DEVELOPMENT OF DC-DC CONVERTER FOR DC MOTOR USING FUZZY LOGIC CONTROLLER

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ABSTRACT

When the DC motor is turned on, the start dc motor speed will experience overshoot at the starting speed of the motor. This overshoot will affect the current rise high as if connected to a load. The use of conventional controllers has long been used to control the dc motor and reduce overshoot starting. Fuzzy logic controller is one controller that can be used to control the speed of a dc motor including motor control overshoot starting. To see the effectiveness of fuzzy logic controller in dc motor speed control, a study done by designing a conventional two-Integrated controllers of proportional controller (PI) and proportional-Integrated-Derivatives controller (PID) and compared with fuzzy logic controller. The design of Fuzzy Logic Controller (FLC) does not require an exact mathematical model. Instead, it is design based on general knowledge of the plant. Both three controllers are connected to a dc motor as a load to control the motor speed to the required level. The effectiveness of the designed FLC is compared with designed conventional controllers to examine aspects of starting overshoot, settling time and ripple factor for dc motor speed.

ABSTRAK

Apabila dc motor dihidupkan, kelajuan permulaan motor arus terus akan mengalami lanjakan semasa permulaan motor. Lanjakan ini akan memberi kesan seperti kenaikan arus yang tinggi jika disambungkan kepada beban. Penggunaan pengawal konvensional telah lama digunakan bagi mengawal motor arus terus dan mengurangkan lanjakan permulaan kelajuan. Fuzzy logic controller merupakan salah satu pengawal yang boleh digunakan untuk mengawal kelajuan sesebuah motor arus terus termasuklah mengawal lanjakan kelajuan permulaan motor. Bagi melihat keberkesanan pengawal logic kabur (FLC) dalam mengawal kelajuan motor arus terus, kajian dilakukan dengan membina dua pengawal konvensional iaitu Proportional-Integrated controller (PI) dan Proportional-Integrated-Derivatives controller (PID). Reka bentuk FLC tidak memerlukan model matematik yang tepat. Sebaliknya, ia adalah reka bentuk berdasarkan kepada pengetahuan am tentang pengawal. Ketiga-tiga penagawal ini disambungkan kepada motor arus terus sebagai beban bagi mengawal kelajuan motor ke tahap yang dikehendaki. Keberkesanan FLC dibandingkan dengan pengawal konvensional dengan meneliti aspek lanjakan permulaan kelajuan motor, penetapan masa dan factor riak bagi kelajuan motor arus terus.

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LIST OF SYMBOLS AND ABBREVIATIONS

D	-	Duty Cycle
T	-	Time
V_S	-	Supply Voltage
V_O	-	Output Voltage
M_V	-	Ratio
V_{REF}	-	Reference Voltage
e	-	Error
ce	-	Change of Error
J	-	Motor Inertia
L	-	Inductance
R	-	Resistance
N_O	-	Output Speed
N_{REF}	-	Reference Speed

CHAPTER I

INTRODUCTION

1.1 Project Overview

With the rapid changes in development of power electronics, switching element for power supplies are widely applied in various field. DC-DC switching converters are the main components of switching power supplies. DC-DC converters are a class of electronics power circuits that is used extensively in regulated dc power supplies and dc motor drive applications due to its advantages features in terms of size, weight and reliable performance [1]. As an importance branch of power electronics, the investigations on DC-DC switching converters are widely carried out in the world [2].

The idea of using DC-DC converter is to convert fix dc source into a variable dc voltage source or desired dc output source. The output of the DC-DC converter can be higher or lower than the input source depends on the application used. The converter is widely used for motor in electric automobile, forklift truck and others. DC converter can be used in regenerative braking of DC motor to return energy braking into the supply and this feature result in energy saving for transportation system with frequent stop and also used in DC voltage regulation [3].

In many ways, a DC-DC converter is the DC equivalent of a transformer. There are four main types of converter usually called the Buck, Boost, Buck-Boost and Boost converter. The Buck converter is used for voltage step-down/reduction, while the Boost converter is used for voltage step-up. The Buck-Boost and Cuk converters can be used for either step-down or step-up [4].

A standard approach for speed control in industrial drives is to use a proportional plus integral (PI) controller. Recent developments in artificial-intelligence-based control have brought into focus a possibility of replacing a Pi speed controller with a fuzzy logic (FL) equivalent [5]. Fuzzy Logic speed control is sometimes seen as the ultimate solution for high-performance drives of the next generation. Such a prediction of future trends is based on comparison of the drive response under PI and FL speed control, which has been compared on a number of occasions. Design of a speed controller is always based on the required response for a single operating point [5]. The existing comparisons fall into one of the two categories: speed response with PI and FL speed control for the design case is substantially different or the speed response is more or less the same [5].

Nowadays, the control systems for many power electronics appliances have been increasing widely. Crucial with these demands, many researchers or designers have been struggling to find the reliable controller meet these demands [4]. The idea is to have a control system in DC-DC converter is to ensure desired output speed can be produced efficiently.

In this project, MATLAB/Simulink is used as a platform in designing the fuzzy logic controller (FLC). MATLAB/Simulink simulation model is built to study the speed control of the FLC compared to the PI controller.

1.2 Problem Statement

DC-DC converter consists of power semiconductor devices which are operated as electronic switches. Operation of the switching devices causes the inherently nonlinear characteristic of the DC-DC converters including one known as the Buck Converter. The switching technique of the Buck converter causes the converter system to be nonlinear system. Nonlinear system requires a controller with higher degree of dynamic response. Proportional-Integral (PI) is one of the controllers used as a switching device for the converter. However the PI controller is known to exhibit sluggish disturbance rejection properties [5].

Classic control has proven for a long time to be good enough to handle control tasks on system control; however his implementation relies on an exact mathematical model of the plan to be controller and not simple mathematical operation [7]. The DC motors have been popular in the industry control area for a long time, because they have enormous characteristics like, high start torque , high response performance, easier to be linear control etc. The proportional integral (PI) controller is the most common form of feedback in the control systems [8].

A study by Zulkifilie Ibrahim and Emil Levi (2002) shows that the PI speed control offers high speed dip and large recovery time when the load is connected. Therefore the implementation of Fuzzy Logic Controller (FLC) that will deal the issue must be investigated. The Fuzzy control is nonlinear and adaptive in nature that gives it robust performances under parameter variation and load disturbances. Since the Buck converter is a nonlinear system, the fuzzy logic controller (FLC) method will be developed to improve overshoot speed at starting of the motor and settling time. The developed FLC has the ability to learn instantaneously and adapt its own controller parameters based on external disturbances and internal variation of the converter. Thus this FLC can overcome the problem stated to obtain better performances in terms of speed control.

1.3 Project Objectives

The objectives of this project are:

i) To develop a DC-DC Buck Converter using Proportional-Integrated Controller (PI) and Proportional-Integrated-Derivative Controller (PID)

ii) To develop a DC-DC Buck converter using Fuzzy Logic controller (FLC)

iii) To compare the FLC with PI performance in terms of starting speed overshoot, settling time and ripple factor.

1.4 Scope of Project

The scopes of the project are:

i) Modelling the DC-DC Buck converter with DC Motor

ii) Modelling the Proportional-Integrated (PI) and Proportional-Integrated-Derivative (PID) controller for speed control

iii) Modelling the Fuzzy Logic Controller (FLC) controller for speed control

iv) Compare the output speed of the DC motor for both PI and PID with FLC in terms of starting overshoot, ripple factor and settling time.

CHAPTER 2

LITERATURE REVIEW

2.1 Existing Papers

Fuzzy control also supports nonlinear design techniques that are now being exploited in motor control applications. A thorough literature overview was done on the usage of fuzzy logic controller as applied to DC-DC converter.

K.Viswanathan, D. Srinivasan, R. Oruganti (2002) proposed a universal fuzzy controller and compares its performances at various operating points with local PI controllers designed for the particular points. The settling time and overshoot for start-up and step response obtained by computer simulations have been compared. The simulation result shown the fuzzy controllers achieve good transient response under different operating conditions is clearly established.

Sinan Pravadalioglu (2005) present the feasibility of a high-performance non-linear fuzzy logic controller which can be implemented by using a general purpose was simulated in MATLAB/Simulink. The theoretical and experimental results indicate that the implemented fuzzy logic controller has a high performance for real-time control over a wide range of operating conditions.

Zulkifilie Ibrahima and Emil Levi (2002) proposed a comparison of the drive behaviour under PI and Fuzzy logic speed control. Experimental result indicated that the superiority of Fuzzy logic speed control is less pronounced than it often portrayed in the literature on the basis of limited comparisons while the PI speed control provided a superior speed response.

Based on those related work, the researchers make a great effort to propose the good to overcome DC-DC converter problems. Their applications of each method differ, thus the further investigation of this controller is needed.

2.2 DC-DC Converters

DC-DC converters are a class of electronic power circuits that is used extensively in regulated dc power supplies and dc motor drive applications due to its advantageous features in terms of size, weight and reliable performances. The main difficulty in controlling dc-dc converters stems from their hybrid nature as their switched circuit topology entails different modes of operation, each with its own associated linear continuous-time dynamics. Hard constraints are also present on the input variable (duty cycle), and additional constraint may be imposed as safety measures, such as current limiting [1].

DC-DC switching converters are the main components of switching power supplies. As an importance branch of power electronics, the investigations on DC-DC switching converters are widely carried out in the world in which control of converters is one of the hotspots [2].

Modern electronics systems require high-quality, small, light-weight, reliable and efficient power supplies. Linear power regulators, whose principle of operation is based on a voltage or current divider, are inefficient [5]. In many industrial applications, it is required to convert a fixed-voltage dc source into a variable-voltage dc source. A DC-DC converter converts directly from DC to DC and is simply known as a DC converter. A DC converter can be considered as DC equivalent to an AC transformer with continuously variable turn’s ratio. Like transformer, it can be used to step down or step up a DC voltage source [5].

DC converters widely used for traction motor in electric automobiles, trolley cars, marine hoists, and forklift trucks. They provide smooth acceleration control, high efficiency, and fast dynamic response. DC converter can be used in regenerative braking of dc motor to return energy bake into the supply, and this feature results in energy 5 saving for transportation system with frequent stop; and also are used, in DC voltage regulation. There are many types of DC-DC convertor which is buck (step down) converter, boost (step-up) converter, buck-boost (step up- step-down) convertor [5].

DC conversion is of great importance in many applications, starting from low power applications to high power applications. The goal of any system is to emphasize and achieve the efficiency to meet the system needs and requirements. Several topologies have been developed in this area, but all these topologies can be considered as apart or a combination of the basic topologies which are buck, boost and flyback [5].

For low power levels, linear regulators can provide a very high-quality output voltage. For higher power levels, switching regulators are used. Switching regulators use power electronic semiconductor switches in ON and OFF states [3].

High-frequency electronic power processors are used in DC-DC power conversion. The function of DC-DC converters are [5]:

1) To convert a dc input voltage V_S into a dc output voltage V_O
2) To regulate the dc output voltage against load and line variations
3) To reduce the ac voltage ripple on the dc output voltage below the required level
4) To provide isolation between the input source and the load (isolation is not always required);
5) To protect the supplied system and the input source from electromagnetic interference (EMI)
6) To satisfy various international and national safety standards

2.2.1 Buck Converter

The step-down DC-DC converter, commonly known as a buck converter. It consists of dc input voltage source V_S, controlled switch S, diode D, filter inductor L, filter capacitor C, and load resistance R as shown below:

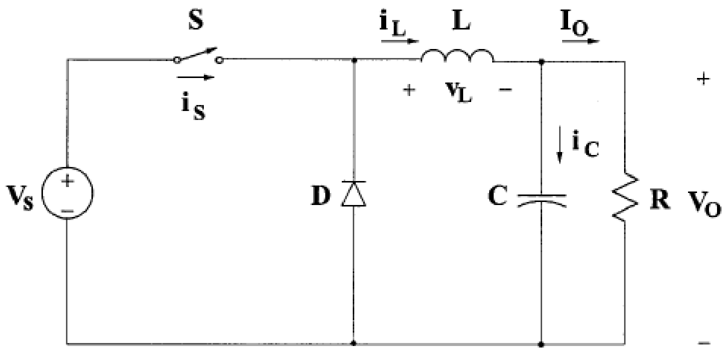


FIGURE 2.1: Equivalent circuit of Buck Converter [10]

The waveform in the converter is shown below under the assumption that the inductor current is always positive [10].

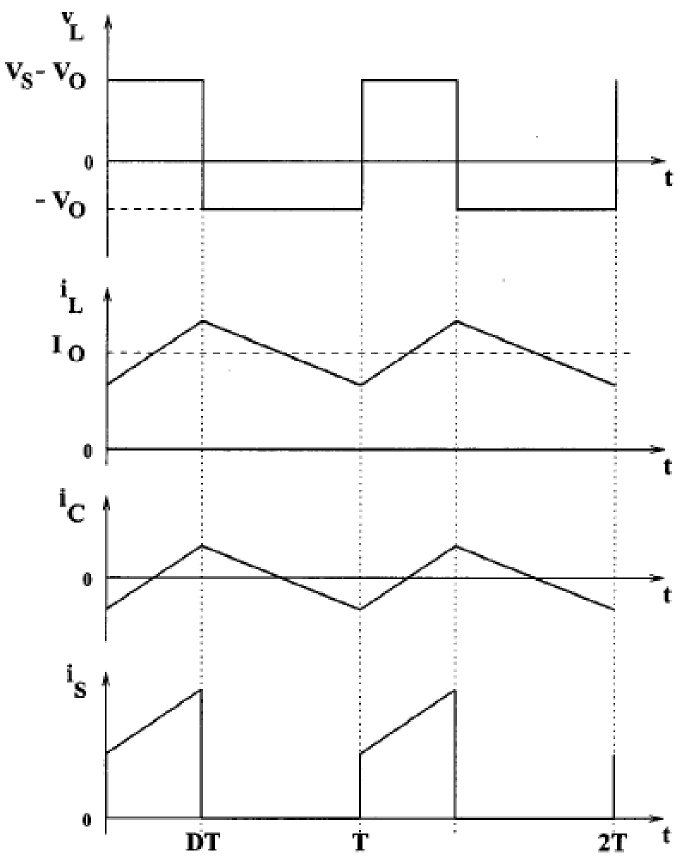


FIGURE 2.2: Output waveform of Buck Converter [10]

It can be seen from the circuit that when the switch S is commanded to the *on* state the diode D is reverse-biased. When the switch S is off, the diode conducts to support an uninterrupted current in the inductor. The relationship among the input voltage, output voltage and the switch duty ratio D can be derived. According to Faraday's law, the inductor volt-second product over a period of steady-state operation is zero. For the buck converter:

$$(V_S - V_O)DT = -V_O(1 - D)T \tag{2.1}$$

Hence, the dc voltage transfer function, defined as the ratio of the output voltage to the input voltage, is:

$$M_V \equiv \frac{V_O}{V_S} = D \tag{2.2}$$

Where D is the duty cycle of the converter

2.3 Fuzzy Logic Controller (FLC)

Fuzzy Logic Controller (FLC) is constitutes a way of converting linguistic control strategy into an automatic by generating a rule base which controls the behaviour of the system. Fuzzy control is control method based on fuzzy logic. Fuzzy provides a remarkably simple way to draw definite conclusions from vague ambiguous or imprecise information [3].

The fuzzy logic foundation is based on the simulation of people's opinions and perceptions to control any system. An expert operator develops flexible control mechanism using words like "suitable, not very suitable, high, little high, much and far too much" that are frequently used words in people's life [7]. Fuzzy logic control is constructed on these logical relationships. There is strong relationship between fuzzy logic and fuzzy set theory that is similar relationship between Boolean logic and classic set theory [7].

Conventional controllers are derived from control theory techniques based on mathematical models of the process. They are characterized with design procedures and usually have simple structures. However in a number of cases, when parameter variations take place, or when disturbance are present or when there is no simple mathematical model, fuzzy logic based control systems have shown superior performance to those obtained by conventional control algorithm. Fuzzy control can be described simply as "control with sentences rather than equations". It provides an algorithm to convert a linguistic control strategy – based on expert knowledge-into an automatic control strategy [11].

A typical Fuzzy Logic Controller (FLC) has the following components: Fuzzification, knowledge base, decision making and defuzzification. The performance of the FLC depends very much on the defuzzification process [12]. This is because the overall performance of the system is determined by the controlling signal (defuzzification output of the FLC) the system receives [12]. There are specific components characteristic of a fuzzy controller between the inputs and output.

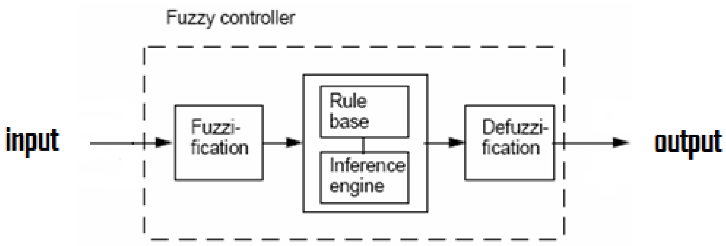


FIGURE 2.3: Structure of FLC [13]

Below is the block diagram of the FLC for DC-DC converters.

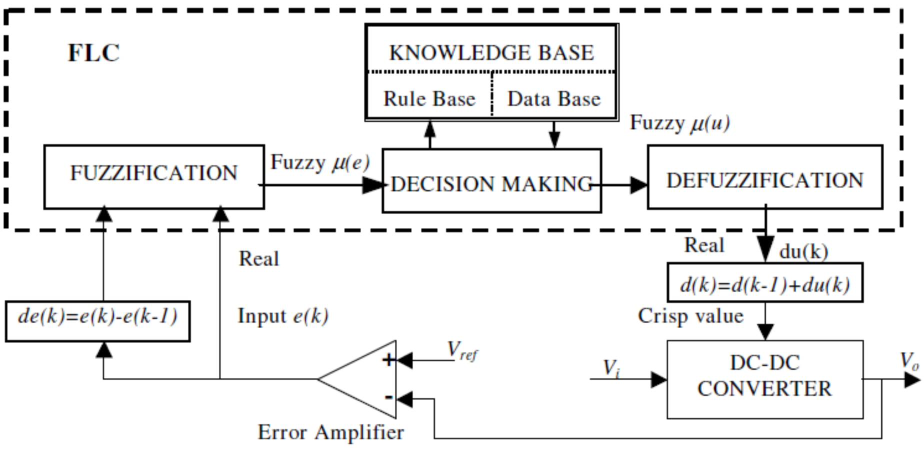


FIGURE 2.4: Block diagram of the FLC for DC-DC converters [14]

According to (Cetin Elmas, Omer Deperlioglu, Hassan Huseyin Sayan)[14] the FLC can be divided into four modules. The first one is fuzzification where used in the classification of input data into suitable linguistic values or sets. The second is knowledge base which includes rule base and data base which contains knowledge of the control rules and linguistic labels while the decision making is the inferring control action from rule base. Lastly the defuzzification is the conversion from the inferred fuzzy value to real crisp value, or control action.

Several researches have contributed in evolving such intelligent controllers for DC-DC converters. The technique of Tse [15] fuzzifies the error and change in error of the output voltage and the Sugeno fuzzy system gives out the change in duty ratio [16]. The [15] has proposed a block diagram of fuzzy for DC-DC Converters as shown in Figure 2 below.

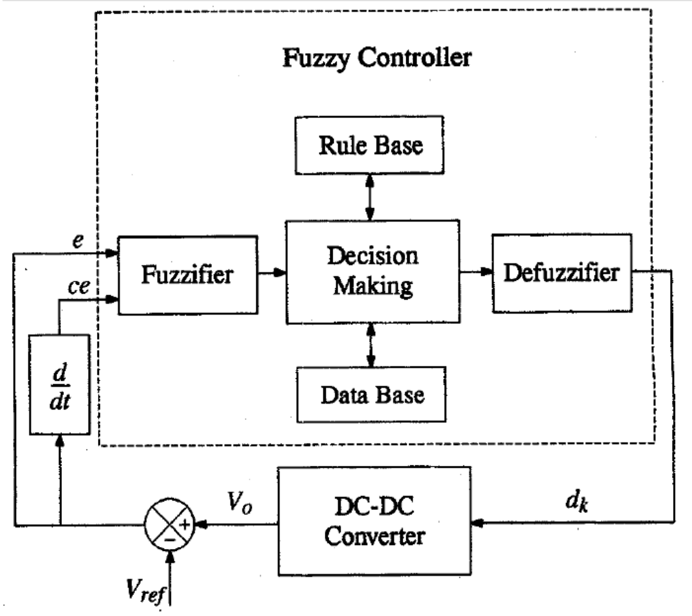


FIGURE 2.5: Block diagram of fuzzy control scheme for DC-DC converters [15]

The input of the fuzzy controller are the error, *e* and the change of error *ce* which are defined as

Error, $e = V_o - V_{ref}$ Change of error, $ce = e_k - e_{k-1}$ (2.3)

Where V_o is the present output voltage, Vref is the reference output voltage and subscript *k* denotes values taken at the beginning of the *k*th switching cycle. The output of the fuzzy controller is the duty cycle and its defined as

$$d_k = d_{k-1} + \eta.\delta d_k \qquad (2.4)$$

where δd_k is the inferred change of duty cycle by the fuzzy controller at the *k*th sampling time and η is the gain factor of the fuzzy controller. According to the sum operator, the above equation acts like an integrator and causes to increase system type which result in state error to be zero [9].

A. *Fuzzification*

The first block inside the controller is fuzzification which converts each piece of input data to degrees of membership by a lookup in one or several membership function. The fuzzification block matches the input data with the conditions of the rules to determine. There is a degree of membership for each linguistic term taht applies to the input variable [3].

B. *Decision Making*

One of the key parts in designing the fuzzy controller is its linguistic rules. Knowing the controllable behaviour of process is needed for the improvement of these rules, but there is no need for the mathematical model of the process [9]. The essential part of a fuzzy controller is a set of linguistic rules which is called rule base [11],

1) If error is Negative and change in error is Negative then output is Negative Big.
2) If error is Negative and change in error is Zero then output is Negative Big

C. *Defuzzification*

Defuzzification is when all the actions that have been activated are combined and converted into a single non-fuzzy output signal which is the control of the system [3]. The output levels are depending on the rules that the systems have and the positions depending on the non-linearities existing to the systems [3]. To achive the result, develop the control curve of the system representing the I/O relation of the systems and based on the information, define the output degree of the membership function with the aims to minimize the effect of the non-linearity [13].

The P.Thepsatorn, A.Numsomran, V.Tipsuwanporn, T.Teanthong (2006) had design the fuzzy set in defining output and input where the output of the design is focusing on the duty cycle of the DC-DC converter. The designed FLC is to minimize speed error where the bigger speed error the biggest controller input is expected. For [7] FLC designed uses the error (*e)* and change of error (*ce*) for linguistic variables which are generated from the control rules. The output variable is the change in control variable (*cα*) of motor drive. *Cα* is integrated to achieve desired alpha value. Here *α* is a angular value determining duty cycle of the converter designed.

$$
\begin{aligned}
e(k) &= [w_r(k) - w_a(k)] \times K1_E \\
ce(k) &= [e(k) - e(k-1)] \times K2_{CE} \\
c\alpha(k) &= [\alpha(k) - \alpha(k-1)] \times K3_{CE}
\end{aligned}
\tag{2.5}
$$

Here K1E, K2E and K3cα are each gain coefficients and k is a time index

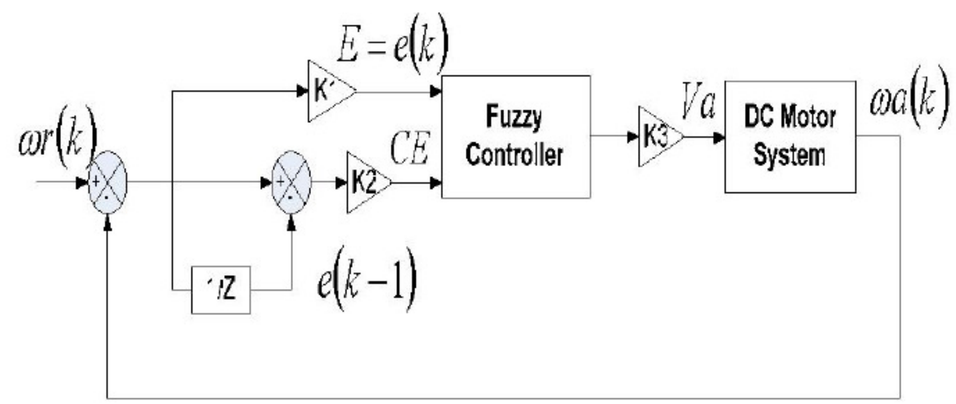


FIGURE 2.6: Block diagram of fuzzy logic controller

2.4 Motor Model.

The resistance of the field winding and its inductance of the motor used are represented by R_f and L_a respectively in dynamic model. Armature reactions effects are ignored in the description of the motor. This negligence is justifiable to minimize the effects of armature reaction since the motor used has either interpoles or compensating winding. The fixed voltage V_f is applied to the field and the field current settles down to a constant value [7]

A linear model of a simple DC Motor consists of mechanical equation and electrical equation as determined in the following equation[7]:

$$J_m \frac{d\omega_m}{dt} = K_m \phi I_a - b\omega_m - M_{load} \quad (2.6)$$

$$L_a \frac{dL_a}{dt} = V_a - R_a I_a - K_b \phi \omega_m \quad (2.7)$$

Where	Ra	=	Armature Resistance (Ω)		
	La	=	Armature Inductance (kg.m^2 / s^2)		
	Jm	=	Motor of inertia (H)		
	K	=	K_b ϕ	=	Motor constant (Nm/Amp)
	K	=	K_m ϕ	=	Motor constant (Nm/Amp)
	b	=	Damping ration of mechanical system (Nms)		

Based on Newton's Law combined with the Kirchoff's law, the equation for (1) and (2) can write by:

$$J\frac{d^2\theta}{dt^2} + b\frac{d\theta}{dt} = Ki \quad (2.8)$$

$$L\frac{di}{dt} + R_i = V - K\frac{d\theta}{dt} \quad (2.9)$$

2.4.1 Transfer Function

Using the Laplace transform, equation (3) and (4) can be write as:

$$Js^2\theta(s) + bs\theta(s) = KI(s) \tag{2.10}$$

$$LsI(s) + RI(s) = V(s) - Ks\theta(s) \tag{2.11}$$

where s denotes the Laplace operator. From (6) we can express *I(s):*

$$I(s) = \frac{V(s) - Ks\theta(s)}{R + Ls} \tag{2.12}$$

And substitute it in (5) to obtain:

$$Js^2\theta(s) + bs\theta(s) = K\frac{V(s) - Ks\theta(s)}{R + Ls} \tag{2.13}$$

This equation for the DC motor is shown in the block diagram in **FIGURE 2.7**

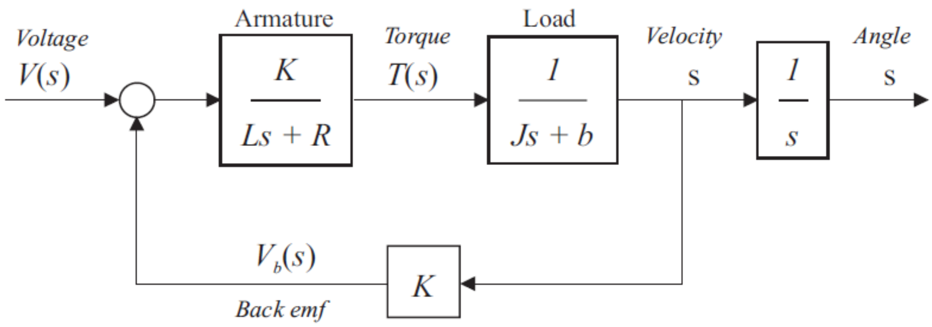


FIGURE 2.7: A block diagram of the DC motor [8]

The dynamic model of the system is formed using these differential equations and Matlab Simulink blocks as shown in **FIGURE 2.8.**

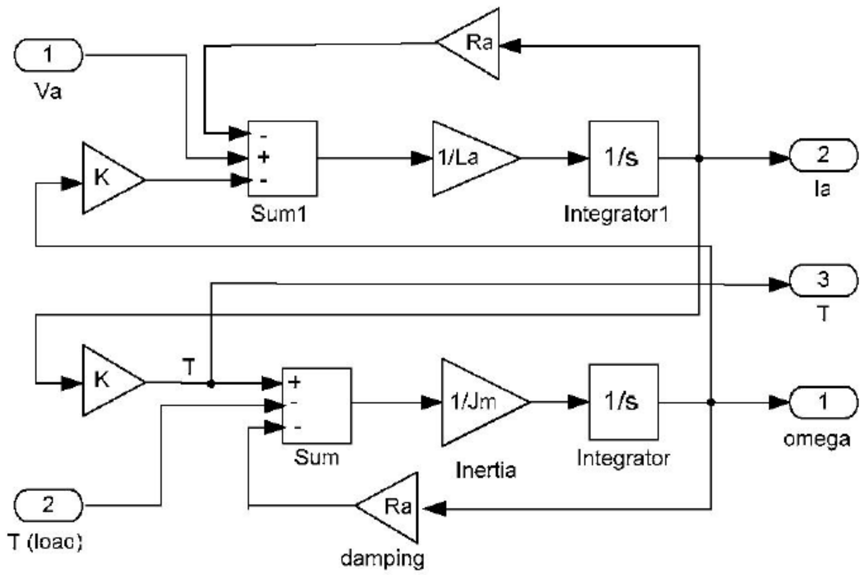


FIGURE 2.8: Matlab/Simulink model of DC motor

2.5 PID Controller

Most of the control techniques in industrial applications are embedded with the Proportional-Integral-Derivative (PID) controller. PID control is one of the oldest techniques. It uses one of its families of controllers including P, PD, PI and PID controllers. There are two reasons why nowadays it is still the majority and important in industrial applications. First, its popularity stems from the fact that the control engineer essentially only has to determine the best setting for proportional, integral and derivative control action needed to achieve a desired closed-loop performance that obtained from the well-known Ziegler-Nichols tuning procedure.

Controllers respond to the error between a selected set point and the offset or error signal that is the difference between the measurement value and the set point. Optimum values can be computed based upon the natural frequency of a system. Too much feedback (positive feedback cause stability problems) causes increasing oscillation. With proportional (gain) only control the output increases or decreases to a new value that is proportional to the error. Higher gain makes the output change larger corresponding to the error. Integral can be added to the proportional action to ramp the output at a particular rate thus bring the error back toward zero. Derivative can be added as a momentary spike of corrective action that tails off.

Typical steps for designing a PID controller are;

i. Determine what characteristics of the system need to be improved.

ii. Use KP to decrease the rise time.

iii. Use KD to reduce the overshoot and settling time.

iv. Use KI to eliminate the steady-state error

$$u = K_p e + K_I \int edt + \frac{de}{dt} \tag{2.14}$$

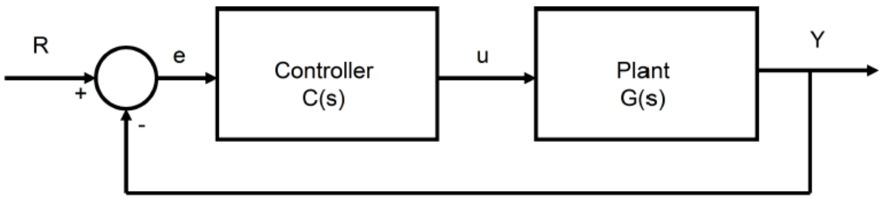


FIGURE 2.9: PID control structure [23]

The variable *e* denotes the tracking error, which is sent to the PID controller. The control signal *u* from the controller to the plant is equal to the proportional gain (K_P) times the magnitude of the error plus the integral gain (K_I) times the integral of the error plus the derivative gain (K_D) times the derivative of the error [23].

CHAPTER 3

METHODOLOGY

3.1 Project Design

The general proposed block diagram for this is is shown in **FIGURE 3.1** and **FIGURE 3.2** shows the overview of the project in flow chart.

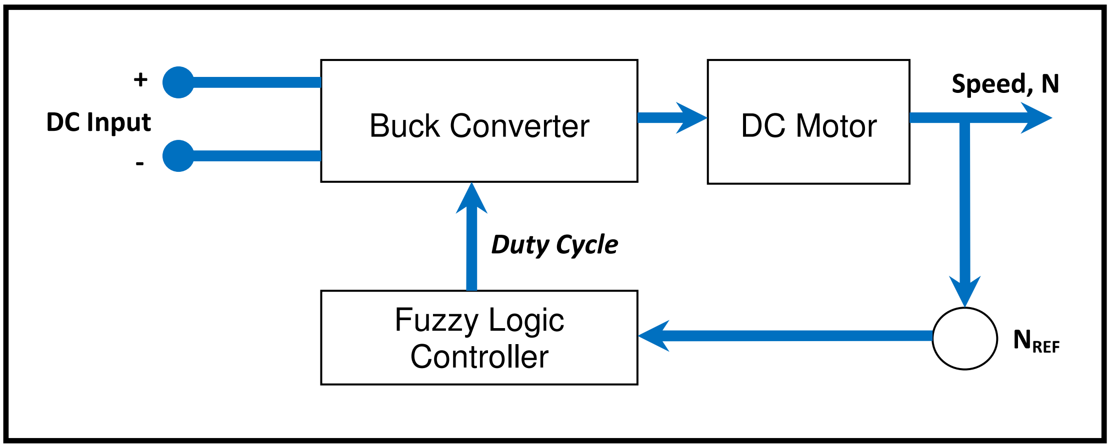


FIGURE 3.1: Block Diagram For Propose DC-DC Buck Converter Using Fuzzy Logic Controller

The proposed design is using Fuzzy Logic Controller as a controller to controller speed to the desired speed. The performance of the controller is compared with the designed conventional controller which is Proportional-Integrated controller, PI. The fuzzy controller used to control the duty cycle of the converter to ensure that the motor with run as same speed as the reference speed. The model is design and simulate by MATLAB/Simulink.

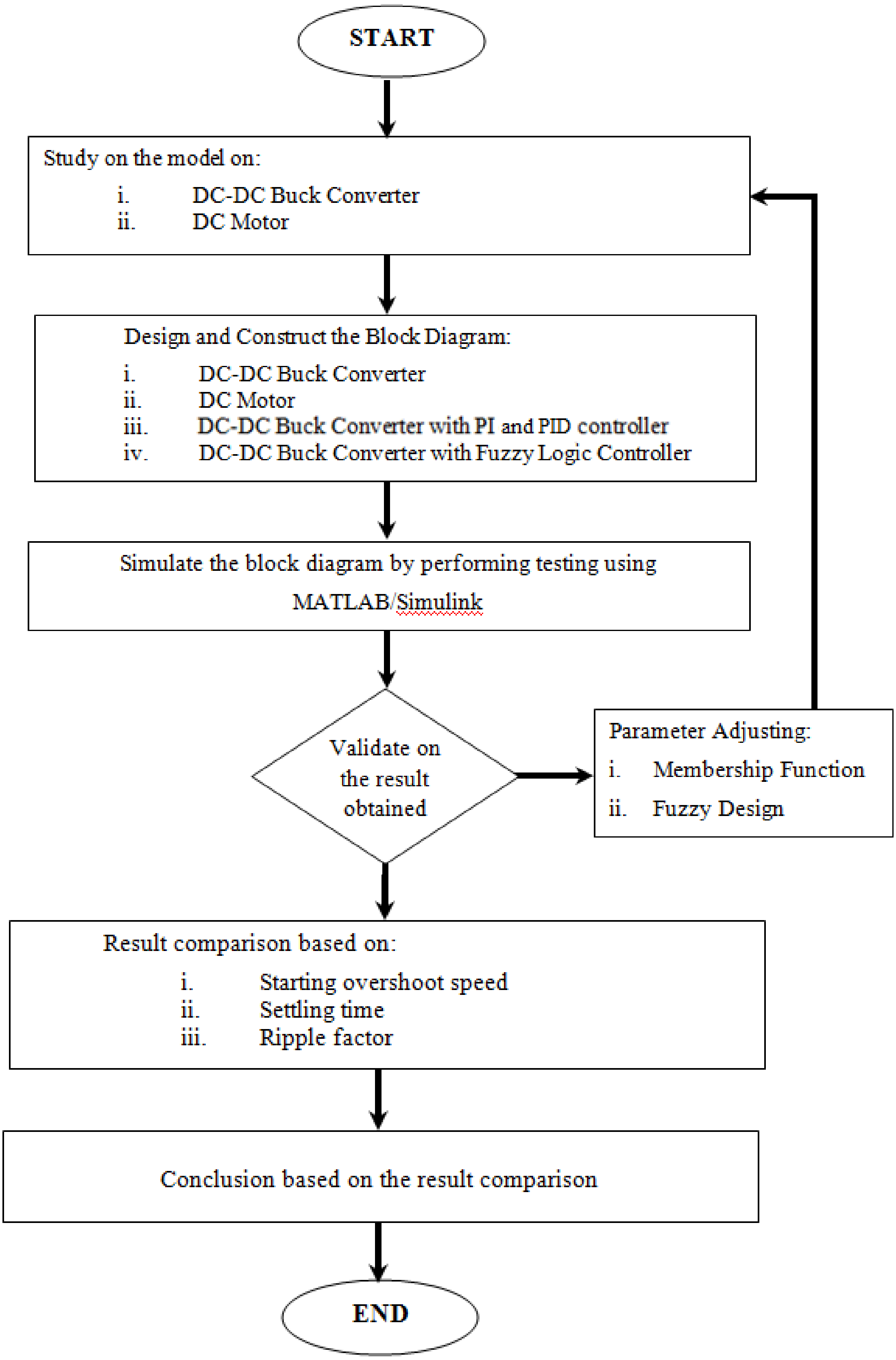


FIGURE 3.2: The Flow Chart of Methodology

3.2 Proposed DC Motor

There were several papers such as Zulkifilie Ibrahim and Emil Levi (2002) and Teresa Orlowska-Kowalska (2001) had proposed the DC motor design using MATLAB/Simulink. The design DC motor is used to analyse of the system dynamics. But for this project, I have made the design made by Zulkifilie Ibrahim and Emil Levi as my reference due to the application of the motor which is quite the same. The design below shows the proposed design of the motor used for the simulation.

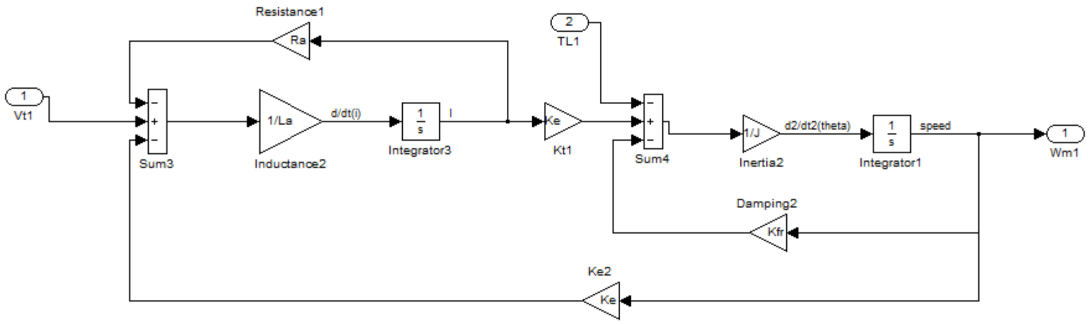


FIGURE 3.3: Proposed design of DC Motor

The input voltage of the motor is connected to the Buck converter to ensure that the motor runs at the desired speed control by the controller. The motor is connected to the fixed load. While the output of the motor is the desired speed, in rad/s. Due to the desired speed is in r.p.m, below equation is used to convert the speed in rad/s to speed,N in r.p.m.

$$N = \frac{60T}{2\pi} \tag{3.1}$$

The proposed project is to control the motor speed to 1200 rpm. The value of motor parameter is based on the Muhammad H.Rashid (2004) and the P.Thepsatorn, A.Numsomran (2006) proposed parameter.

3.3 Proposed PI controller

The design of the PI controller is as below where the value for gain was refers to the model proposed Muhammad H. Rashid (2004).

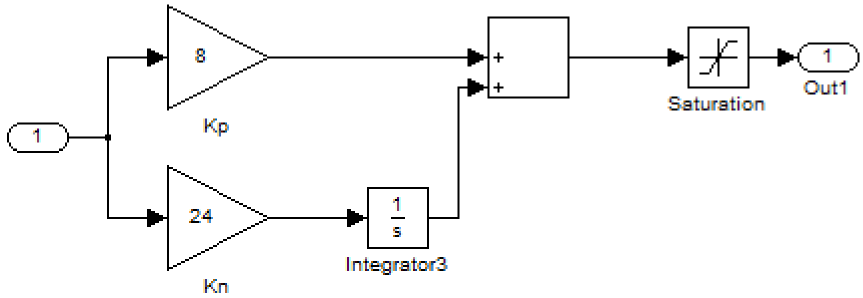


FIGURE 3.4: The model for PI controller in MATLAB/Simulink

3.4 Proposed PID controller

The design of the PI controller is as below where the value for gain was refers to the model proposed Muhammad H. Rashid (2004). The PID will only produce an output with the value range between 0 and 1. This is because the duty cycle range is from 0 to 1

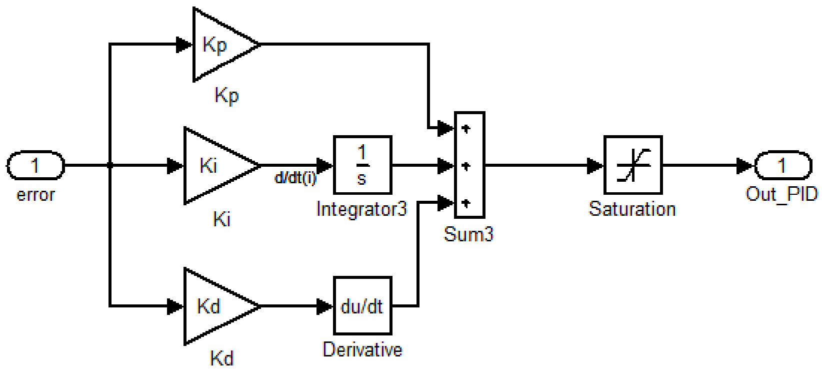


FIGURE 3.5: The model for PID controller in MATLAB/Simulink

3.5 Proposed Fuzzy Controller

The structure block diagram of the proposed controller is shown below. The goal of designed fuzzy logic controller in this study is to control the speed of Dc motor at the desired speed. The bigger speed error the bigger controller input is expected. The change of error plays an important role to define the controller input. Consequently fuzzy logic controller was uses error (e) and the change of error (ce) for linguistic variable which are generated from the control rules. However, for this design fuzzy, the input of fuzzy is only used the error of the previous speed.

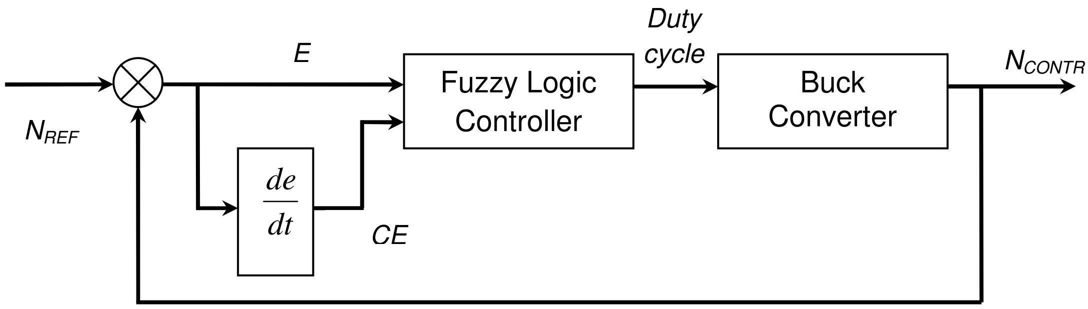


FIGURE 3.6: The proposed model of the controller

3.6 Fuzzy Logic Controller Design

The controller designed is based on the target of the system, therefore, there are few elements need to be considered in order to design the fuzzy logic controller which are fuzzification interface, fuzzy rules and defuzzification interface.

3.6.1 Fuzzification interface

For this design the input of the fuzzy controller is only error which defined as:

$$e = N_{ref} - N_o \tag{3.2}$$

where the N_o is the desired output voltage while N_{ref} is the reference speed. The output of the fuzzy controller is the duty cycle and is defined as:

$$d_k = d_{k-1} + n.\delta d_k \qquad (3.3)$$

where δd_k is inferred change of duty cycle by the fuzzy controller at the sampling time kth sampling time and n is the gain factor of the fuzzy controller. Adjusting n can be change the effective gain if the controller. Specifically the fuzzy rules are in the form:

$$\text{If } e \text{ is A, then } d_k \text{ is C} \qquad (3.4)$$

Where A is fuzzy subset in their universe of discourse and C is a fuzzy singleton. Each universe of discourse is divided into four fuzzy subsets: Negative Big (NB), Negative Small (NS), Positive Small (PS) and Positive Big (PB) are representing the linguistic variables for error (input). The range of error is set from -1 to +1. While for Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB) are represent the linguistic variables for output. The range of output is set from 0 to 1. **FIGURE 3.5** shows the FIS editor that the variable are divided into one input variable and single output variable.

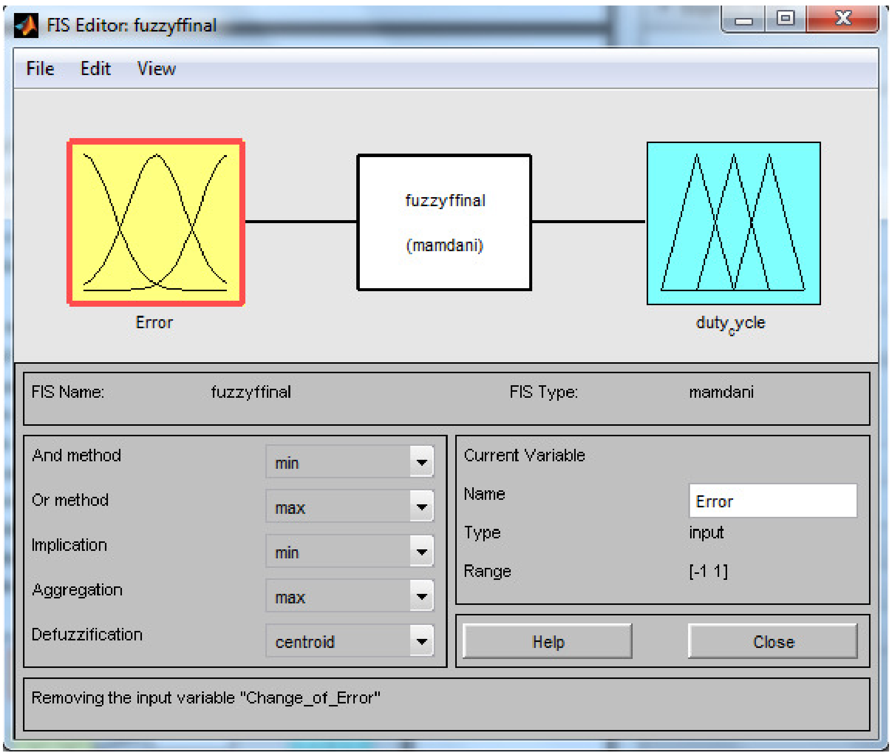
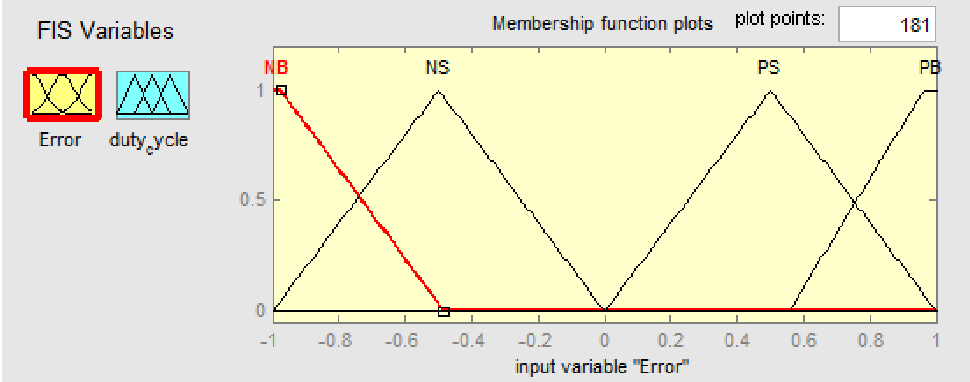
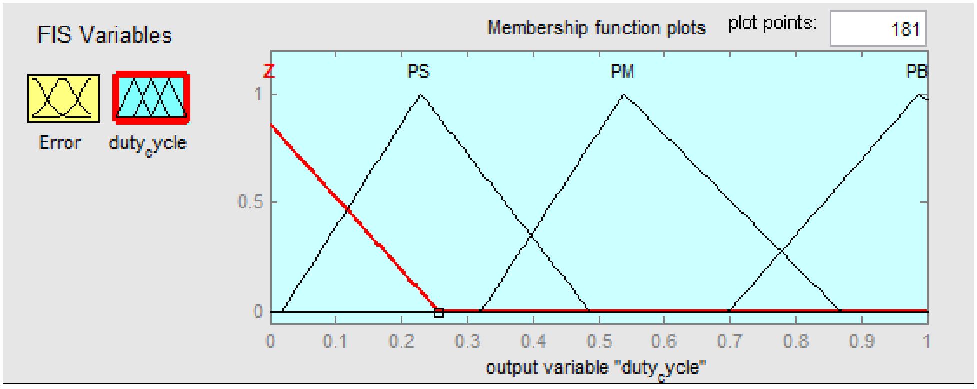


FIGURE3.7: FIS Editor



(a) Error



(b) Output

FIGURE 3.8: Trapezoidal membership function for (a) error and (b) output

3.6.2 Fuzzy Rules

The rules are set based upon the knowledge and working of the system. The rule base adjusts the duty cycle for the DC-DC Buck converter based upon the changes in the input of the fuzzy logic controller. The number of rules can be set as desired. The rules based include 4 rules which are based on the four membership function of the input variable.

Speed, N	*Output*	
Error, e	NB	**PB**
	PS	**PS**
	NS	**PM**
	PB	**Z**

TABLE 3.1: Rules for Error

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