FRIT-BASED CONTROLLER TUNING OF A DC-DC BOOST CONVERTER

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ABSTRAK

Laporan ini membentangkan reka bentuk Fictitious Reference Iterative Tuning (FRIT) untuk penukar DC-DC Boost berdasarkan pendekatan Model-Bebas. Fictitious Reference Iterative Tuning adalah teknik penalaan berdasarkan data yang menggunakan sekali eksperimen untuk membentuk input pengawal model plant yang tidak ditentukan. FRIT memastikan output plant sesuai bersama output model rujukan dengan mengoptimumkan indeks prestasi, yang terdiri daripada output rujukan fiksyen yang dikira daripada keputusan input dan output sekali eksperimen. Penukar DC-DC Boost adalah suatu penukar yang meningkatkan voltan output yang lebih tinggi daripada voltan input. Sistem penukar ini mempunyai ciri-ciri dinamik yang tidak datar, kerana ia berfungsi dalam mod suis. Pemodelan system DC Boost yang ditukar mula-mula disediakan untuk membentuk pengumpulan data dan terbitan isyarat rujukan fiksyen. Konfigurasi sistem tidak datar yang dibincangkan di sini dianggap diketahui, tetapi parameter masih tidak diketahui. Analisis reka bentuk dan simulasi menggunakan perisian MATLAB telah dijalankan untuk pengesahan keputusan. Selain itu, kami merumuskan algoritma dalam menentukan parameter pengawal optimum berdasarkan pendekatan Model-Bebas. Akhir sekali kami mengesahkan dan membandingkan output teknik yang telah dicadangkan dengan sebarang teknik reka bentuk pengawal sedia ada.

ABSTRACT

This report presents a Fictitious Reference Iterative Tuning design for a DC-DC boost converter based on a Model-Free approach. A Fictitious Reference Iterative Tuning is a data-driven controller tuning technique that uses one-shot experimental data to construct the input controller of an undefined plant model. Fictitious Reference Iterative Tuning ensures that the plant output fits the reference model output by optimizing the performance index, which comprises a fictional reference output calculated from one-shot experimental input-output results. A DC-DC boost converter is a step-up converter with an output voltage higher than the input voltage. This converter system has a nonlinear dynamic behaviour, as it works in switch mode. The modelling of a Boost converted system is first provided to form data collection and fictitious reference signal derivation. The configuration of a nonlinear system discussed here is assumed to be known, but the parameters remain unknown. Design and simulation analyses using *MATLAB* software have been conducted for results validation and verification. Furthermore, we formulate the algorithm for determining the optimal controller parameters based on the Model-Free approach. Lastly, we verify and compare the proposed tuning technique's output with any controller design techniques.

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LIST OF SYMBOLS

$\mathbb{R}$	Real number
ω_n	Natural frequency
ζ	Damping ratio
$\sum$	Summation
$\int$	Integral
ρ	rho
∞	Infinity
Ω	Ohm

LIST OF ABBREVIATIONS

PWM	Pulse Width Modulation
DC	Direct Current
FRIT	Fictitious Reference Iterative Tuning
PID	Proportional, Integral, and Derivative
CCM	Continuous Current Mode
DCM	Discontinuous Current Mode
MOSFET	Metal-oxide-semiconductor Field-effect Transistor
BMO	Barnacles Mating Optimizer
C	Capacitor
D	Diode
Vs	Input Voltage
Vo	Output Voltage
L	Inductor
R	Resistor
LSM	Least Square Method

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter discussed the research background for a DC-DC Boost converter using FRIT-Based controller tuning. In addition, the project's problem statement and scope were discussed.

1.2 Project Background

DC-DC converters are commonly used in controlled switch applications. A DC Boost converter is one of the simplest forms of switch-mode converters. It is utilized when the intended output voltage exceeds the input voltage while stepping down the current. The duty cycle of the switching frequency must be increased to boost the voltage. The switched-mode power supply (SMPS) switch must rapidly turn on and off and have minimal losses for maximum efficiency. A DC Boost converter is extensively utilized in various applications, including electric vehicles, solar cells, and DC motor drives. All these applications need the input DC voltage to be Boosted in the output voltage. They are very efficient, have a reasonable acceleration control, and have a rapid dynamic reaction. The DC-DC boost converter's general schematic diagram is shown below.

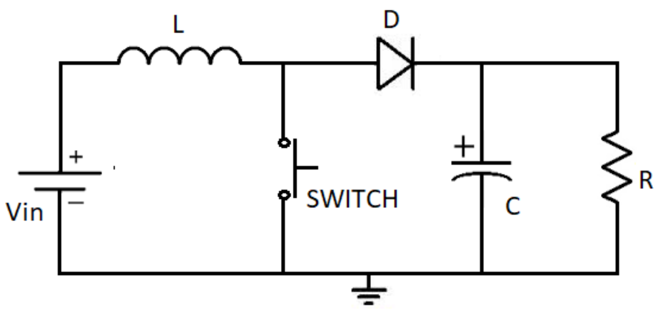

Figure 1.1 Basic schematic diagram of a DC-DC Boost converter

In this project, we will use the FRIT method. FRIT is a Fictitious Reference Iterative Tuning. It's a model-free way to build the feedback controller for an unknown plant model rather than a model-based approach. As depicted in **Figure 1.2**, this is the block diagram for a closed-loop system in which we inject a reference value at the input R(s) and tune the controller to get the same value at the output Y(s).

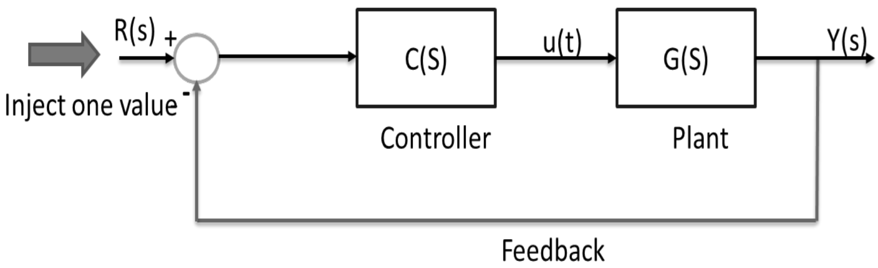

Figure 1.2 Block diagram of a closed-loop system

1.3 Problem statement

Nowadays, the classical method of controller designs requires information on the plant-to-be-controlled. Hence, having the plant's dynamics in terms of its mathematical models and parameters is crucial in the controller design process. However, external factors such as ageing and disturbances will cause the plant's dynamic to change, leading to inconsistency in obtaining the optimal controller's parameters.

As a result, there is a need to develop a new method for determining the best controller parameters based on the plant's recorded input and output data.

1.4 Objective

The objectives of this project are as follows:

1. To design a state feedback controller with integral action for a DC-DC Boost converter by utilizing only recorded input and output data sets.

2. To formulate a model-free tuning algorithm based on the Fictitious Reference Iterative-Tuning (FRIT) approach in determining the optimal controller's gains so that the desired transient response specifications can be achieved.

3. To verify and compare the proposed tuning technique with the existing controller design techniques.

1.5 Scope of work

MATLAB Simulink was utilized as a simulation tool in this study to develop a control tuning algorithm for the proposed controller technique. This project's scope of work includes, but is not limited to, a literature review, system development, data analysis, and report writing. **Figure 1.3** illustrates the overall flowchart of this project.

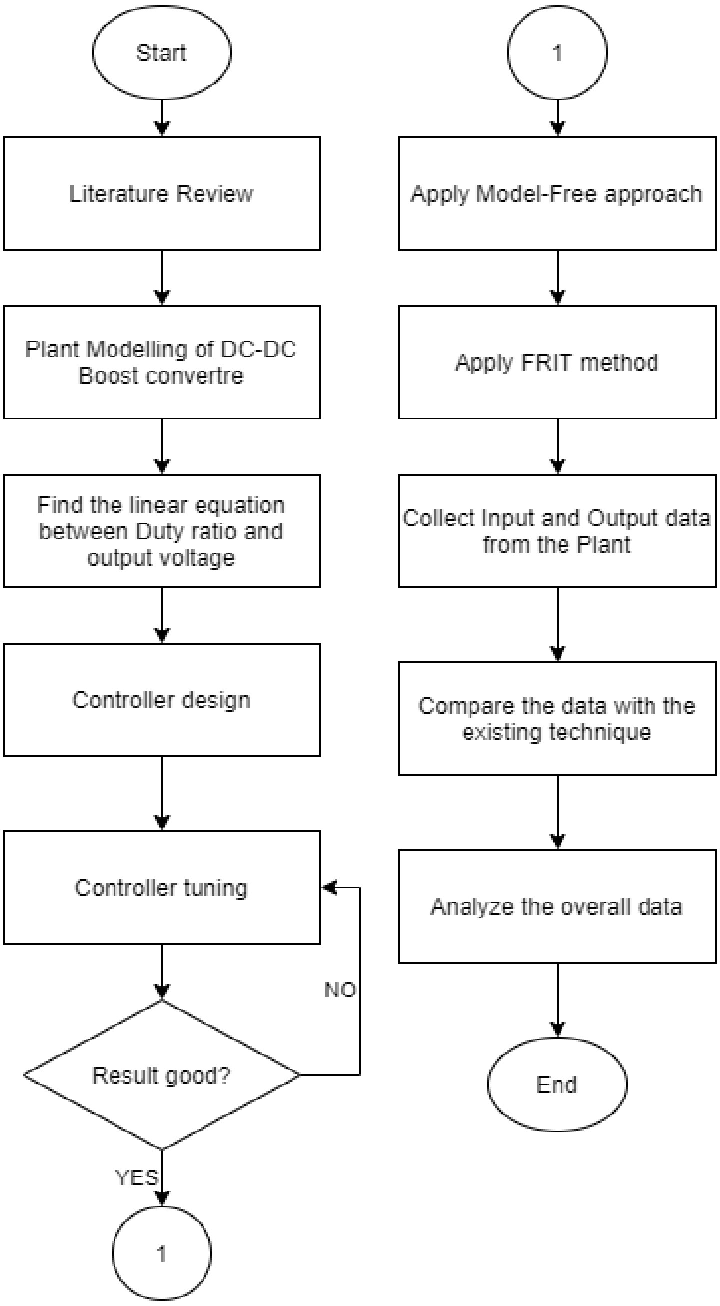

Figure 1.3 The overall flow chart of this project

1.6 Thesis outline

This thesis is divided into five chapters: introduction, literature review, methodology, result and discussion, and conclusion.

Chapter 1 introduced the project's background, problem statement, research objectives, and project scope.

Chapter 2 emphasized various researches on relevant studies that serve as the foundation for this project.

Then, in Chapter 3, a complete description of the Fictitious Reference Iterative Tuning and Model-Free method of designing a DC-DC Boost converter.

In Chapter 4, several simulation analyses and case studies explain the proposed method.

Finally, in Chapter 5, we discussed our results and made suggestions for further research.

1.7 Mathematical Preliminaries

We denote $\mathbb{R}$ and $\mathbb{R}^n$ as the sets of a real number and real vector with n-dimension, respectively. Meanwhile, we use $\mathbb{R}^{m\times n}$ to represent the set of real matrices with m-number of rows and n-number of columns and T is the transposition.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter summarizes chosen references that are relevant to this project. We discussed the topics such as DC-DC Boost converters, Fictitious Reference Iterative Tuning, and Model-Free method.

2.2 DC-DC Boost converter

According to the researchers in [1], the output voltage of a boost converter is higher than the converter's input voltage. A conventional DC-DC boost converter circuit consists of an input voltage Vs, an inductor, a controlled semiconductor switch such as a MOSFET, a diode, a capacitor, and a load resistance. It's a switching converter that goes from ON to OFF. The boost converter makes both continuous and discontinuous current modes possible. These modes may also be calculated using the current inductor value, and they can be calibrated using the duty ratio. This project explains the continuous current mode (CCM). The diode is reverse biased when the switch is in an ON state. The inductor's voltage is almost identical to the input voltage. The current increases, and the energy held in the inductor is converted to heat. When the switch is switched to the OFF position, the diode becomes forward biased. The current flows in the load's direction from the inductor and input source to receive the stored energy. The stored energy is released when the inductor's current diminishes.

The DC-to-DC converters may be used in a wide range of applications. Personal computers, office equipment, spaceship power systems, laptops, telecommunications equipment, and direct current motor drives featured [2]. The growing usage of battery-powered portable devices, such as mobile phones and laptop computers, causes DC-to-DC conversion power sources, such as switched-mode power supplies. The popularity of distributed energy sources such as solar photovoltaic systems, which provide direct current electricity, has increased the demand for DC-to-DC converters. According to the researchers in [3], the DC-DC boost converter offers excellent efficiency, adequate acceleration control, and quick dynamic response. They may be used to regenerate DC engines to restore energy to the source. This characteristic saves energy for frequent-step transit systems.

2.3 Pulse-width Modulation (PWM)

PWM (pulse width modulation) is a simple way to control analogue circuitry with digital outputs. The main component of a boost converter's design is PWM. The output voltage is controlled by adjusting the duty cycle of the switch when employing pulse-width modulation (PWM) control. When referring to the "duty cycle," we mean the ratio of the power semiconductor's output to the total cycle time. PWM is used in many applications, including measurement and communications, power management, and conversion. Typically, a microcontroller is used to adjust the output of PWM. The transistor switch is the most crucial factor of the switched supply since it limits the amount of power provided to the load. Additionally, it is suggested that Power MOSFETs are better suited than BJTs for power outputs up to 50 W. When selecting a transistor, it is also necessary to investigate its fast switching speed and ability to tolerate voltage spikes generated by the inductor[4].

PWM has its purpose in controlling the output voltage by applying a PWM signal[5]. The intersective approach is the most straightforward approach to produce a PWM signal since it involves just a sawtooth or triangle waveform and a comparator. A comparison will be made between the triangle waveform and the controller's output signal. The triangle waveform and the output controller intersection result in either a high or a low state for the PWM signal compared to the reference signal [4]. The PWM waveforms using the intersection method are shown in **Figure 2.1**, and the example of a Pulse Width Modulation waveform generated by an Arduino microcontroller is shown in **Figure 2.2**.

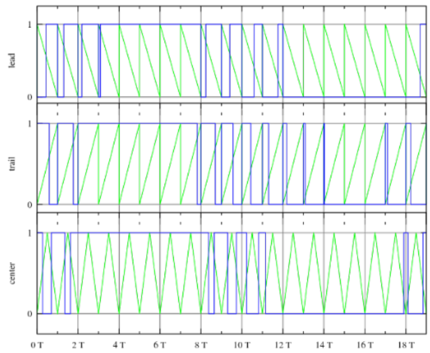

Figure 2.1 The PWM waveforms using the intersection method

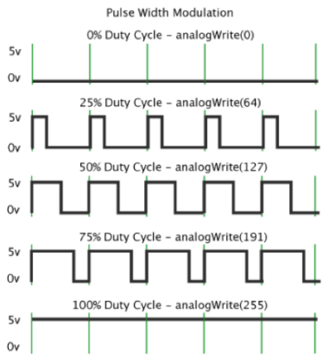

Figure 2.2 Pulse Width Modulation waveform controlled by Arduino

2.4 Pole Placement

The DC-DC boost converters are nonlinear systems because they exhibit complicated dynamic behaviour and must be managed. The pole placement approach can stabilize a complex system by reassigning the pole placements to provide the system with the most gain. In [6], the pole placement approach entails intuitively changing gain settings to understand the system's pole and zero location behaviour on the complex plane. This approach stabilized an under-actuated cart inverted pendulum system. Their observation explains why, when pole sites are chosen more negatively, output responsiveness increases, yet the system displays a greater degree of overshoot. However, gain values alone do not guarantee the system's success in the face of steady-state inaccuracy. Therefore, the controlled system was enhanced with a pre-gain value to improve output responsiveness and steady-state error[6].

2.5 State Feedback and Integral Control

State feedback control allows for more freedom in locating poles by time-domain standards, and its implementation is more straightforward than VMC or CMC for boost converters [7]. Numerous practical applications, including positioning controls in mechanical systems and temperature management in process control systems, include this condition. In general, state feedback gains are obtained based on the mathematical model that accurately represents the dynamics of a system. However, it should be highlighted that there are several instances when the consequences of secular or abrupt shifts cannot be ignored. In such cases, the implemented controller must be changed or tweaked. Generally, updating a controller starts with renewing the mathematical model upon which the controller was built or modifying a parameter[8]. The integral state feedback provides many advantages, including a simple structure, ease of design, and the ability to be utilized in a multi-input multi-output system[7]. The PI controller is a conventional linear control approach employed in various applications today. The linear PI controllers for DC-DC converters are often constructed using frequency-domain methodologies applied to small-signal models. The reaction of the PI controller to changes in the operating points may be weak. The PI controllers are inadequate for controlling a higher-order system because they do not supply enough parameters to locate the needed closed-loop poles. As a result, state feedback control has been employed to create a robust and reliable output controller [9].

2.6 Proportional Integral Derivative (PID) Controller

The PID controller uses the weighted sum of three gains to determine the system's output. The proportional gain creates an output value proportional to the present value of the error[10]. The system becomes unstable if the gain is set too high while tuning the proportional gain. The output may overshoot significantly, increasing the time required to reach the desired level. The responsiveness of the control action to system disturbances may be inadequate if the proportional gain is set too low. The absolute error over time is equal to the integral gain. Minimize the integral gain to reduce overshoot [11]. However, since the integral term responds to previous cumulative errors, the current value may overshoot if the gain is too significant.

In contrast, derivative gain calculates the difference between the current and past errors over time. The derivative lowers the controller's transient response, but it also can reduce the integral component's overshoot and increase the controller-process stability. The PID controller is very sensitive to tune, and as a result, an effective tuning technique is required to ensure the PID controller is efficient with the system. The block diagram of a PID controller in a feedback loop is shown in **Figure 2.3.**

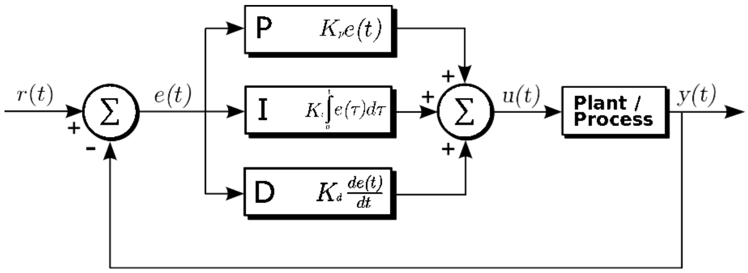

Figure 2.3 The block diagram of a PID controller in a feedback loop

2.7 Model-Free approach

Researchers in [12] stated that Model-Free Adaptive Control integrates present and conventional control theory and dismantles its constraints. It gives an excellent and straightforward control mechanism that does not depend on mathematical models to maintain the stability of the closed-loop system. Constructing a mathematical model for a time-varying or nonlinear system is not straightforward and sometimes impossible in the controlled system. Even if the mathematical model of the controlled system is developed, problems with model-free dynamics cannot be avoided. The researchers in [13] also stated that many techniques rely on model-based control mechanisms that are generally difficult to implement in practice. This is because their control techniques do not adequately reflect a system character. As a result, a model-free approach will seem more appealing.

2.8 Fictitious Reference Iterative Tuning (FRIT)

In [14], Fictitious Reference Iterative Tuning is a data-driven or Model-free tuning technique that utilizes only one-shot experimental data. It has been improved to enable the tuning of parametrized internal model controllers. Furthermore, it is shown that the cost function may be lowered in a fictitious reference. Both desired tracking and model achievement are linked to repeated adjustment. It is a novel approach of iterative parameter tuning based on a single-shot experiment intending to reduce the cost and time necessary to arrive at the controller's optimal parameter during iterative tuning[15]. Our method works based on tuning the controller's parameter offline using a fictional reference signal. Consequently, we came up with the term "Fictitious Reference Iterative Tuning" to describe our alternative method [15].

2.9 Barnacles Mating Optimizer (BMO)

Optimization is the process of discovering the optimal combination of variables or parameters that satisfy the constraints required to attain the objective function, whether it is for minimization or maximum of a variable or parameter [16]. Barnacles are hermaphrodites, which means they have male and female reproductive organs. Barnacles are unique in that they grow very long penises for mating to compensate for their sessile lifestyle. In solitary barnacles, sperm is thrown. Sperm-cast mating is a technique in which the eggs are fertilized by the sperms discharged into the water. The creation of BMO is motivated by these traits when tackling optimization challenges[16]. When test functions were used to 23 benchmarks the performance of the proposed algorithm in terms of exploitation, exploration, and convergence features, the results show that BMO surpasses state-of-the-art optimization approaches. BMO was able to give highly competitive outcomes, according to the results. The BMO method is developed in three steps: first, initialization, then selection, and lastly, off-spring generation[17].

CHAPTER 3

METHODOLOGY

3.1 Introduction

The general method for completing this project will be discussed in this chapter. Only MATLAB SIMULINK simulations were employed for State-Feedback and Integral action controller to find the best parameter. This study aims to provide some mathematical derivations and then provide simulated and experimental data to demonstrate the effectiveness of the suggested DC-DC Boost converter architecture.

3.2 Overview

In this project, we used a model-based and model-free approach. The model-based approach requires information on the plant's model, like the component's parameters. For example, one of the methods used in the model-based approach is Pole-Placement. While the model-free technique requires less knowledge of the plant, it does need knowledge of the relationship between the input and output data. We can tune the controller using this information. Our proposed method for a model-free approach is Fictitious Reference Iterative Tuning (FRIT). It is a technique for developing the feedback controller for a previously unidentified plant model[18]. The overall flowchart for this project is shown in **Figure 3.1**.

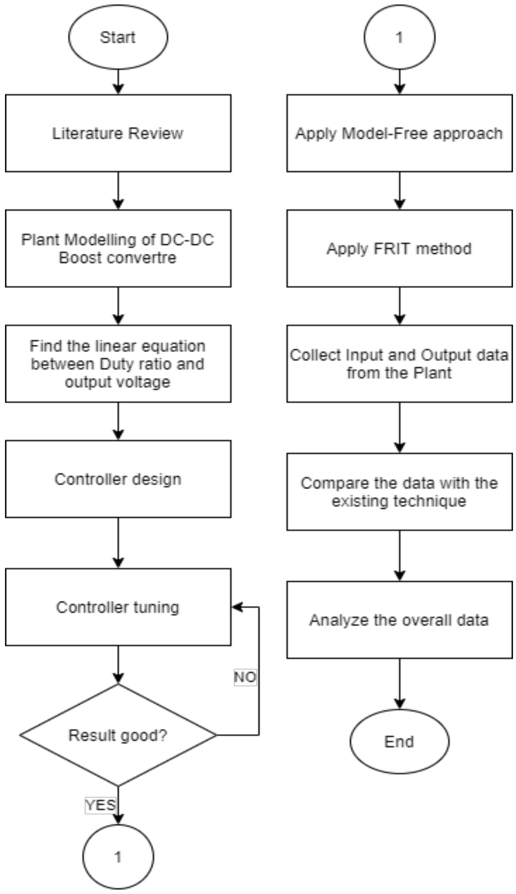

Figure 3.1 Overall Project flowchart

3.3 Project development

Our research focuses on developing a model-based state feedback controller with integral control for a DC-DC Boost converter system. By modifying the mathematical structure of the system, a state feedback controller may optimize a closed-loop system. This controller would replace the whole poles system with the specified mathematical structure. Due to a significant steady-state error from the state feedback controller, an integral action control was included in the control's design system to address the problem. Thus, this project's purpose is to reconfigure the dynamics of the existing plant and control design such that $\lim_{t\to\infty} e_d(t) = 0$ as shown in **Figure 3.2** below.

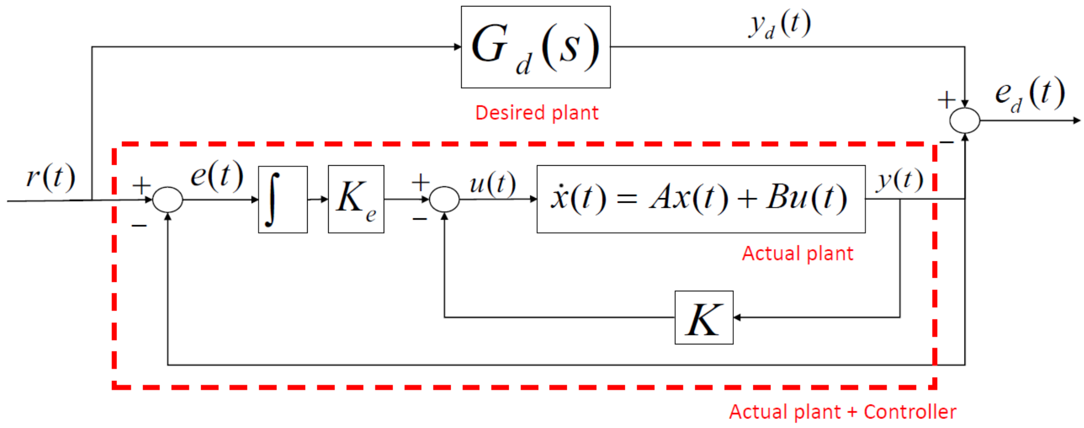

Figure 3.2 State Feedback with Integral action

A model-free technique like our proposed method, which is Fictitious Reference Iterative Tuning (FRIT), the controller is tuned to optimize gain by using sets of the initial input, u^o and output data, y^o as seen in **Figure 3.3**. This method is used to minimize the cost function in continuous time, $J = \sum_{t=1}^{N} \| e_d(t) \|_t^2$

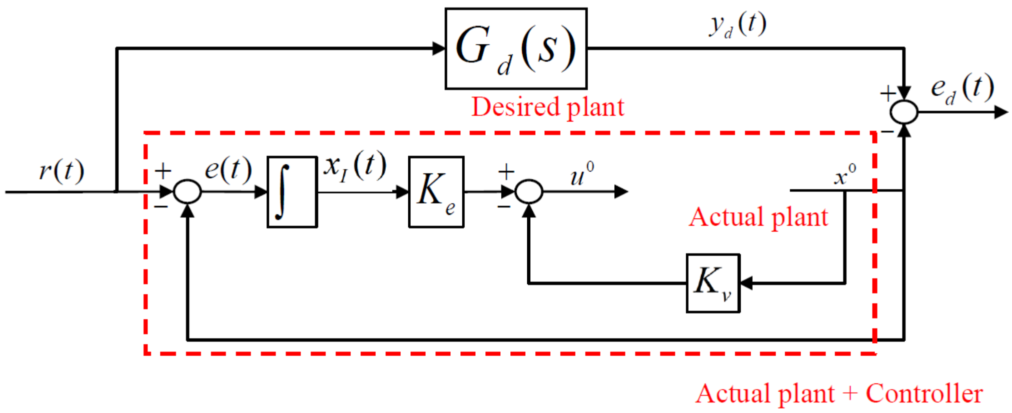

Figure 3.3 Block diagram of the Fictitious Reference Interactive Tuning

3.4 Modelling of a DC-DC Boost converter

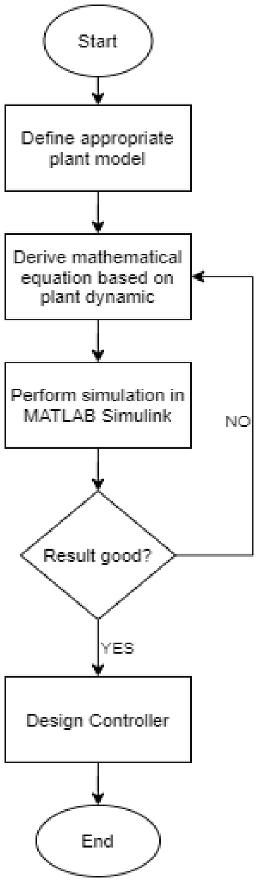

Figure 3.4 Plant model's flow chart

We must first derive the mathematical equations for a model-based design before developing our plant, a DC-DC boost converter. The phrase "boost converter" refers to a device with greater output than the input voltage. This switching converter works by regularly closing and opening an electrical switch, as shown in **Figure 3.5-3.7**.

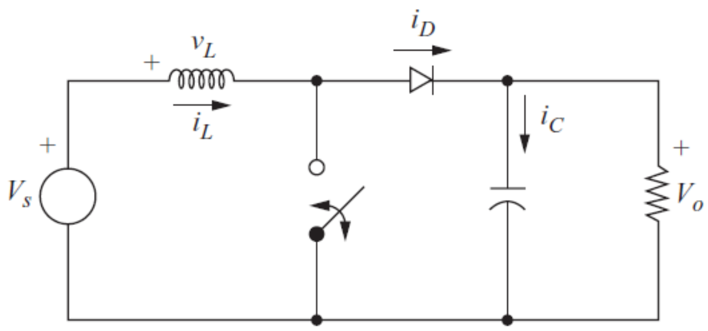

Figure 3.5 Standard boost converter circuit

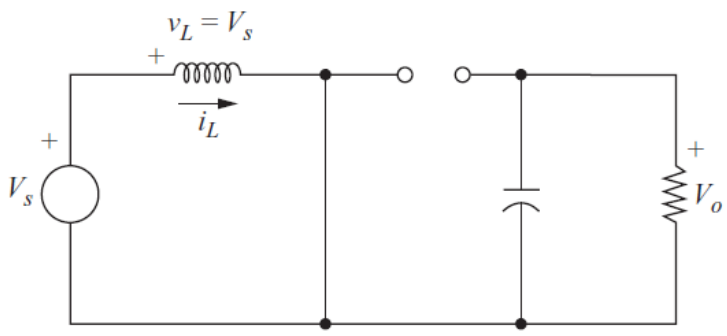

Figure 3.6 Circuit when the switch closed

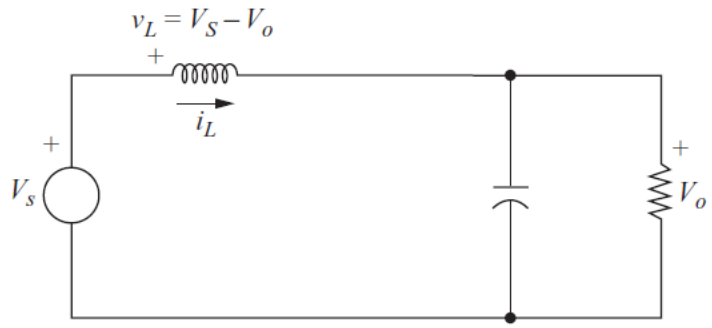

Figure 3.7 Circuit when the switch opened

The study assumes that steady-state conditions exist. The switching period is then T, with the switch being closed during the time DT and opened during the time (1-D) T. The current passing through the inductor then remains constant (always positive). Consequently, the capacitor is huge, the output voltage is constant at Vo, and the components are ideal.

After then, the analysis is performed with the switch closed and then open. The analysis shows that the diode is reverse biased when the switch is closed. Kirchhoff's voltage law applies to the source, inductor, and closed switch circuit.

$$v_L = v_s = L\frac{di_L}{dt} \tag{1}$$

While the switch is closed, the current has a constant rate of change, which means it rises linearly. The difference in inductor current is computed from:

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_s}{L} \tag{2}$$

Solving for Δi_L for the switch closed,

$$(\Delta i_L)_{(closed)} = \frac{V_s DT}{L} \tag{3}$$

The inductor current cannot change instantly; thus, the diode becomes forward biased to provide a conduit for the inductor current. The voltage across the inductor, assuming a constant output voltage, is:

$$\begin{aligned} v_L &= V_s - V_o = L\frac{di_L}{dt} \\ \frac{di_L}{dt} &= \frac{V_s - V_o}{L} \end{aligned} \tag{4}$$

The current must fluctuate linearly while the switch is open because the inductor current changes at a constant rate. The change in inductor current when the switch is open is:

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_s - V_o}{L} \tag{5}$$

Solving for Δi_L,

$$(\Delta i_L)_{(open)} = \frac{(V_s - V_o)(1-D)T}{L} \tag{6}$$

The net change in inductor current must be zero for steady-state functioning.

$$\begin{aligned} &(\Delta i_L)_{(closed)} + (\Delta i_L)_{(open)} = 0 \\ &\frac{V_s DT}{L} + \frac{(V_s - V_o)(1-D)T}{L} = 0 \end{aligned} \tag{7}$$

Solving for Vo,

$$V_s(D+1-D)-V_o(1-D)=0$$
$$V_o=\frac{V_s}{1-D} \tag{8}$$

As a result, for continuous current in the boost converter, the minimal inductance and switching frequency combination is

$$L_{(min)}=\frac{D(1-D)^2 R}{2f} \tag{9}$$

Following that, an equation for ripple voltage is

$$\frac{\Delta V_o}{V_o}=\frac{D}{RCf}$$
$$C=\frac{D}{R(\frac{\Delta V_o}{V_o})f} \tag{10}$$

Then, the boost converter was modelled using the state-space averaging method. Consequently, depending on whether the switch S1 is on or off, the converter has two equivalent states at any one time throughout operation [7].

3.4.1 State Space Average Model

As discussed in this section, state-space modelling derives the transfer function for a boost converter. The boost converter's output voltage and duty cycle transfer function are calculated using the State Space Average Model. The circuit equations are as follows when the switch is switched on:

$$\frac{di_L}{dt} = \frac{v_s}{L} \tag{11}$$

$$\frac{dv_c}{dt} = -\frac{v_c}{RC} \tag{12}$$

The system's state-space representation during the switch-on time is:

$$\dot{x} = A_{on}x + B_{on}u \tag{13}$$

$$y = C_{on}x \tag{14}$$

Where $x = \begin{bmatrix} i_L \\ v_C \end{bmatrix}$, $u = v_s$

$$A_{on} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix}, B_{on} = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, C_{on} = \begin{bmatrix} 0 & 1 \end{bmatrix} \tag{15}$$

When the switch is turned off, the circuit equations are OFF:

$$i_L = -\frac{v_c}{L} + \frac{v_s}{L} \tag{16}$$

$$v_C = \frac{i_L}{C} - \frac{v_C}{RC} \tag{17}$$

The system's state-space representation during the switch-off time is:

$$\dot{x} = A_{off}x + B_{off}u \tag{18}$$

$$y = C_{off}x \tag{19}$$

Where $x = \begin{bmatrix} i_L \\ v_C \end{bmatrix}, u = v_{in}$

$$A_{off} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, B_{off} = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, C_{off} = \begin{bmatrix} 0 & 1 \end{bmatrix} \tag{20}$$

Finally, the average of the boost converter state-space A and B matrices for the 'ON' and 'OFF' states may be calculated using the switching duty cycle, d. **Equations (21)** and **(22)** produce the average A and B matrices.

$$\overline{A} = A_{on}d + A_{off}(1-d) \tag{21}$$

$$\overline{B} = B_{on}d + B_{off}(1-d) \tag{22}$$

The following are the equivalents of **Equations (21)** and **(22)**:

$$\overline{A} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} d + \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} (1-d) \tag{23}$$

$$\overline{B} = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} d + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} (1-d) \tag{24}$$

3.4.1 State Space Small-Signal Model

The small-signal model of the system is generated by averaging **Equations (21)** and **(22)**, then linearizing around the operational point:

$$\dot{x} = Ax + B_1 d + B_2 v_s \tag{25}$$

$$y = Cx \tag{26}$$

The following are the equivalents of **Equations (25)** and **(26)**:

$$\dot{x} = \begin{bmatrix} 0 & -\frac{1-D}{L} \\ \frac{1-D}{C} & -\frac{1}{RC} \end{bmatrix} x + \begin{bmatrix} \frac{V_o}{L} \\ -\frac{1}{C} \end{bmatrix} d + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_s \tag{27}$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} x \tag{28}$$

To simplify the above equation to become $\dot{x} = Ax + Bu$, below is the updated Equation:

$$\dot{x} = \begin{bmatrix} 0 & -\frac{1-D}{L} \\ \frac{1-D}{C} & -\frac{1}{RC} \end{bmatrix} x + \begin{bmatrix} \frac{1}{L} & \frac{V_o}{L} \\ 0 & -\frac{1}{C} \end{bmatrix} u \tag{29}$$

Where $x = \begin{bmatrix} \frac{i_L}{v_C} \end{bmatrix}, u = \begin{bmatrix} \frac{v_s}{d} \end{bmatrix}, d =$ variation of duty ratio.

The small-signal model of the boost converter's transfer function can then be derived using the matrix equation:

$$X(s) = (sI - A)^{-1} Bu(s) \tag{30}$$

$$Y(s) = CX(s) \tag{31}$$

$$G_1(s) = \frac{v_o(s)}{v_s(s)} = C(sI - A)^{-1} B_1 \tag{32}$$

$$G_2(s) = \frac{v_o(s)}{d(s)} = C(sI - A)^{-1} B_2 \tag{33}$$

We create a controller that generates duty cycle, d, while maintaining a constant output voltage. In this sense, consider the transfer function described in **Equation (33)**, which may be represented as:

$$\frac{v_o(s)}{d(s)} = \frac{v_s}{(1-D)} \frac{1 - s\dfrac{L}{R(1-D)^2}}{[(\dfrac{LC}{(1-D)^2})s^2 + (\dfrac{LC}{R(1-D)^2})s + 1]} \tag{34}$$

Where D is the nominal duty cycle, v_o is the output voltage, and d is the variation of the duty cycle.

3.5 Parameter selection for the DC-DC boost converter

We used some procedures while designing our plant, a DC-DC boost converter. Assume our DC-DC Boost converter is needed to have a 20V output voltage and a 1A load current. The input voltage is 9V, and a PWM generator controls the duty ratio to maintain a steady output voltage. The switching frequency is set to 25 kHz, while the load resistance is set to 50 ohms. We can determine the inductor (L) and capacitor (C) values compatible with our design requirements by employing the mathematical formula above. As seen in Figure 3.6, we construct our circuit using MATLAB SIMULINK.

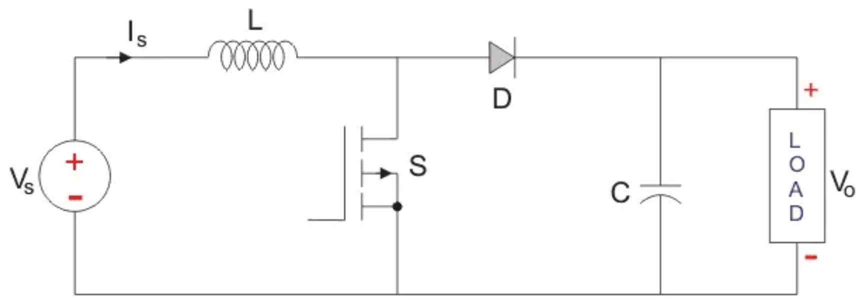

Figure 3.8 Basic DC boost topology

To simulate the circuit in MATLAB Simulink, we must first determine the inductor (L) and capacitor (C) values using the mathematical formulae in **Chapter 3.4**. The calculation is as follows:

1) Determine the duty ratio by using Equation (8):

$$V_o = \frac{V_s}{1-D}$$

$$D = 1 - \frac{V_S}{V_O} = 1 - \frac{9}{22.5} = \mathbf{0.6}$$

2) Determine the minimum inductance for continuous current by using **Equation (9)**:

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

$$= \frac{0.6(1-0.6)^2(50)}{2(25000)} = 96\mu H$$

$$L = 1.25\ (96\mu H) = \mathbf{120\mu H}$$

3) Determine the minimum capacitance by using **Equation (10)**:

$$C \geq \frac{D}{R\left(\frac{\Delta V_O}{V_O}\right)f}$$

$$C = \frac{0.6}{50(0.01)(25000)} = \mathbf{48\mu F}$$

After obtaining all the component values, we can construct our circuit in MATLAB Simulink. We design the circuit as shown in **Figure 3.9**.

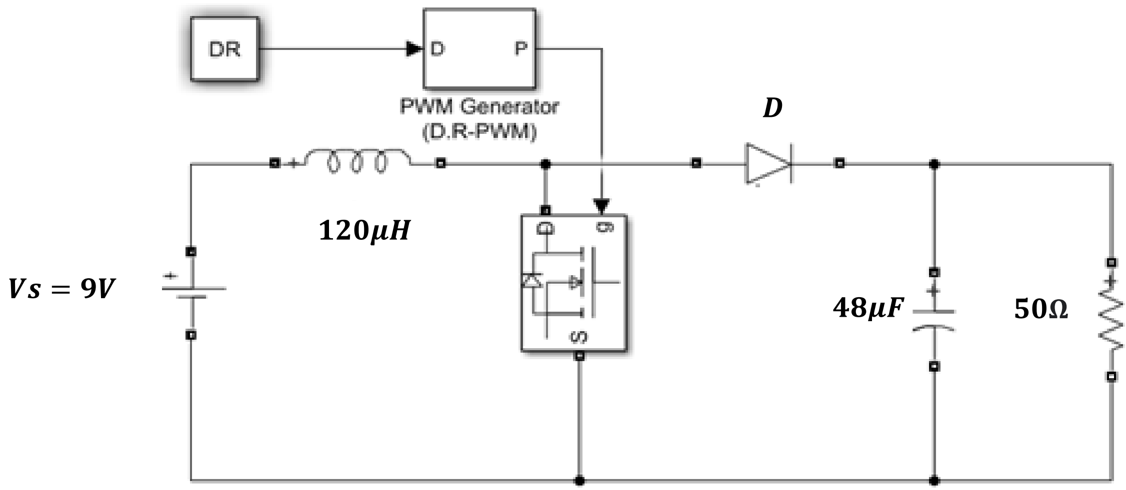

Figure 3.9 DC boost design in MATLAB Simulink

3.6 Establishing Linear Relation Between Duty Cycle and Output Voltage by Least Square Method

Linear regression is a technique for linearly modelling the relationship between a dependent variable and one or more independent variables. It is referred to as simple linear regression when there is just one independent variable. The Least Square Method will be used in this project to determine the relationship between the duty ratio and output voltage of the DC-DC Boost converter. The purpose is to determine the linear regression.

We want to establish the relationship between the duty ratio and the output voltage of the DC-DC Boost converter. This is due to the fact that we want to know the duty ratio at a specific output voltage. We are attempting to get a perfect linear equation and we must linearize it using the Least Squares method, modify the y-data, $voutdata$ with a semi-log scale ($\log_{10}$), and rename it as $y\log$. Instead of utilizing a duty ratio value between 0 until 1, we seek an appropriate value between 0 until the peak value and use it as our relevant peak data.

Assume that X represents the duty ratio data, $DRdata$ and Y represents the output voltage data, $voutdata$. Between these two variables, we will establish a linear relationship as follows:

$$Y = mX + c \tag{35}$$

The y-intercept is c, and m is the line's slope. This equation will be used to develop our model using a dataset and predict the value of $X = DRdata$ for every given value of $Y = y\log = \log_{10}(voutdata)$. Then we can substitute the obtained data into **Equation (35)**, the new equation as below:

$$\log_{10}(voutdata) = m * DRdata + c \tag{36}$$

To determine the best-fit line, we must first attempt to solve the above equations in the unknowns m and c, which is problematic. Because the data we obtained do not perfectly lie on a line, there is no proper solution. Thus, we must instead calculate using a Least Square method to address the problem. Before we utilize the Least Square method, we must first plot the data in many points in order to get more precise data. Then, we can use the Least Squares method to determine the optimal way to fit a curve to a data-point graph. To do that, we applied the Least Square method formula and derived it in MATLAB.

In linear regression, the line of best fit is a straight line, as illustrated in **Figure 3.10** below:

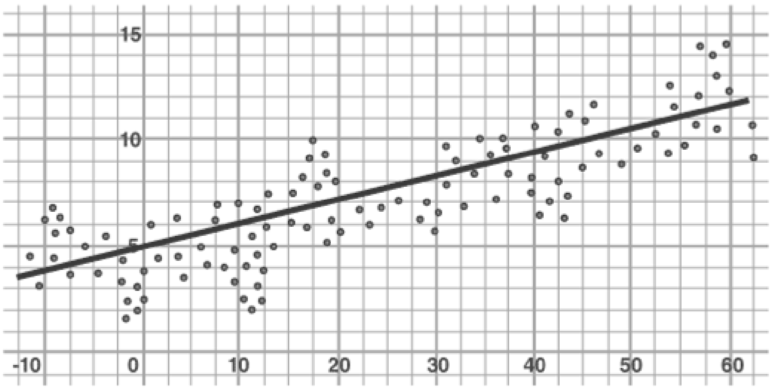

Figure 3.10 The line of best fit in linear regression

We are attempting to solve $Ax = b$, for the following linear equations, which we have converted to matrix form:

$$A = \begin{bmatrix} DRdata & 1 \end{bmatrix}^T \tag{37}$$

$$x = \begin{bmatrix} m \\ c \end{bmatrix} \tag{38}$$

$$b = \begin{bmatrix} y\log \end{bmatrix}^T \tag{39}$$

So now, let $A \in \mathbb{R}^{100\times 2}$, $x \in \mathbb{R}^2$ and $b \in \mathbb{R}^{1\times 100}$. The solutions to the matrix problem are the Least Squares solutions of $Ax = b$:

$$A^T Ax = A^T b \tag{40}$$

We must minimize the data points in order to produce the linear line. We only divided the data points into 60 data points instead of 100 data points. Then we use the modified data, the previous equation will also change according to the new set of obtained data of $DRdata$ and $y\log$. So now, let $A \in \mathbb{R}^{60\times 2}$, $x \in \mathbb{R}^2$ and $b \in \mathbb{R}^{1\times 60}$. The new data may be used to determine m and c values. The Least Squares solution for this problem is as follows:

$$x = (A^T A)^{-1} A^T b \tag{41}$$

From **Equation (41),** we obtained the value of m and c as below:

$$m = 0.6851$$

$$c = 0.9357$$

Then, we can reuse **Equation (36)** by substituting the value of m and c. The equation will be:

$$\log_{10}(voutdata) = 0.6851 * DRdata + 0.9357 \tag{42}$$

To derive the equation in terms of duty ratio and predict the value of duty ratio for every given value of output voltage, we need to rearrange **Equation (42)** as follows:

$$DRdata = \frac{\log_{10}(voutdata) - 0.9357}{0.6851} \tag{43}$$

3.7 State Feedback Controller Design

To improve the dynamic behaviour of DC-DC converters, use linear state feedback control with the Pole placement technique. The easiest controlled strategy for improving a system is pole placement control. This method reassigns the system's pole position by altering the gain parameter. The control system also added an integral control to eliminate the steady-state error. This chapter discusses the theoretical foundations for using these approaches, including state feedback through pole placement and state feedback with integral action.

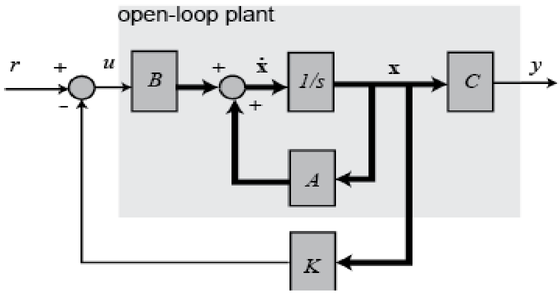

Figure 3.11 Full State Feedback block diagram

Considering the DC-DC converter linearized model:

$$\dot{x} = Ax + Bu \tag{44}$$

$$y = Cx \tag{45}$$

If the above system is considered entirely controllable, the control law is as follows:

$$u = -Kx \tag{46}$$

As seen in **Figure 3.11**, the system transforms into a closed-loop control system:

$$\dot{x} = (A - BK)x \tag{47}$$

The required closed-loop poles are the eigenvalues of the matrix $[A - BK](\mu_1, \mu_2, \dots \mu_n)$. To determine the system's poles through state feedback, the system must satisfy a required namely controllability, which is represented by the matrix $M = [\,B\ AB\ \dots\ A^{n-1}B]$, the matrix should be complete in rank. For example, the DC Boost converter has two states so that the state-feedback gain matrix will be [K1 K2].

3.7.1 State Feedback with Integral action

The state feedback with integral control block diagram in **Figure 3.12** depicts this architecture:

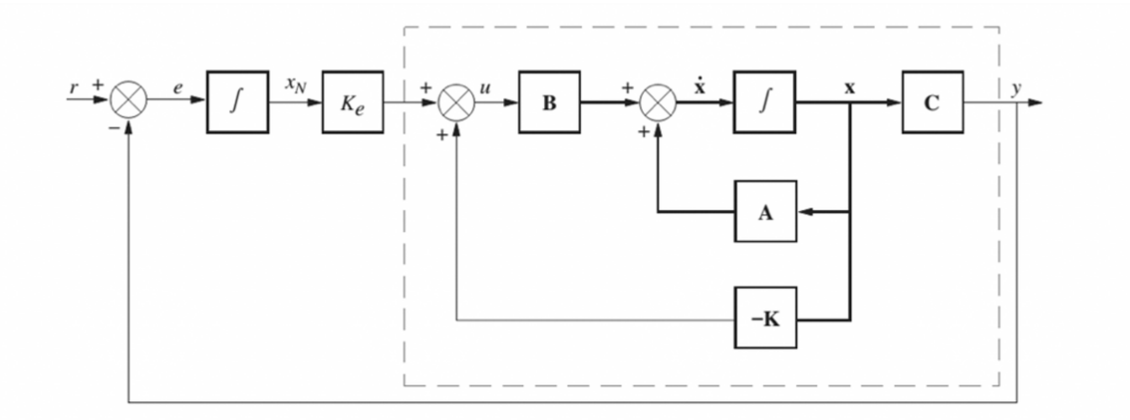

Figure 3.12 The structure of State-Feedback with Integral action

The State-Feedback with Integral action design method, as shown in **Figure 3.12**, contains an integrator into the feed-forward circuit between the plant's error signal and the feed-forward circuit between the plant's error signal. This integrator will remove the steady-state inaccuracy while also introducing a new state. However, since our plant lacks an integrator when state feedback control is applied, the steady-state error cannot be zero [12]. Therefore, the error of the derivative of this variable for the State-Feedback with Integral action is as below:

$$\dot{x}_N = -Cx + r \tag{48}$$

$$y = Cx \tag{49}$$

Next, we can obtain the new control law as below:

$$u = -Kx + K_e x_N \tag{50}$$

When the control law (50) is adopted, the modified closed-loop dynamical system may be described as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{x}_N \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} \begin{bmatrix} x \\ x_N \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r \tag{51}$$

$$y = \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x \\ x_N \end{bmatrix} \tag{52}$$

3.7.2 Selection of the plant's model of the desired system

The system designer makes assumptions about settling time, Ts and percentage overshoot, %OS for the proposed closed-loop system. We can determine the damping ratio, ξ, and the natural frequency, ω_n using these two pieces of information, which will be utilized to locate the poles of the required closed-loop transfer function. The following transfer function characterizes a generic second-order system:

$$G(s) = \frac{b}{(s^2 + as + b)} \tag{53}$$

The above transfer function may be rewritten in the conventional form of the second-order system (closed-loop transfer function):

$$G(s) = \frac{\omega_n^2}{(s^2 + 2\zeta\omega_n^2 + \omega_n^2)} \tag{54}$$

ω_n =Natural frequency

ζ =Damping ratio

The pole placement approach may compute the state-feedback gain matrix K and the integral gain constant K if the appropriate closed-loop poles are present. Assume the system dynamic is undamped in the closed-loop transfer function. The needed poles are positioned at

$$Poles; = -\omega_n\zeta \pm \omega_n\sqrt{\zeta^2 - 1} \tag{55}$$

Poles are complex if $\xi < 1$

3.7.3 Fictitious Reference Iterative Tuning (FRIT)

This method is our primary purpose in this project. FRIT is a model-free approach. In this method, we collect, record, and use the data from the actual plant's input, $u^0(k)$, state, $x^0(k)$ and output, $y^0(k)$. To verify that the plant output matches the reference model output, FRIT optimizes the performance index, which is made up of a fictitious reference signal derived from one-shot experimental input-output data [14]. Following that, we will utilize a model-free approach to tune the controller, in which we collect the input and output data from the Plant (DC-DC Boost converter).

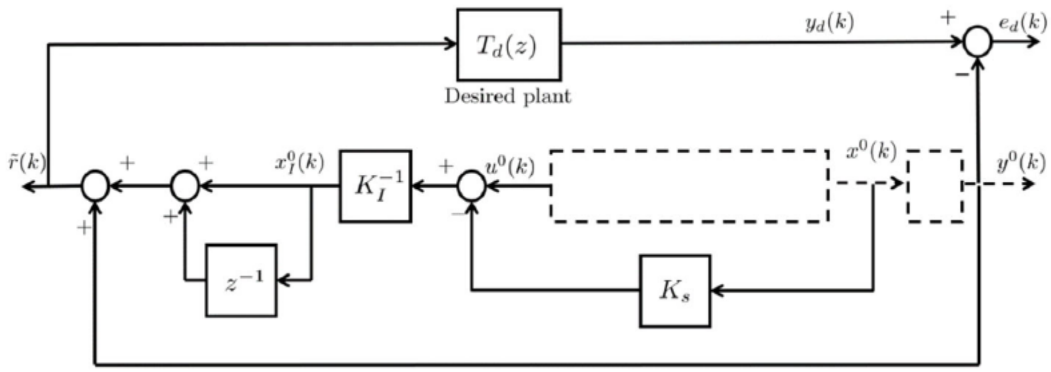

Figure 3.13 The modified block diagram of the Fictitious Reference Signal

From **Figure 3.13,** we can formulate the fictitious reference signal, $\tilde{r}(t)$ as Equation (56):

$$\tilde{r}(t) = y_0(k) + (1 - z^{-1})\left(\frac{K_S}{K_I}x_o(k) + \frac{1}{K_I}u_o(k)\right) \tag{56}$$

Then, we can obtain a cost function, J .Where, cost function, J is the summation of the error square as seen in **Equation (57)**. From that, we know our J is when we minimize the square of norm of recorded output, $y_o(k)$ and minus the fictitious signal, $\tilde{r}(t)$ multiply with the desired plant as seen in **Equation (58)**.

$$J = \sum_{k=1}^{N} \| e_d(k) \|_k^2 \tag{57}$$

$$J(\rho, k) := \| y_0(k) - T_d \tilde{r}(k) \|_k^2 \tag{58}$$

We aim to find the optimal solution to minimize the cost function, J, and this can be achieved using the **Barnacles Mating Optimizer (BMO)** algorithm. The equation of the optimal solution is as below:

$$\rho^* = \arg\min_{\rho} J(\rho) \tag{59}$$

3.8 Barnacles Mating Optimization (BMO) Algorithm

BMO is selected as a meta-heuristic algorithm because of its competitiveness with other current meta-heuristic algorithms [19]. This section provides an overview of barnacles in nature and the BMO mathematical model and plan. Barnacles exist in the ocean and follow their own body of law. Barnacles physically adhere to hard surfaces such as rocks, pilings, and buoys. Barnacles are unique because of their penis length, possibly the longest among creatures in their body size [20]. With such characteristics, barnacles may engage in mating behaviour to overcome their unresponsive state. Barnacles have a life cycle that is seen in **Figure 3.14.**

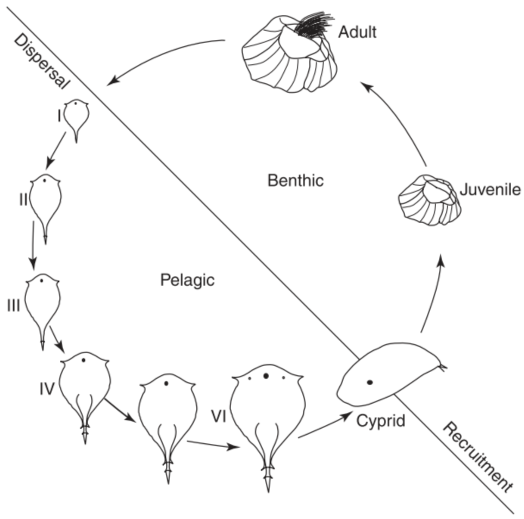

Figure 3.14 The barnacle's life cycle[21]

In BMO's offspring generation, the Hardy–Weinberg principle will be used [17]. In the simplest scenario, two alleles of D and M with frequency $f(D) = p$ and $f(M) = q$, respectively, indicate the Dad and Mom. Under normal mating, the predicted genotype frequencies may be stated as $f(DD) = p^2$ for homozygotes of DD, $f(MM) = q^2$ for homozygotes of MM, and $f(DM) = 2pq$ for heterozygotes. A Punnett square may be used to highlight the many ways to establish genotypes for the following offspring generation, as seen in **Figure 3.15**.

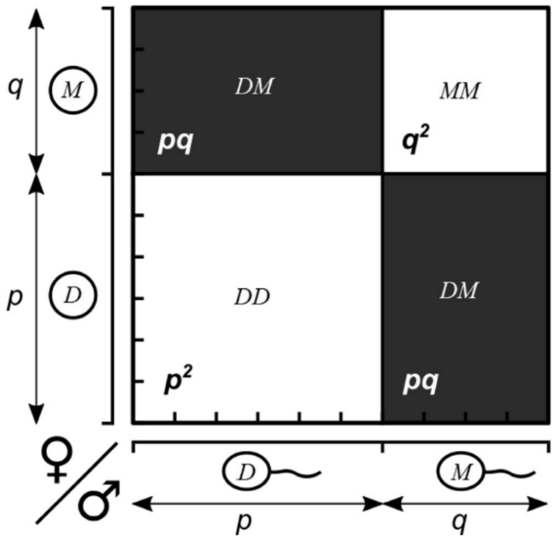

Figure 3.15 The Punnett square

By using barnacles' characteristics, the BMO is developed as described as follows :

3.8.1 Initialization

The possible solutions are first expressed in the following equation. It was necessary to complete this stage in order to generate candidate solutions, which were generated at random. Then, the sorting process will be used to determine the candidate's initial performance as below:

$$X = \begin{bmatrix} x_1^1 & \cdots & x_1^N \\ \cdots & \cdots & \cdots \\ x_n^1 & \cdots & x_n^N \end{bmatrix} \tag{60}$$

N signifies the size of the set of control variables that must be optimized, and n denotes the number of barnacles that might be regarded as potential candidates for the solution.

The following two equations illustrate how the problem's bounds confine the control variables in (60):

$$ub = [ub_1, \ldots, ub_i] \tag{61}$$

$$lb = [lb_1, \ldots, lb_i] \tag{62}$$

Where ub is the upper bound and lb is the lower bound of i-th variables.

3.8.2 Selection process

The BMO takes a unique approach to mate selection since the selection of two barnacles depends on the length of their penises, pl. The selection is arbitrary but is limited to the barnacle's penis length, pl. Based on the following assumption, the selection process is designed to simulate the behaviour of barnacles. The BMO algorithm is written with the assumption that one barnacle may fertilize each barnacle just once.

For example, in the case of barnacles, the maximum penis length is seven times greater than the maximum size ($pl = 7$). In this manner, barnacle No.1 may only mate with one of the barnacles No.2 through No.7 at any given iteration. Choosing barnacle No.8 exceeds the limit if barnacle No.1 is chosen. Because of this, the usual mating procedure is not carried out. The following selections are made, all of which is stated mathematically:

$$barnacle_d = rand\ perm(n) \tag{63}$$

$$barnacle_m = rand\ perm(n) \tag{64}$$

3.8.3 Off-spring generation

In BMO, new off-spring are reproduced using the Hardy-Weinberg principle [22], this statement indicates that the new off-spring will acquire the features of its parents.

$$x_i^{N^{new}} = px_{barnacle_d}^N + qx_{barnacle_m}^N \qquad k \le pl \tag{65}$$

Within the range [0, 1], p signifies the pseudo-random numbers that are regularly distributed, $q = 1 - p$, $x_{barnacle_d}^N$ and $x_{barnacle_m}^N$ represents the Dad and Mum variables barnacles, respectively. Sperm cast occurs when the number of barnacles chosen for mating surpasses the previously given value of penis length, pl. The sperm casting procedure is described as follows:

$$x_i^{n^{new}} = rand() + x_{barnacle_m}^N \qquad k > pl \tag{66}$$

When a random number is created between the ranges of [0, 1], it is denoted by the function $rand()$. It is worthwhile to emphasize that the value of pl has a significant impact on the exploitation and exploration activities. If the barnacles chosen for mating are within the range of the penis length of Dad's barnacle, the exploitation process occurs.

3.8.4 Application of BMO with Fictitious Reference Iterative Tuning (FRIT)

By solving the optimization issue using the BMO method, we may find the optimum parameters for the state-feedback and integral action controllers. This implies the optimal parameter, $\overset{*}{\rho}$ to satisfy. To describe our method by using the BMO algorithm, we devised the following algorithm using the fictitious signal, $\tilde{r}(k)$ as displayed in **Figure 3.13** to meet our aim of achieving the optimum $\overset{*}{\rho}$ value. Below are the steps:

Step 1: By arbitrarily choosing the initial gains of K_I and K_S, a one-shot experiment is run to generate and record the input, $u^0(k)$, state, $x^0(k)$ and output, $y^0(k)$, respectively.

Step 2: From recorded data, a fictitious reference signal is formulated based on **(56)** with a tunable gain of $\overset{*}{\rho}$.

Step 3: Define parameters like the search agent, iteration, lower bound, upper bound, parameter dimension, and most importantly, the size of the pl. Then, inside the defined search region, randomize the beginning location of all agents. The value of each position's cost function is then calculated. We may utilize **(58)** as a suitable candidate for the cost function since the optimization aim is to solve the $\overset{*}{\rho}$.

Step 4: At the end of the iteration, max iteration, all the agents shall converge to the optimal position, $\overset{*}{\rho}$ which corresponds to the optimal solution to **(59)**.

Step 5: Assign the optimum parameters gain, $\overset{*}{\rho}$ into the gain K_s and K_I. Validate the performance in the actual system. Repeat **Step 2** if the result is unsatisfying.

CHAPTER 4

RESULT

4.1 Introduction

This chapter will provide an analysis based on simulation results generated by the MATLAB program for both uncontrolled and controlled systems. The results are presented to compare the system's performance before and after tuning. The results of the Pole Placement technique and FRIT-BMO are then compared.

4.2 The relationship between the duty ratio and the output voltage

As shown in **Figure 4.1**, when the duty ratio increases, the output voltage also increases. At the beginning of the study, we plot the graph with 10 points, as below:

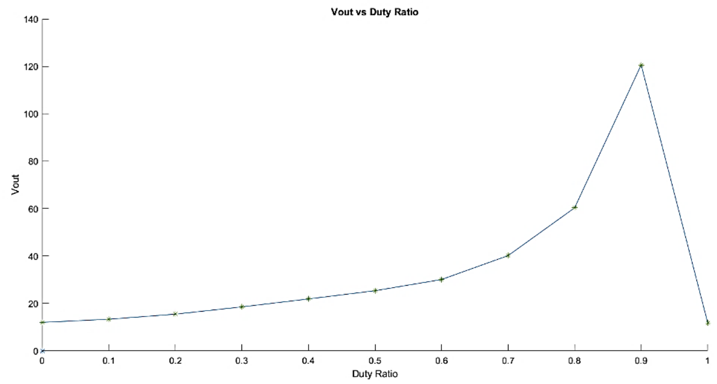

Figure 4.1 The relationship between the duty ratio and the output voltage of the DC-DC Boost converter

As shown in **Figure 4.1** above, it is currently not linear. Before we utilize the Least Square method to linearize the line, we must first plot the data in many points in order to get more precise data. So, we plot the graph with 100 points data, as illustrated in **Figure 4.2** and the straight line in the illustration below is the line of best fit.

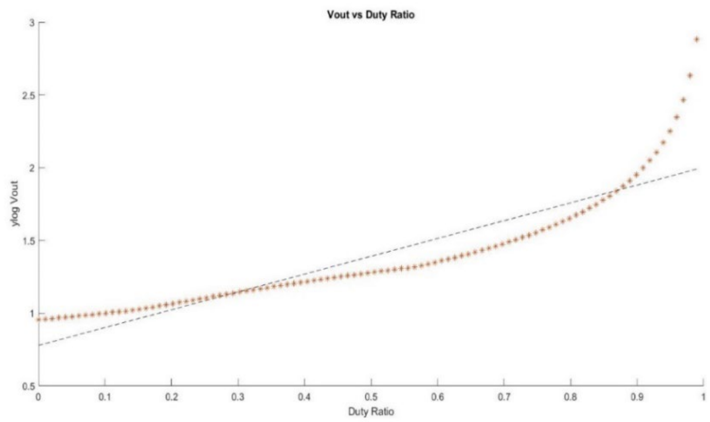

Figure 4.2 The relationship between the output voltage and duty ratio by using LSM

We divided the obtained data, $y\log$ and $DRdata$ into 60 data points to make **Figure 4.2** perfectly linear. Limiting the number of data points is necessary as we want to reduce each point's residuals or offsets from the obtained line. The result is shown in **Figure 4.3**.

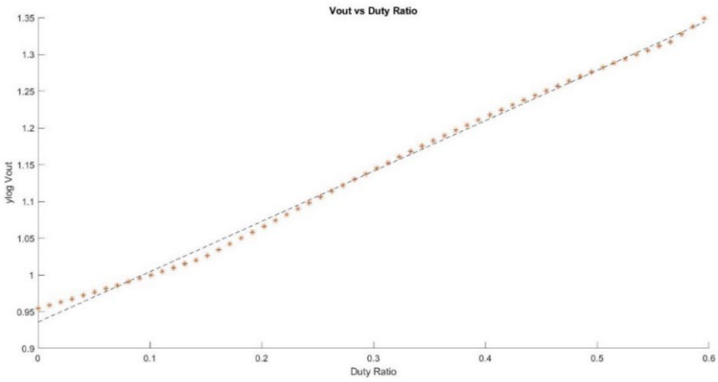

Figure 4.3 The relationship between the duty ratio and the output voltage using LSM in 60 data points

4.3 Behaviour Model System

For the boost converter circuit, simulations were run using the settings shown in **Table 1**. In MATLAB/Simulink, the behaviour of the State feedback and Integral action for the boost converter is simulated. The pole placement will be generated using the boost converter transfer function in MATLAB. To produce the pole location and provide the optimal step response, use the Place command in MATLAB. For controller design, the located point and relevant gain are used. The boost converter closed loop is simulated with and without state feedback and integral action.

Table 4.1 The Boost converter parameter

Parameters	Description	Value	Unit
Vs	Input Voltage	9	V
L	Inductance	120×10^{-6}	H
C	Capacitance	48×10^{-6}	F
R	Resistor	50	Ω
Fs	Switching Frequency	25×10^{3}	Hz

First, starting simulation to generate the Boost converter transfer function obtained earlier in **Equation (34)** gives the output voltages in the duty ratio **Equation (67)**. After substituting the values in the transfer function, it will be:

$$\frac{v_o(s)}{d(s)} = \frac{-9498.5s + 1.59 \times 10^9}{s^2 + 379.9s + 6.383 \times 10^7} \tag{67}$$

After rearranging the transfer function to find poles, zeros, and gain, it will be as shown below:

$$\frac{v_o(s)}{d(s)} = \frac{-9498.5(s - 1.68 \times 10^5)}{(s^2 + 379.9s + 6.383 \times 10^7)} \tag{68}$$

Then, we can produce the root locus plot for the actual system from the above transfer function and find the zeros and poles by using MATLAB command, `rlocus`.

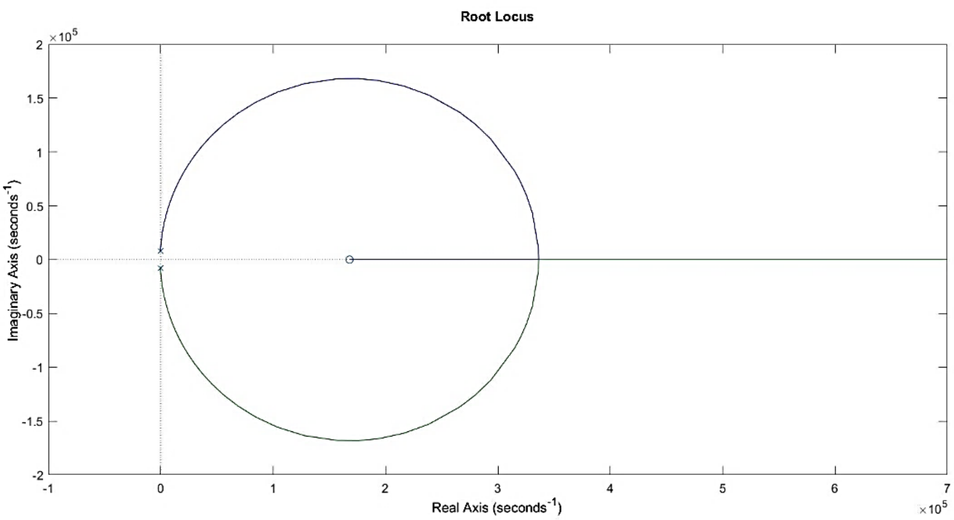

Figure 4.4 System root locus

From the root locus above, the poles are:

$$p1 = -190 + 79871\text{i}$$

$$p2 = -190 - 79871\text{i}$$

4.4 Uncontrolled Actual system

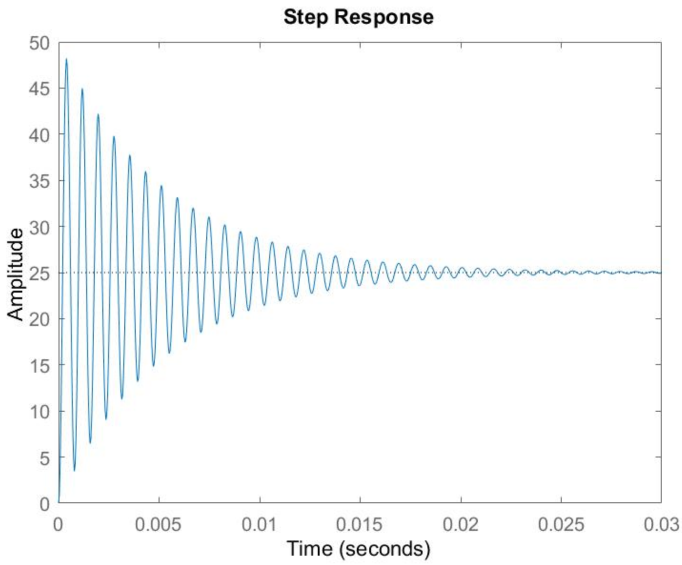

Figure 4.5 Output response of uncontrolled DC-DC Boost converter

This project employs a linear model system for model system design to reduce the system's complexity. According to the simulation, the uncontrolled system has an oscillating response that varies from the projected output response. Therefore, proper control methods must stabilize the system and respond appropriately. This linear system is represented using **state-space representations (27)** and **(28)**. We can get the State-feedback and Integral action gain by referring to **subchapter 3.7.2** utilizing a small signal model as our mathematical formulation.

$$A = \begin{bmatrix} 0 & -5000 \\ 12765.95745 & -379.93921 \end{bmatrix} \tag{69}$$

$$B = \begin{bmatrix} 125000 \\ -9498.48024 \end{bmatrix} \tag{70}$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \tag{71}$$

4.5 Desired system

With the knowledge of settling time, Ts and percentage overshoot, $\%O.S.$, the poles of the desired system may be identified. Ts =0.5s and percent $\%O.S.$=2% are used in this numerical example. The damping ratio, ξ, and undamped natural frequency,ω_n were computed as 0.78 and 10.28, respectively. As a result, the required closed-loop system's poles are specified as follows:

$$G_d(s) = \frac{105.06}{(s^2 + 16 + 105.06)} \tag{72}$$

$$s_{1,2} = -8 \pm j6.414$$

$$\omega_n = 10.25, \xi = 0.78$$

Which has dominant poles located at $s_{1,2} = -8 + j6.414$, $-8 - j6.414$. Since the integral control was added to our original state feedback controller, which increased the system type, we arbitrarily chose one additional pole located ten times more than the dominant poles, $s = -80$ to be added to the original plant model. By this selection, the desired plant model became:

$$G_d(s) = \frac{8411}{(s^2 - 96s^2 + 1385s - 8411)} \tag{73}$$

It is important to note that adding the extra pole does not affect the desired plant's overall transient response. This is due to the fact that the new pole is far away from the dominating poles in the complex s-plane.

4.6 Pole Placement

The result simulation discusses on implementation of pole placement and integral control to the DC-DC Boost converter system. This project was recognized as a conventional method to tune the DC-DC Boost converter system. Specifically, this technique requires a mathematical structure of the dynamic system to tune the system compared to propose method. The output response after the implementation of pole placement and integral control is shown in **Figure 4.6 and Figure 4.7**, respectively.

4.6.1 State-Feedback

The following is the output when the State-Feedback control is used. We obtain the state-feedback gain parameters as $K_S = \begin{bmatrix} 0.1495 & 0.0077 \end{bmatrix}$. Where $K_S = \begin{bmatrix} K1 & K2 \end{bmatrix}$.

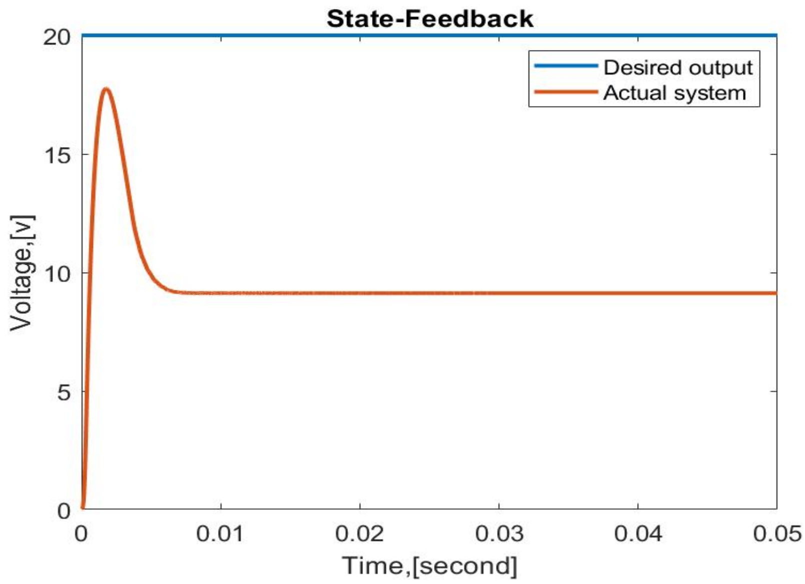

Figure 4.6 Output response of State-Feedback

As seen in **Figure 4.6,** when we use only state-feedback control, there is a huge steady-state error. As a result, we need integral control to handle this issue.

4.6.2 State-Feedback with Integral action

The following diagram illustrates the result of utilizing State-Feedback with Integral control. $K_I = 1074.6, K_S = \begin{bmatrix} 0.1689 & 0.2226 \end{bmatrix}$ are the parameters for the state-feedback with integral control gains.

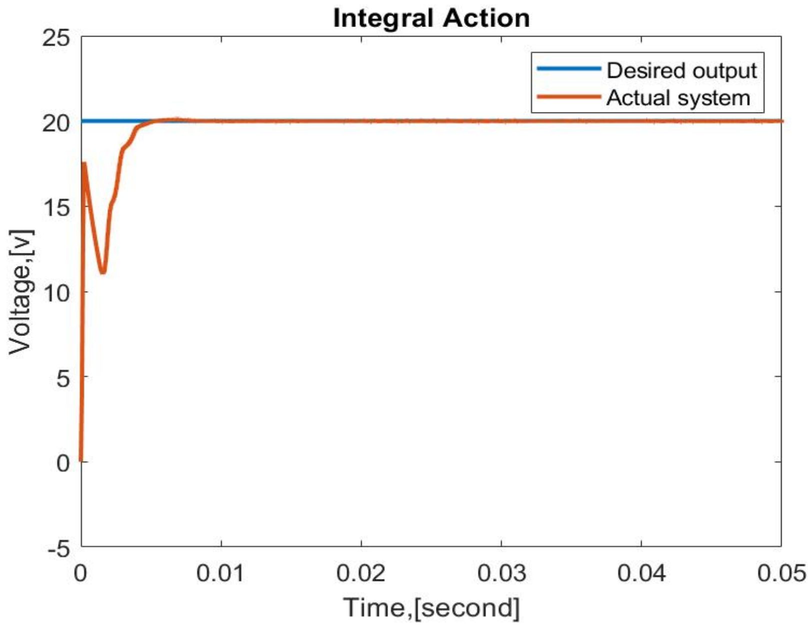

Figure 4.7 Output response of State-Feedback with Integral action

After implementing pole placement and integral control, the simulation result in **Figure 4.7** demonstrates that the system response followed the required response of 20V. Furthermore, when an integral control is introduced to the regulated system, the system experiences zero steady-state error. Based on these results, this conventional approach can tune a linear DC-DC Boost converter. Despite this, the controlled system must recalculate the mathematical structure and repeat the tuning process anytime a dynamic system changes. In industries, it is an expensive and ineffective technique. As a result, data-driven control was developed to improve the system by removing the necessity for mathematical structure in a controlled system.

4.7 Fictitious Reference Iterative Tuning (FRIT)

Initial input and output data are collected by initializing gain parameters and initial conditions. These initial values are selected with reasonable values. The values selected are defined as $K_I = 0.5, K_S = \begin{bmatrix} 1 & 1 \end{bmatrix}$, the initial gain. The output response in the initial condition or before tuning by using FRIT is shown in **Figure 4.8** below.

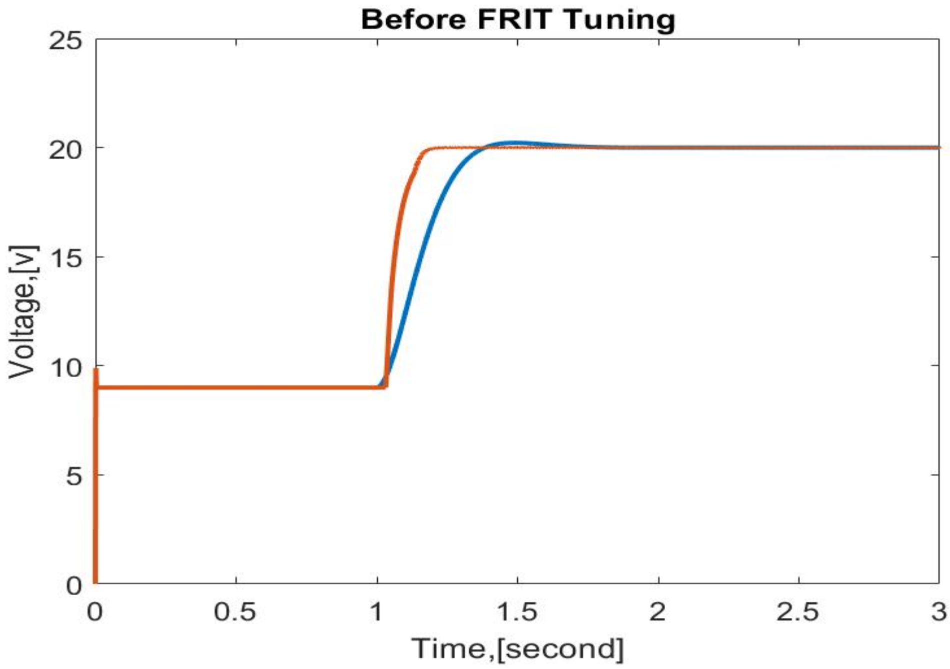

Figure 4.8 Output response before FRIT tuning

The output response of the DC-DC Boost converter is a little quicker than the desired system, as seen in **Figure 4.8**. Between the actual system and the desired system, there is a 0.5-second delay. It demonstrates that these initial settings could not provide the voltage desired to desire a final position in a reasonable amount of time. A data-driven pole placement controller was implemented to increase the system's responsiveness. The controller will start collecting initial input and output data from the initial condition.

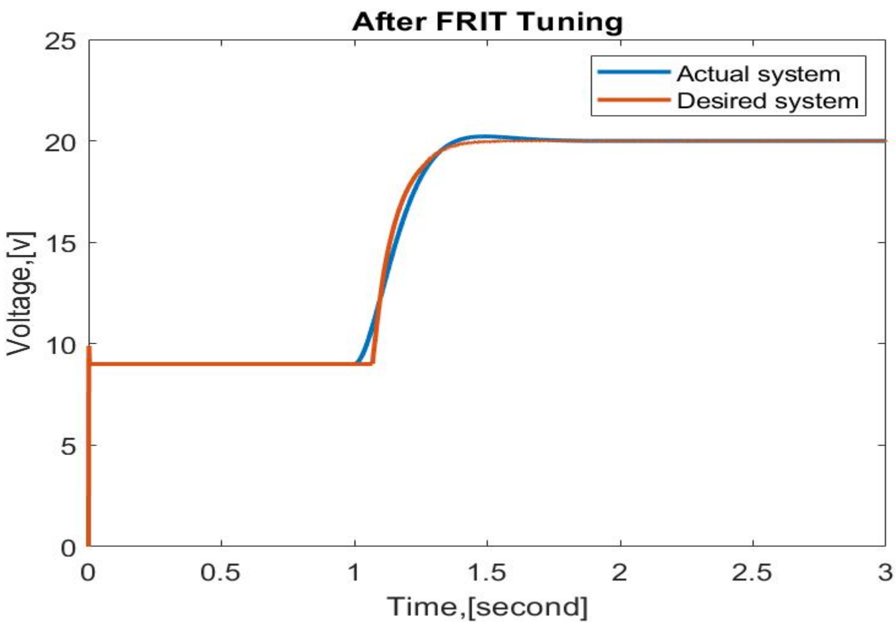

Figure 4.9 Output response after FRIT tuning

According to the simulation result illustrated in **Figure 4.9**, the system responsiveness was enhanced by quickly moving the voltages to the desired position. This research and discussion indicate that using Fictitious Reference Iterative Tuning techniques combined with a pole placement controller may improve a DC-DC Boost converter system. Where $K_I = 0.062552, K_S = \begin{bmatrix} 1.1748 & 4.4422 \end{bmatrix}$ are the new parameter gains.

4.7.1 Trajectory Tracking

This trajectory tracking is intended to validate and determine if the acquired parameters gains are optimal. We performed trajectory tracking on our plants using the obtained parameters gained from FRIT tuning.

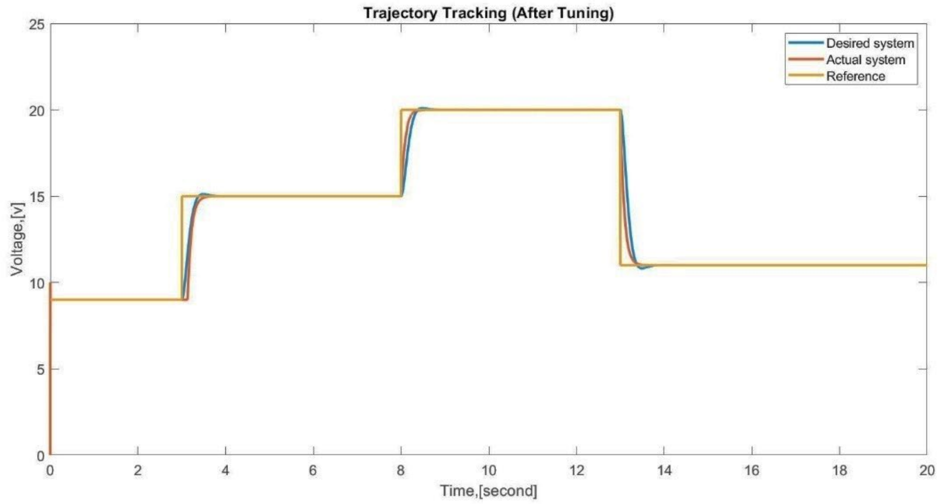

Figure 4.10 The Trajectory Tracking of the optimum gain

The results are validated in **Figure 4.10**, which depicts a continuously changing step input. As a result, the final result may be considered successful since the plant's output signal is consistent with the setpoint. In terms of trajectory tracking, the overall system state feedback with Integral action and tuning using a Fictitious Reference Iterative Tuning approach performed better.

4.8 Barnacles Mating Optimizer (BMO) Algorithm

The BMO algorithm is used to acquire the required parameters, K_I, K_1, K_2. We used the values $pl = 7$, $iterations = 100$, and 30 search agents in total. The search agent converged at approximately one location, as shown in **Figure 4.11**. The BMO has discovered the optimal parameter, and the optimal value or cost function J is 603.1324 .

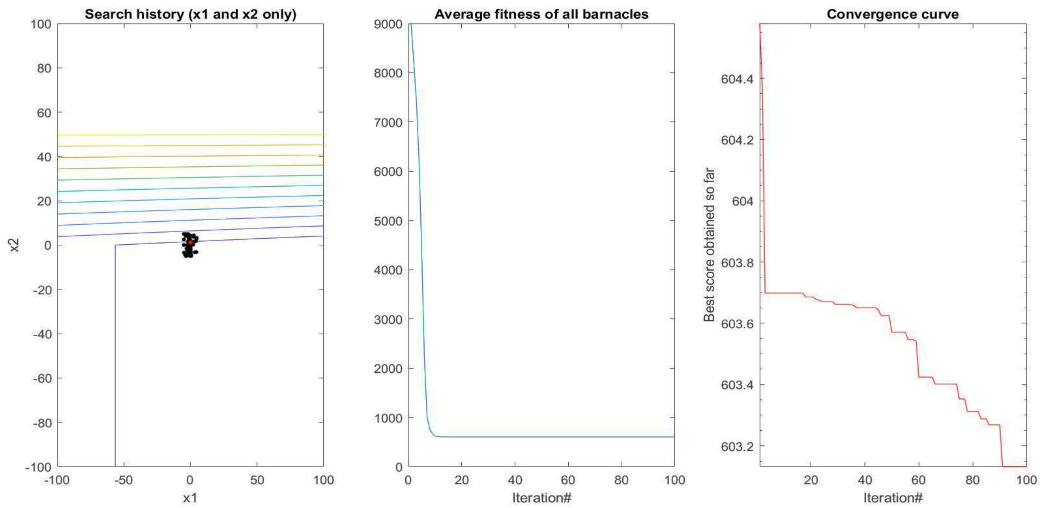

Figure 4.11 Results of BMO algorithm

4.9 Summary

Although the conventional approach can tune the DC-DC Boost converter system response to the desired response much faster than the proposed method, the data-driven control technique has become significantly more practicable for implementation with DC-DC Boost converter systems because the conventional approach is impracticable. Compared to the system response in the initial condition, the proposed technique enhanced system responsiveness after being applied to the DC-DC Boost converter system. As a result, the data-driven pole placement state-feedback with an Integral action controller has been shown to be an effective controller for DC-DC Boost converter systems that quickly and efficiently change voltages to the required position while minimizing the error.

CHAPTER 5

CONCLUSION

5.1 Conclusion

The objectives of this research were accomplished since we were able to develop a state feedback controller with integral action for a DC-DC boost converter system by utilizing a set of input-output data and tuning it using FRIT and BMO algorithms. The DC-DC Boost converter's trajectory can track the desired position while minimizing error according to the shown results. Compared to the conventional technique, the proposed method reduces the necessity for mathematical dynamics in controller design.

5.2 Suggestion for Future Work

The first suggestion is the proposed method can be extended by performing a validation procedure utilizing the real-experimental hardware setup. Next, it is suggested that the potential application of the metaheuristics optimization technique be studied and implemented as part of the tuning process to seek and attain the optimal controller parameters, which we strongly believe may lead to a better output system performance.

REFERENCES

[1] J. F. H. Karrar S. Faraj, "Analysis and comparison of DC-DC Boost Converter and Interleaved DC-DC Boost Converter," *Eng. Technol. J.*, vol. 38, no. 0, pp. 198–205, 2020, doi: 10.1109/ICCTET.2014.6966287.

[2] L. K. Grewal and N. K. Brar, "Analysis , Design and Simulation of DC-DC Boost Converter," no. 7, pp. 29–32, 2016.

[3] P. B. JN Rai, Nikhil Gupta, "Design and Analysis of a Multilevel DC–DC Boost Converter," *Int. J. Adv. Res. Innov.*, vol. 4, no. 3, pp. 1065–1075, 2016, doi: 10.1007/978-981-15-0633-8_108.

[4] M. Barr, "BEGINNER ' S CORNER Lint," *Embed. Syst. Program.*, no. May, pp. 55–56, 2002.

[5] S. Arulselvi, G. Uma, and M. Chidambaram, "Design of PID controller for boost converter with RHS zero," *Conf. Proc. - IPEMC 2004 4th Int. Power Electron. Motion Control Conf.*, vol. 2, no. I, pp. 532–537, 2004.

[6] I. Siradjuddin, Z. Amalia, B. Setiawan, R. P. Wicaksono, and E. Yudaningtyas, "Stabilizing a cart inverted pendulum system using pole placement control method," *QiR 2017 - 2017 15th Int. Conf. Qual. Res. Int. Symp. Electr. Comput. Eng.*, vol. 2017-Decem, no. November 2018, pp. 197–203, 2017, doi: 10.1109/QIR.2017.8168481.

[7] K. K. Patri and S. Samanta, "State feedback with integral control for boost converter & its microcontroller implementation," *2018 IEEMA Eng. Infin. Conf. eTechNxT 2018*, pp. 1–5, 2018, doi: 10.1109/ETECHNXT.2018.8385374.

[8] Y. Okano and O. Kaneko, "Fictitious reference signal based real-time update of state feedback gains and its experimental verification," *J. Robot. Mechatronics*, vol. 28, no. 5, pp. 625–632, 2016, doi: 10.20965/jrm.2016.p0625.

[9] D. Giaouris, C. Yfoulis, S. Voutetakis, and S. Papadopoulou, "Stability analysis of digital state feedback controlled boost converters," in *IECON Proceedings (Industrial Electronics Conference)*, 2013, pp. 8391–8396, doi: 10.1109/IECON.2013.6700539.

[10] K. H. Ang, G. Chong, and Y. Li, "PID control system analysis, design, and technology," *IEEE Trans. Control Syst. Technol.*, vol. 13, no. 4, pp. 559–576, 2005, doi: 10.1109/TCST.2005.847331.

[11] Mirza Fuad Adnan, Mohammad Abdul Moin Oninda, Mirza Muntasir Nishat, and Nafiul Islam, "Design and Simulation of a DC - DC Boost Converter with PID Controller for Enhanced Performance," *Int. J. Eng. Res.*, vol. V6, no. 09, pp. 27–32, 2017, doi: 10.17577/ijertv6is090029.

[12] H. Lihong and L. Ke, "Simulation study on model-free control method in DC-DC converter," *Proc. - 2016 8th Int. Conf. Intell. Human-Machine Syst. Cybern. IHMSC 2016*, vol. 2, no. 1, pp. 60–63, 2016, doi: 10.1109/IHMSC.2016.213.

[13] Y. Okano and O. Kaneko, "Fictitious reference signal based real-time update of state feedback gains and its experimental verification," *J. Robot. Mechatronics*, vol. 28, no. 5, pp. 625–632, 2016, doi: 10.20965/jrm.2016.p0625.

[14] O. Kaneko, "Fictitious reference iterative tuning of internal model controllers for a class of nonlinear systems," *2015 IEEE Conf. Control Appl. CCA 2015 - Proc.*, pp. 88–94, 2015, doi: 10.1109/CCA.2015.7320615.

[15] S. Soma, O. Kaneko, and T. Fujii, "A new method of controller parameter tuning based on input-output data —Fictitious Reference Iterative Tuning (FRIT)—," *IFAC Proc. Vol.*, vol. 37, no. 12, pp. 789–794, 2004, doi: 10.1016/S1474-6670(17)31566-5.

[16] M. H. Sulaiman, Z. Mustaffa, M. M. Saari, H. Daniyal, I. Musirin, and M. R. Daud, "Barnacles mating optimizer: An evolutionary algorithm for solving optimization," *Proc. - 2018 IEEE Int. Conf. Autom. Control Intell. Syst. I2CACIS 2018*, pp. 99–104, 2019, doi: 10.1109/I2CACIS.2018.8603703.

[17] M. H. Sulaiman, Z. Mustaffa, M. M. Saari, and H. Daniyal, "Barnacles Mating Optimizer: A new bio-inspired algorithm for solving engineering optimization problems," *Eng. Appl. Artif. Intell.*, vol. 87, no. September 2019, p. 103330, 2020, doi: 10.1016/j.engappai.2019.103330.

[18] S. Masuda, M. Kano, and Y. Yasuda, "A fictitious reference iterative tuning method with simultaneous delay parameter tuning of the reference model," *Proc. 2009 IEEE Int. Conf. Networking, Sens. Control. ICNSC 2009*, pp. 422–427, 2009, doi: 10.1109/ICNSC.2009.4919313.

[19] Z. Mustaffa and M. H. Sulaiman, "COVID-19 Confirmed Cases Prediction in China Based on Barnacles Mating Optimizer-Least Squares Support Vector Machines," *Cybern. Inf. Technol.*, vol. 21, no. 4, pp. 62–76, 2021, doi: 10.2478/cait-2021-0043.

[20] Z. Mustaffa *et al.*, "An application of barnacle mating optimizer in infectious disease prediction: A dengue outbreak cases," *Iraqi J. Sci.*, vol. 61, no. 8, pp. 2132–2141, 2020, doi: 10.24996/ijs.2020.61.8.28.

[21] L. Khandeparker and A. C. Anil, "Underwater adhesion: The barnacle way," *Int. J. Adhes. Adhes.*, vol. 27, no. 2, pp. 165–172, 2007, doi: 10.1016/j.ijadhadh.2006.03.004.

[22] M. H. Sulaiman, Z. Mustaffa, and O. Aliman, "An application of barnacles mating optimizer for solving economic dispatch problems," *2019 IEEE Jordan Int. Jt. Conf. Electr. Eng. Inf. Technol. JEEIT 2019 - Proc.*, pp. 835–839, 2019, doi: 10.1109/JEEIT.2019.8717377.

APPENDIX A

SIMULINK BLOCK DIAGRAM

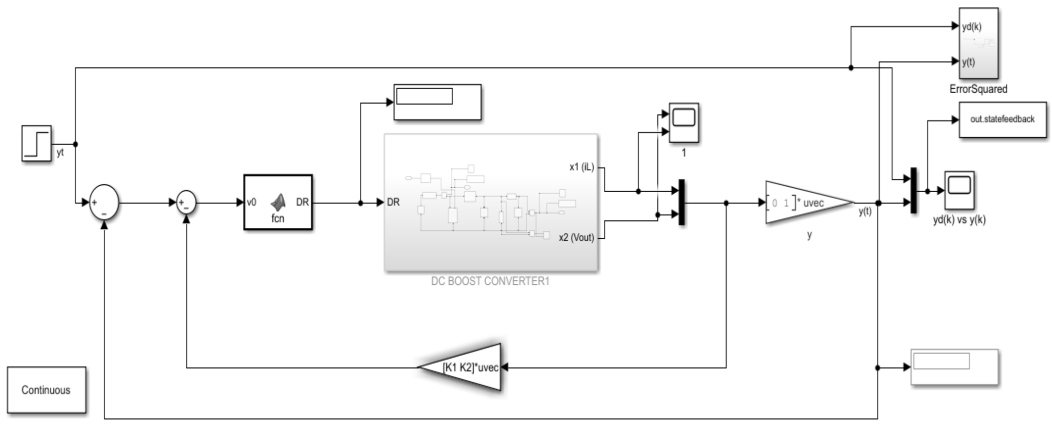

Figure A. 1 State Feedback

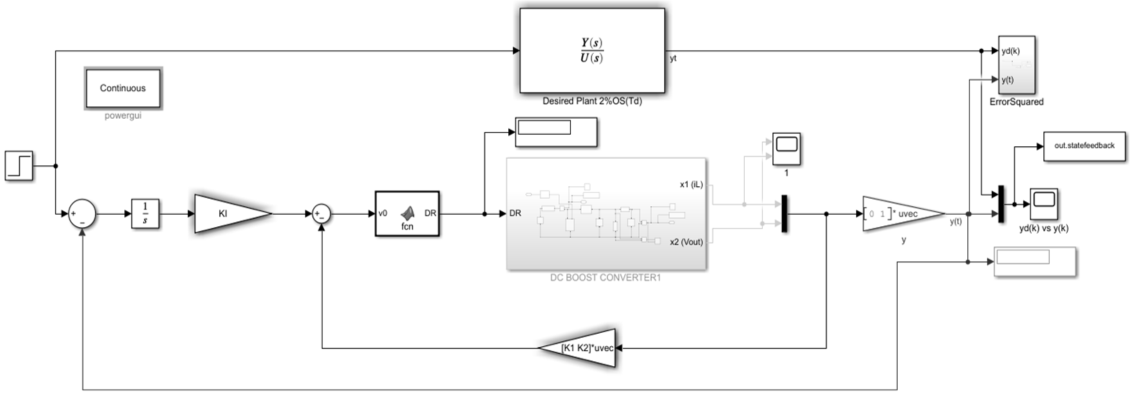

Figure A. 2 State Feedback with Integral action

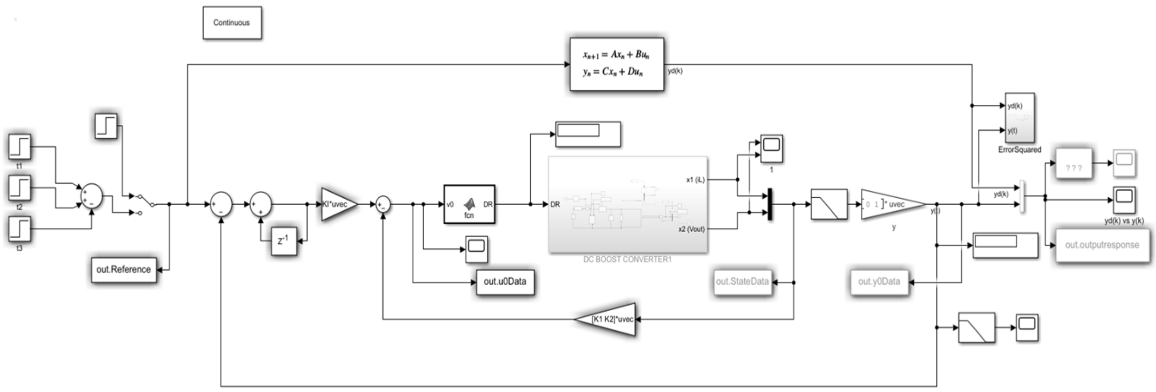

Figure A. 3 FRIT with Pole Placement

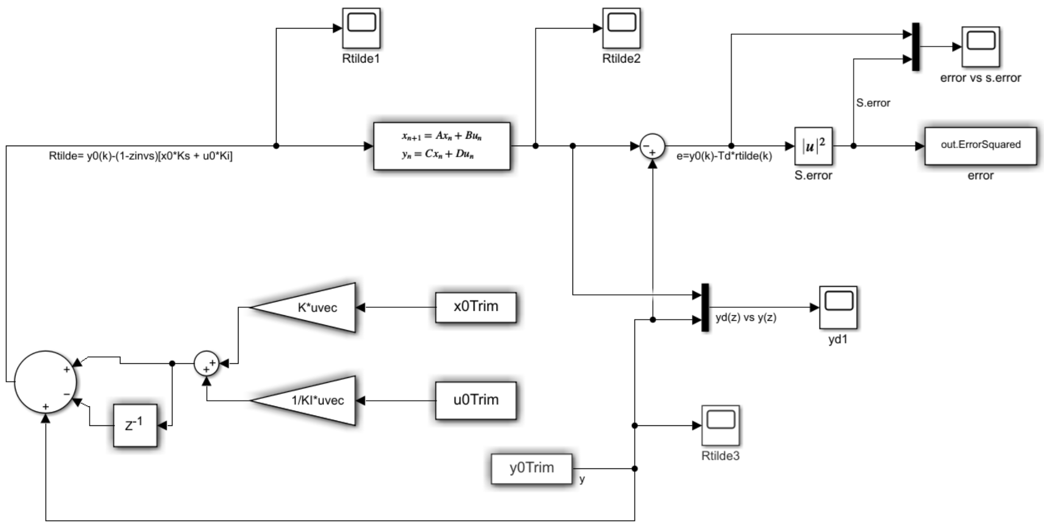

Figure A. 4 FRIT Tuning

APPENDIX B

MATLAB PROGRAM

Establishing the relationship between the output voltage and the duty ratio:

```
clc
clear
close all
SimTime = 0.5;
x=linspace(0,1,100);
DRdata=zeros(length(x));
voutdata=zeros(length(x));

for k=1:1:length(x)
    DR=x(k);
    sim('Testing_9V_dcboost_2021.slx');
    DRdata(k)=DR;
    voutdata(k)=vout(end); %last data
end

%max data
[m,I]=max(voutdata);
I=60;
voutdata=voutdata(1:I);
DRdata=DRdata(1:I);
ylog=log10(voutdata);

%Vout Vs Duty Ratio
hold on;
figure(1)
subplot(1,3,1)
hold on;
xlabel('Duty Ratio');
ylabel('Vout');
title('Vout vs Duty Ratio');
plot(DRdata,voutdata,'*');

%yLog Vs Duty Ratio
hold on;
subplot(1,3,2)
hold on;
xlabel('Duty Ratio');
ylabel('ylog Vout');
title('Vout vs Duty Ratio');
plot(DRdata,ylog,'*');

%curve fitting LSM
hold on;
%subplot(1,3,3);
hold on;
Y = ylog';
X = DRdata';
```

```
A = [ones(length(Y),1),X];
b=Y;
Z = inv(A'*A)*A'*b;

%linear equation y=mx+c
hold on;
c=Z(1)
m=Z(2)
yest=m*DRdata+c;
disp (Z)
xlabel('Duty Ratio');
ylabel('ylog Vout');
title('Vout vs Duty Ratio');
plot(X, yest,'--k');
hold on;
plot(DRdata,ylog,'*');
```

Algorithm of Pole Placement:

```
%Model for boost converter
%steady state
clear all;
clc;

%syms L C R DR D Vin l c r vg s;
vg = 9; % Input u
D = 0.4; % duty ratio
l = 120e-6 ; % Inductor
c = 47e-6 ; % Capacitor
r = 56 ; % Resistor

%Steady State Model (On + Off time)
As = [0 -(1-D)/l;(1-D)/c -1/(r*c)]
Bs = [1/l 0;0 0]
Cs = [0 1;1 0]  %output V and I
Ds = 0

Vo = -Cs(1,:)*inv(As)*Bs(:,1)*vg %first row all columns
Ig = -Cs(2,:)*inv(As)*Bs(:,1)*vg %Second row all colums

%Small Signal Model (use for controller design)
a = [0 -(1-D)/l;(1-D)/c -1/(r*c)]
b = [vg/(l*(1-D));-vg/(r*c*((1-D)^2))] %d
c = [0 1] %interested in output voltage only
d = 0

%labels
u = ['d'];
y = ['vo ig'];
x = ['il vc'];

%Small signal State Space Model
```

```
printsys(a,b,c,d,u,y,x)
%Transfer Function
disp(['Transfer Function in s-domain'])
disp(['vo/dr (s)'])
TFBoost = zpk(tf(ss(a,b,c,d))) %zero poles gain form
%Boost converter has zeros at right plane

%tf
[num,den] = ss2tf(a,b,c,d)
systf=tf(num,den)
% step(systf)

%state space system for 'vo/dr (s)'
sys = ss(TFBoost)
sys = ss(a,b,c,d)

%Check controllability
Co=ctrb(a,b)
rank(Co)

%CHECK ACTUAL SYSTEM STEP RESPONSE
% step(sys)
% step(num,den)
stepinfo(systf)

%Eigenvalues
E = eig(a)

%closed loop
Gc=feedback(systf,1)
step(Gc)


%% StateFeedback
% DESIRED SYSTEM POLES x5
P = [-9500-6i -9500+6i];
% P =[-8+6.414i -8-6.414i]
%FIND GAIN K (State Feedback)
Ks = place(a,b,P)
K1= Ks(1)
K2= Ks(2)
%DESIRED SYSTEM
Ades = a - b*(Ks)

%DESIRED SYSTEM EIGENVALUES
Edes = eig(Ades)

%DESIRED SYSTEM STATE SPACE FORM
sysdes = ss(Ades, b, c, d)

%Transfer function for Desired system (State Feedback)
TFBoostSF = zpk(tf(ss(Ades,b,c,d)))
% step(TFBoostSF)

[numSF,denSF] = ss2tf(Ades,b,c,d,1);
systfSF=tf(numSF,denSF)
```

```
%% Run state feedback
open_system('DCBoost_StateFeedback.slx')
data = sim('DCBoost_StateFeedback.slx')

%.State Feedback Response
tSF=data.statefeedback.time;
outSF=data.statefeedback.signals.values(:,2);
figure(1),plot(tSF,outSF,'linewidth',2)
xlabel('Time,[second]')
ylabel('Voltage,[v]')
title('State-Feedback')
set(gca,'FontSize',12)
legend('Desired output','Actual system');
SF = stepinfo(tSF,outSF)

%% INTEGRAL CONTROL STATE SPACE FORM
hold on;hold on;hold on;
Ai=[Ades zeros(2,1);-c 0]
Bi=[b;0]
yi=[c 0]

%CREATE INTEGRAL CONTROL STATE SPACE
sysi = ss(Ai, Bi, yi, d)
% step (sysi)

%INTEGRAL CONTROL EIGENVALUES
Ei = eig(Ai)

%INTEGRAL CONTROL NEW POLES x10
Pi= [-19000 -9500-6i -9500+6i]
%Pi= [-28500 -19000-6i -19000+6i]
%Pi= [-80 -8+6.414i -8+6.414i]

%INTEGRAL CONTROL GAIN Ki
Ki= acker(Ai,Bi,Pi)

%Desired Integral system
AdesI = Ai - Bi*(Ki)
Ei=eig(AdesI)

%% ASSIGN GAIN
K1=Ki(1)
K2=Ki(2)
KI=-Ki(3)

%% Run Integral Control
hold on
open_system('DCBoostFRIT.slx')
data = sim('DCBoostFRIT.slx')

%.State Integral Control Response
tIC=data.IntegralControl.time;
outIC=data.IntegralControl.signals.values(:,2);
figure(2),plot(tIC,outIC,'linewidth',2)
xlabel('Time,[second]')
```

```
ylabel('Voltage,[v]')
title('Integral Action')
set(gca,'FontSize',12)
legend('Desired output','Actual system');
Si = stepinfo(tIC,outIC)
sys=(tIC,outIC)
```