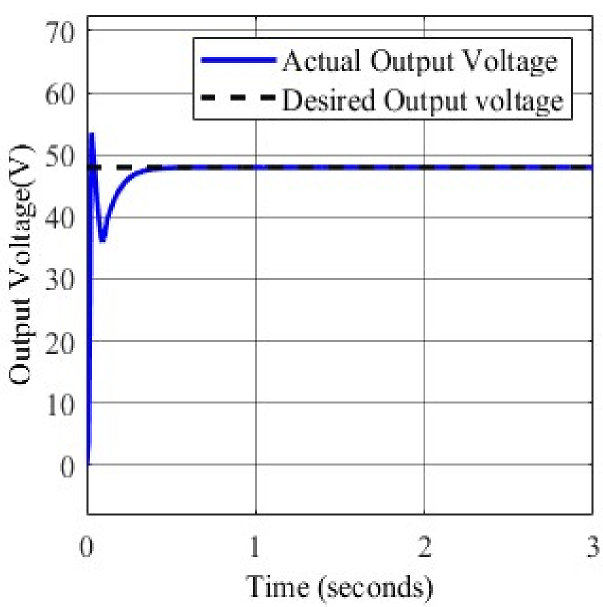
4.4. Performance of Boost Converter Using PID Controller under Disturbance in Input Voltage and Load Resistance

To see the performance of a DC-DC boost converter with the PID controller, let us vary the nominal input voltage (12V) as follows. The input voltage is increased from its nominal value (12V) to 17V and decreased from 12V to 9V.

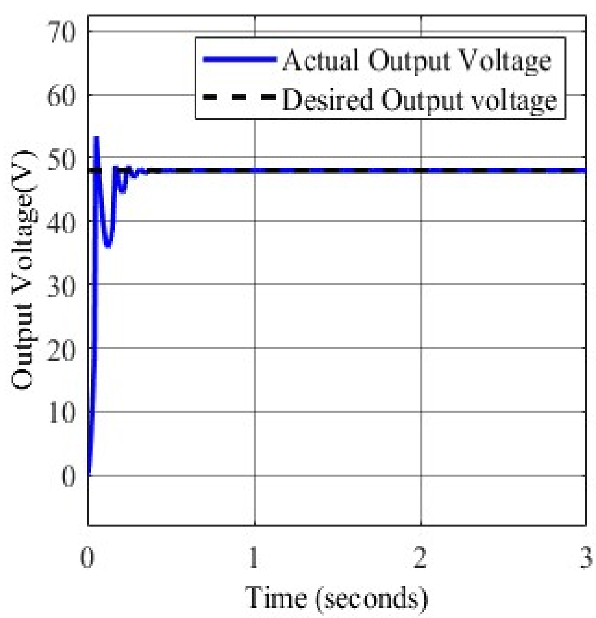
Table 4. 3: Performance of DC-DC Boost converter Using PID for input voltage variation

Voltage variation	Rise Time(Sec)	Settling Time(Sec)	Overshoot	Undershoot	e_{ss}
From 12V-17V	0.0102	0.299	11.6137%	0.0066 %	0.0V
From 12V-9V	0.0283	0.288	11.2410%	0.0035 %	0.0V

For the simulation results given in Figure 4.6 (a) and (b) below the performance is summarized in Table 4.3 above and it is clearly observed that overshoot is increased, settling time increased, undershoot increased, and rising time decreased for voltage change from 12V-17V. For voltage change from 12V-9V overshoot increased, settling time increased, undershoot decreased, and rising time increased.



(a) Input voltage change from 12V to 17V



(b) Input voltage change from 12V to 9V

Figure 4. 6 : Simulation results of boost converter using PID for input voltage variation

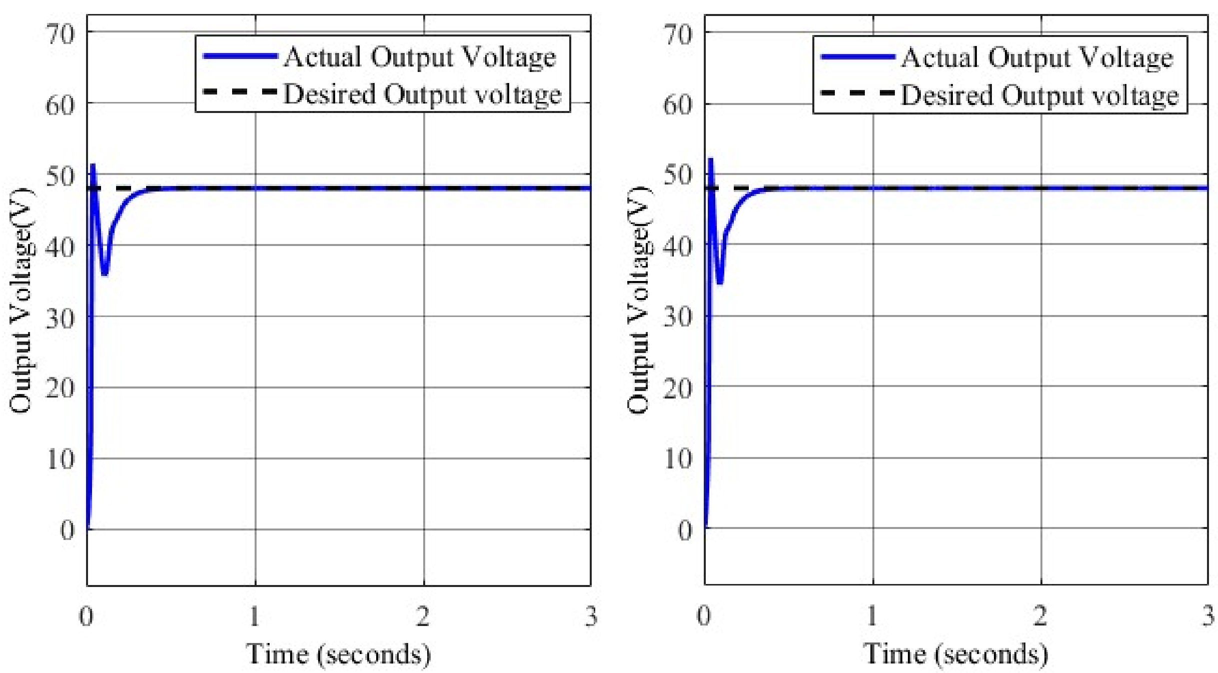
In order to see the effect of load resistance variation, the load resistance is increased from nominal value (200 Ω) to 240 Ω and decreased from 200 Ω to 150 Ω as follows. The simulation results are shown in Figure 4.7 (a) and (b) below as follows.

Table 4. 4: Performance of Boost converter Using PID for load resistance variation

Load resistance variation	Rise Time(Sec)	Settling Time(Sec)	Overshoot	Undershoot	e_{ss}
From 200 Ω -240 Ω	0.0168	0.2845	7.2604 %	0.0047 %	0.0V
From 200 Ω -150 Ω	0.0177	0.2672	8.9572 %	0.0047 %	0.0V

For the simulation result given in Figure 4.7 below the performance is summarized in Table 4.4 above and it is clearly observed that, rise time decreased, settling time increased, overshoot decreased, and undershoot no change for load resistance change from 200 Ω -240 Ω. For load resistance change from 200 Ω -150 Ω rise time increased, settling time decreased, overshoot increased, and undershoot no change.

The variation of input voltage has more affected the performance of PID in the operating point especially in overshoot than variation of load resistance.



(c) Load resistance change from 200 Ω to 240 Ω (d) Load resistance change from 200 Ω to 150 Ω

Figure 4. 7 : Result of DC-DC boost converter using PID for variation of Load resistance

4.5. Performance of Boost Converter Using PID Controller under External Disturbance

A sinusoidal input is added to the system as a disturbance to see the performance effect. The simulation result is given in Figure 4.8 below and its performance is given in Table 4.5 below.

Table 4. 5: Performance of Boost converter Using PID controller under external disturbance

Rise Time	Settling Time	Overshoot	Undershoot	e_{ss}
0.0172 Second	0.2706 Second	7.6330 %	0.0047 %	0.2V

From the simulation result there is insignificant change in rise time, settling time, and overshoot. But it is observed that there is steady-state error.

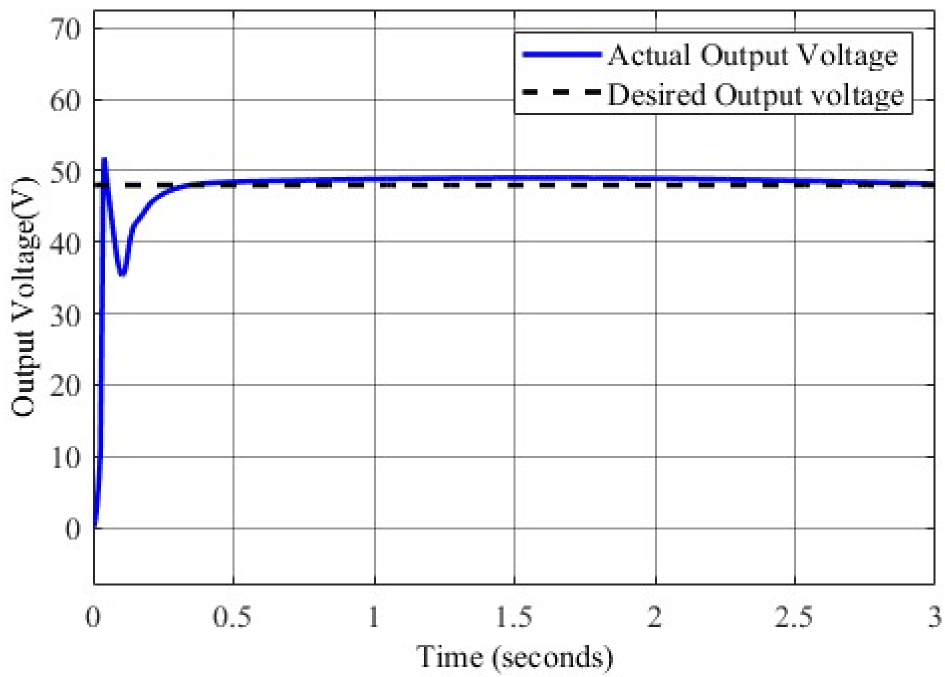


Figure 4. 8 : Simulation response using PID controller for external disturbance

4.6. Performance of Boost converter using MRAC

To investigate the performance of a DC-DC boost converter using Lyapunov rule-based MRAC in MATLAB/Simulink the same parameters are taken for the converter as given in Table 3.3 above. The simulation result of the DC-DC boost converter using the proposed controller that is MRAC based on the Lyapunov rule is given in Figure 4.9 below. The actual output voltage perfectly follows the reference model and it quickly attends the desired output voltage.

From the simulation results it is observed that, overshoot is minimized, and the performance specifications like, settling time, undershoot, oscillation, and steady-state error are improved. In short, the performance specifications are summarized in Table 4.6 as follows.

Table 4. 6: Performance of DC-DC Boost converter Using MRAC

Rise Time	Settling Time	Overshoot	Undershoot	e_{ss}
0.0519 Sec	0.1458 Sec	4.5993 %	0.0%	0.0V

From the simulation results given in Figure 4.9 below undershoot is removed, and the system achieved the desired value at a fast rising time and settling time.

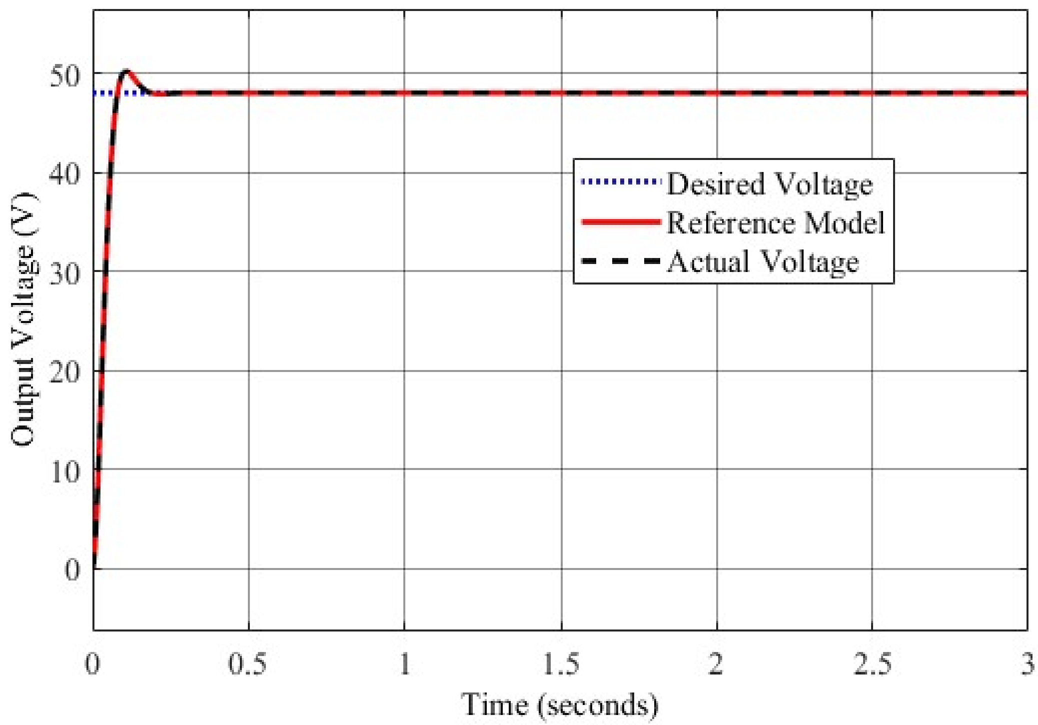


Figure 4. 9 : Simulation result of Output Voltage using MRAC

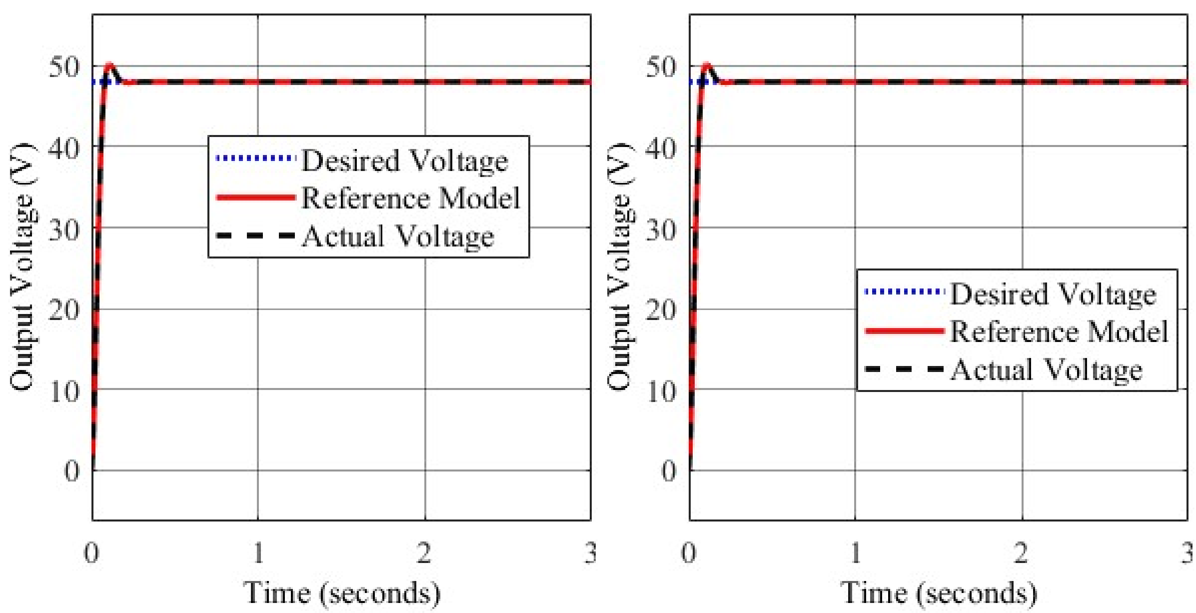
4.7. Performance of Boost Converter Using MRAC under Input Voltage and Load Resistance Variations

To see the effects of the input voltage variation and load resistance variation with MRAC, the nominal input voltage and nominal load resistance are changed as follows. Input voltage is increased from nominal value (12V) to 17V and decreased to 9V.

For the variation of input voltage as shown in Figure 4.10 (a) and (b) below the simulation result shows that there is slight change in rise time and overshoot. It is summarized in Table 4.7 as shown below.

Table 4. 7: Performance of DC-DC Boost converter Using MRAC for input voltage variation

Voltage variation	Rise Time(Sec)	Settling Time(Sec)	Overshoot	Undershoot	e_{ss}
From 12V-17V	0.0517	0.1458	4.5996 %	0.0%	0.0V
From 12v-9v	0.0519	0.1458	4.5986 %	0.0%	0.0V



(a) Input voltage change from 12V to 9V (b) Input voltage change from 12V to17V

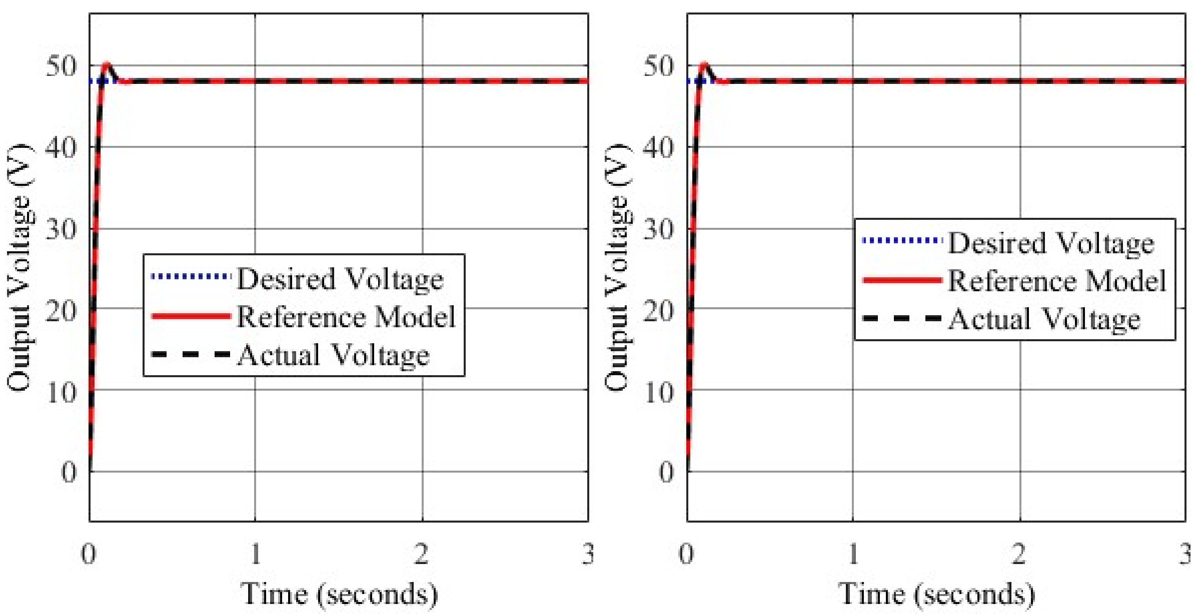
Figure 4. 10 : Simulation result using MRAC for variation of input voltage

The effects of load resistance variation from nominal load resistance (200 Ω) using MRAC is given by increasing load resistance from 200 Ω to 240 Ω and decreasing from 200 Ω to 150 Ω. The simulation result is given in Figure 4.11 below.

For the variation of load resistance as given in Figure 4.11 below (a) and (b), the simulation result has almost no change with that of the nominal load resistance response. It is summarized in Table 4.8 as shown below.

Table 4. 8: Performance of Boost converter Using MRAC for load resistance variation

Load resistance variation	Rise Time(Sec)	Settling Time(Sec)	Overshoot	Undershoot	e_{ss}
From 200 Ω -240 Ω	0.0519	0.1458	4.5994 %	0.0%	0.0V
From 200 Ω -150 Ω	0.0519	0.1458	4.5990 %	0.0%	0.0V



(a) Load resistance change from 200 Ω to150 Ω   (b) load resistance change from 200 Ω to 240 Ω

Figure 4. 11 : Simulation result using MRAC for variation of Load resistance

4.8. Performance of Boost Converter Using MRAC under External Disturbance

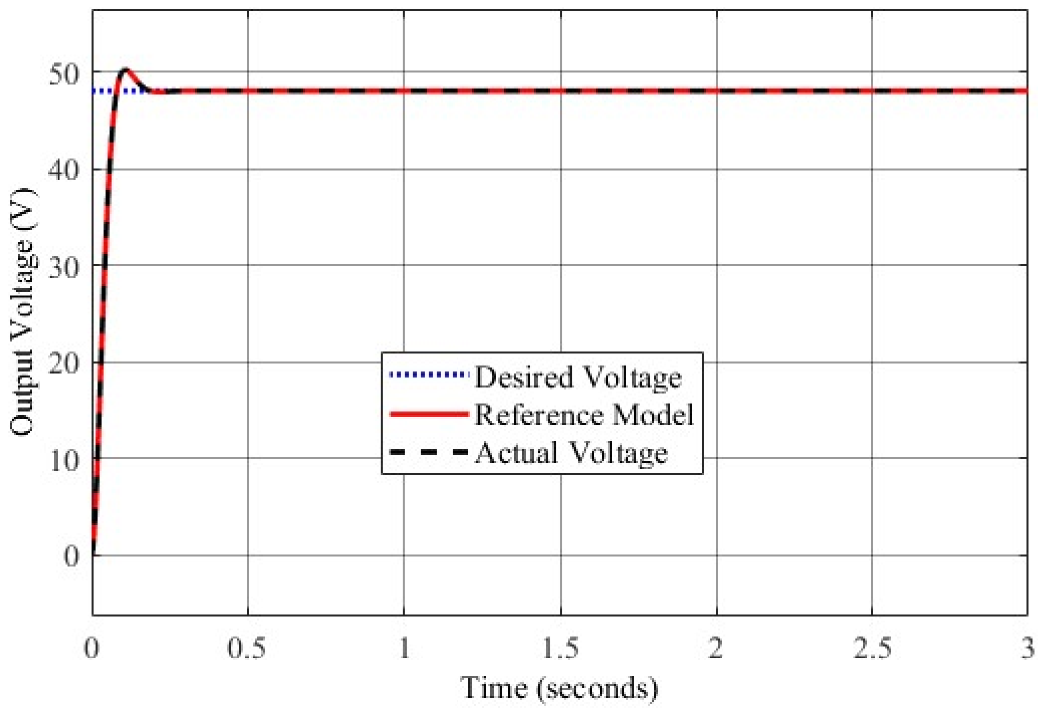


Figure 4. 12 : Simulation result using MRAC for external disturbance

By keeping the operating values of input voltage and load resistance at their nominal values, and a sinusoidal input is applied to the system as a disturbance. Then the response of the DC-DC boost converter using MRAC tracks the desired value and has no steady-state error as given in Figure 4.12 above. The simulation response given in Figure 4.12 is summarized in Table 4.9 below.

Table 4. 9: Performance of Boost converter Using MRAC for external disturbance

Rise Time	Settling Time	Overshoot	Undershoot	e_{ss}
0.0519 Sec	0.1458 Sec	4.5993 %	0.0%	0.0V

From the result given in Figure 4.12 above the Lyapunov rule based MRAC maintained the actual output voltage value tracking the desired voltage value with no steady-state error under the external disturbance to the system. This is due the adaptive and non-linear nature of the lyapunov rule based MRAC.

4.9. Comparison of MRAC and PID Controller for Boost Converter

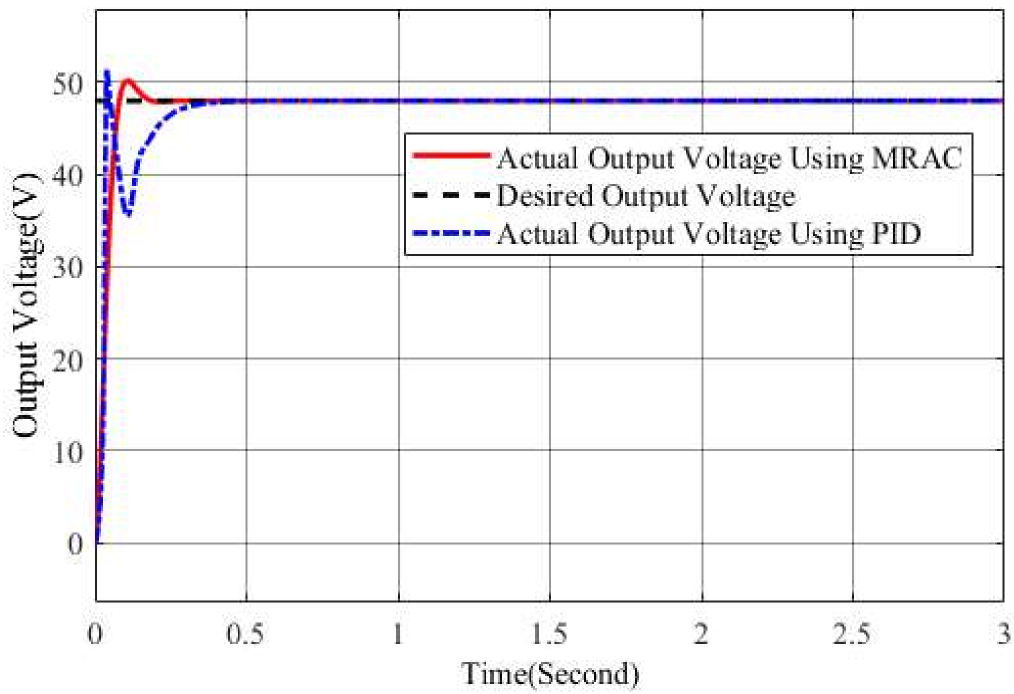


Figure 4. 13 : Output voltage response for comparison of MRAC and PID

Figure 4.13 above shows the output voltage response performance comparison of DC-DC boost converter using MRAC and PID controller. The performance comparison is summarized in Table 4.10 as shown below.

Table 4. 10: Performance comparison of boost converter using MRAC and PID controller

Controller type	Rise Time	Settling Time	Overshoot%	Undershoot%	e_{ss}
MRAC	0.0519 Sec	0.1458 Sec	4.5993 %	0.0%	0.0V
PID	0.0171Sec	0.2770 Sec	7.7717 %	0.0047 %	0.0V

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In this thesis, the Lyapunov rule based MRAC has been designed to achieve fast and stable performance of the DC-DC boost converter. The PID controller has been used as a bench mark. The performance of DC-DC boost converter has been tested using MATLAB/Simulink with-out controller and with controller. To test the performance of the DC-DC boost converter, it is assumed that, the input voltage has been decreased and increased from its nominal operating point by 25% and 41.67% respectively. Also the load resistance is assumed to be decreased and increased by 25% and 20% from its nominal operating load resistance respectively. An external disturbance was applied to the system to check how the controller handles uncertainty. The overshoot and settling time have improved by reducing from 67.5229% to 7.7717% and 0.6985 Sec to 0.277 Sec respectively in the case of PID controller. In the case of the proposed controller (Lyapunov rule based MRAC), overshoot, settling time, and undershoot have improved by reducing from 67.5229% to 4.5993%, from 0.6985 Sec to 0.1458 Sec, and from 0.0036% to 0.0% respectively. The steady-state error in both controllers has also improved. In the PID controller performance, the input voltage variation effect is more significant than the load resistance variation. But, in the case of MRAC the effect of both variation has almost no change and insignificant. When an external disturbance is applied to the system, the PID controller has shown deviation from the desired value. But, the controller MRAC maintained the desired value under the external disturbance.

Generally the proposed Lyapunov rule based MRAC controller performs better than the classical PID controller. The classical PID controller performs well in linear and fixed operating point systems. But, whenever the system dynamics is varying and is nonlinear, an advanced controller that continuously updates its behavior is required. Hence, the Lyapunov rule based MRAC is an adaptive, and nonlinear controller that updates its behavior continuously and achieved the expected results successfully.

5.2. Recommendation for Future Work

As a future work the following can be recommended

By using more advanced controllers like artificial neural network it can be improved the performance of the converter over a wide range of variation in operating point allowing the system to better handle nonlinearities and uncertainties in the converter dynamics. Finally, this work is done only in simulation based and one can design and develop prototypes to experimentally validate the proposed MRAC strategies, ensuring its practical feasibility and effectiveness.

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Appendix A: Parameter Specifications of boost converter

The parameter values of the converter used for MATLAB/Simulink are given as follows:

- ✓ The switching frequency is 75 kHz.
- ✓ The nominal input voltage is 12V.
- ✓ The nominal load resistance is 200Ω.
- ✓ The desired output voltage is 48V.
- ✓ The capacitor ripple voltage is assumed to be 1% of the output voltage.

Given these parameters, it is possible to calculate the minimum value of inductor that determines the boundary between continuous conduction mode and discontinuous conduction mode. Also, it is possible to calculate the minimum capacitor value to limit ripple voltage below a certain value and to minimize overshoot. Using the above given values the duty ratio is calculated as:

$$D = 1 - \frac{V_{in}}{V_O} = 1 - \frac{12}{48} = 0.75$$

The minimum inductor is given as,

$$L_{min} = \frac{D(1-D)^2 R}{2f} = \frac{0.75(1-0.75)^2 200\Omega}{2 * 75 * 10^3} = 3.75 * 10^{-4} H$$

The converter is designed for continuous conduction mode only and the value of inductor should be greater than the minimum value. Therefore to ensure continuous conduction mode of operation let the value of inductor $L = 75mH$.

The minimum capacitor required is given by,

$$C_{min} = \frac{D}{\Delta V\% Rf} = \frac{0.75}{1\% * 200 * 75 * 10^3} = 5\mu F$$

To limit the peak to peak value of the ripple voltage below a certain and minimize the voltage overshoot, for continuous conduction mode the value of capacitor should be greater than the minimum value. To ensure this the value of capacitor$C = 720\mu F$.