VOLTAGE TRACKING OF A DC-DC BUCK-BOOST CONVERTER USING GAUSSIAN FUZZY LOGIC CONTROL

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ABSTRACT

DC - DC converters are the most widely used circuits in power electronics. They can be found in almost every electronic device nowadays, since all semiconductor components are powered by DC sources. DC-DC converter usually consists of power semiconductor devices which are operated as electronic switches. Operation of the switching devices causes the inherently nonlinear characteristic to the dc-dc converters including the buck-boost converter. Proportional-Integral-Differential (PID) controllers have been usually applied to the dc-dc converters because of their simplicity design. However, implementations of this control method to the nonlinear system such as the buck-boost converters will suffer from dynamic response for the converter output. To achieve a stable and fast response, nonlinear controller were applied to control buck-boost converters. Gaussian Fuzzy Logic Control (GFLC) was designed for the buck-boost converters. MATLAB/Simulink was used as the platform in designing both of Gaussian Fuzzy Logic and PID controllers. The controllers performance are compared based on dynamic respond of the controllers in term of settling time (ts), overshoot ratio, peak time (tp) and voltage deviations. Based on simulation results, GFLC have a superior dynamic respond performance compare to PID controller. GFLC produced 0.02% overshoot ratio, 0% voltage deviation and lower setting time (36.08ms) which is a very good dynamic respond in order to achieve desired output voltage values for buck-boost converter.

ABSTRAK

Penukar arus terus kepada arus terus merupakan litar yang paling banyak digunakan dalam litar elektronik kuasa. Pada masa ini, ianya boleh dijumpai dalam hampir setiap alatan elektronik kerana semua komponen semikonduktor menggunakan bekalan arus terus. Penukar arus terus kepada arus terus biasanya mempunyai komponen semikonduktor yang bertindak sebagai suis elektronik. Operasi pensuisan ini akan mengakibatkan berlakunya fenomena *nonlinear* ke atas penukar arus terus kepada arus terus termasuklah penukar *buck-boost*. Pengawal konvensional jenis PID yang mempunyai rekabentuk yang ringkas sebelumnya telah digunakan bagi mengatasi fenomena ini. Namun, pengawalan litar suapbalik menggunakan kaedah PID ini ke atas sistem *nonlinear* seperti litar penukar *buck-boost* akan menjejaskan voltan keluaran dari sudut tindakbalas dinamiknya. Bagi menghasilkan voltan keluaran yang stabil yang mempunyai tindakbalas yang pantas, pengawal jenis *nonlinear* perlu disambung ke penukar *buck-boost*. GFLC telah direkabentuk sebagai pengawal litar suapbalik bagi mengatasi permasalahan ini. MATLAB/Simulink digunakan sebagai *platform* bagi merekabentuk pengawal GFLC dan PID ini. Prestasi setiap jenis pengawal ini dinilai dari sudut tindakbalas dinamik yang terdiri daripada masa penetapan gelombang (ts), nisbah terlajak gelombang, jangka masa puncak gelombang (tp) dan nisbah sisihan voltan keluaran. Berdasarkan hasil simulasi, GFLC menghasilkan gelombang voltan keluaran yang mempunyai tindakbalas dinamik yang lebih baik berbanding dengan pengawal PID. GFLC menghasilkan 0.02% nisbah terlajak gelombang, 0% nisbah sisihan voltan keluaran dan nisbah masa penetapan gelombang (ts) pada 36.08ms. Kesimpulannya, GFLC merupakan jenis pengawal yang diperlukan oleh penukar *buck-boost* bagi menghasilkan voltan keluaran yang dikehendaki.

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A	-	Ampere.
Δe	-	delta of error
e	-	error
μ_t	-	Controller output
BOA	-	Bisector of Area
CCM	-	Continuous Conduction Mode
COG	-	Centroid of Gravity
DC	-	Direct Current
DCM	-	Discontinuous Conduction Mode
DSP	-	Digital Signal Processing
ESL	-	Equivalent Series Inductance
ESR	-	Equivalent Series Resistance
FIS	-	Fuzzy Inference System
FLC	-	Fuzzy Logic Controller
GFLC	-	Gaussian Fuzzy Logic Controller
gaussmf	-	Gaussian Membership Function
gbellmf	-	Generalized Bell Membership Function
IGBT	-	Insulated Gate Bipolar Transistor
Kd	-	Differential gain
Ki	-	Integral gain
Kp	-	Proportional gain
MF	-	Membership Function
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
NB	-	Negative Big
NS	-	Negative Small
P	-	Proportional

PB	-	Positive Big
PI	-	Proportional Integral
PID	-	Proportional Integral Differential
PS	-	Positive Small
PWM	-	Pulse Width Modulation
RHPZ	-	Right Half Planes Zero
trapmf	-	Trapezoidal Membership Function
trimf	-	Triangular Membership Function
ts	-	Settling time
tp	-	Peak time
V	-	Voltage
Z	-	Zero

CHAPTER 1

INTRODUCTION

1.1 Project Background

DC - DC converters are the most widely used circuits in power electronics. They can be found in almost every electronic device nowadays, since all semiconductor components are powered by DC sources. They are basically used in all situations where there is the need of stabilizing a given dc voltage to a desired value. This is generally achieved by chopping and filtering the input voltage through an appropriate switching action, mostly implemented via a pulse width modulation (PWM) [2]. In this project, we concentrate our research towards buck-boost DC converter.

The buck-boost is a popular non-isolated, inverting power stage topology, sometimes called a step-up/down power stage. Power supply designers choose the buck-boost power stage because; the output voltage is inverted from the input voltage, and the output voltage can be either higher or lower than the input voltage. The topology gets its name from producing an output voltage that can be higher (like a boost power stage) or lower (like a buck power stage) in magnitude than the input voltage [5]. Buck-boost converter is an intriguing subject from the control point of view, due to its intrinsic non-linearity.

One of the design targets for electronic engineers is to improve the efficiency of power conversion. For PWM (pulse-width modulation) converters, switching loss is an important performance measure. Fuzzy logic control has been applied successfully to a wide variety of engineering problems, including dc to dc converters. Fuzzy control is an attractive control method because its structure, consisting of fuzzy sets that allow partial membership and “if - then” rules, resembles the way human intuitively approaches a control problem. This makes it easy for a designer to incorporate heuristic knowledge of a system into the controller. Fuzzy control is obviously a great value for problems where the system is difficult to model due to complexity, non-linearity, and imprecision. DC-DC converters fall into this category because they have a time-varying structure and contain elements that are non-linear and have parasitic components [13].

In this project, MATLAB simulink is used as a platform in designing the buck-boost converter and Gaussian fuzzy logic controller in order to study the dynamic behaviour of dc to dc converter and performance of proposed 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 to the dc-dc converters including the buck-boost converter. Consequently, this converter requires a controller with a high degree of dynamic response. (PID) controllers have been usually applied to the converters because of their simplicity. However, implementations of this control method to the nonlinear system such as the power converters will suffer from dynamic response of the converter output. In general, PID controller produces long rise time when the overshoot in output voltage decreases [1]. To achieve a stable steady-state response and fast transient response under varying operating points, nonlinear controllers were used to control buck-boost converters. Thus, this research ***'Voltage Tracking of a DC-DC Buck-Boost Converter Using Gaussian Fuzzy Logic Control'*** is conduct in order to achieve the ideal/stable output voltage.

1.3 Objectives of the Project

The main objectives of this research are to:

i. Develop modeling of large signal buck-boost converter.
ii. Develop simulation modeling of Gaussian Fuzzy Logic Controller for buck-boost converter.
iii. Investigate the effectiveness of Gaussian Fuzzy Logic Controller is compared to the conventional PID.

1.4 Scopes of the Project

i. All of the projects modeling are carried out in simulation method only using MATLAB Simulink software.
ii. The large signal buck-boost converter is design to produce a stable voltage output varies from 2v to 22v.
iii. The effectiveness between Gaussian Fuzzy Logic Controller and PID is studied in terms of maximum overshoot ratio, peak time (tp), settling time (ts) voltage deviations.

CHAPTER II

LITERATURE REVIEW

2.1 Related work

Digital control for DC-DC converters is theoretically interesting because it is a multi-disciplinary research. Theory in the areas of power electronics, systems and control, and computer systems are all needed to conduct research in digital control of DC-DC converters. The increasing interest in digital control of switch mode power supplies is shown in international conference proceedings and journal publications in the past few years.

Guo Liping (2007) has found that to achieve a stable steady-state response and fast transient response under varying operating points, nonlinear controllers need to be used. Fuzzy controller has many advantages such as: exact mathematical models are not required for the design of fuzzy controllers, complexities associated with nonlinear mathematical analysis are relatively low, and fuzzy controllers are able to adapt to changes in operating points but extensive tuning may be required based on trial and error method and the system's response is not easy to predict [10].

Mohd Azri Bin Akhiak (2012) applied and testing both PID and fuzzy logic as rotary crane system controller. The performance of fuzzy logic controller outperforming the conventional controller named PID controller. In addition, fuzzy logic controller is non-based model which is no need complexity of mathematical derivation. Gaussian membership function gives a little bit better rise time and settling time among other membership functions. The simplification of Gaussian's equation makes it easy to develop membership function by using source code writing [12].

K. Guesmi, N. Essounbouli, A. Hamzaoui and J. Zaytoon (2006) has found that when DC-DC Power converters are characterized by cyclic switching of circuit topologies; its gives rise to a variety of nonlinear behaviors hence makes the system analysis and behaviour prediction more complicated. A fuzzy logic controller has been designed to ensure the converter averaged input current to be close to the reference in wide range of system parameters variation. Compared to the original behavior of the system, simulation results showed the fuzzy logic controller ability to suppress the undesirable nonlinear phenomena, to ensure the desired regulation performance and to enlarge the desired period one operating domain. Moreover, the system behaviour prediction and analysis become easier [14].

Liping Guo, John Y. Hung, and R. M. Nelms (2009) performed a comparative evaluation of the DSP based PID and fuzzy controllers for application to DC-DC converters. Comparison between the two controllers is made with regard to design methodology, implementation issues, and experimentally measured performance. Design of fuzzy controllers is based on heuristic knowledge of converter behaviour, and tuning requires some expertise to minimize unproductive trial and error. The design of PID control is based on the frequency response of the dc–dc converter. The fuzzy controller was able to achieve faster transient response in most tests, had a more stable steady-state response, and was more robust under some operating conditions. For the boost converter, the performance of the fuzzy controller was superior in some respects to that of the PID controllers but in the case of the buck converter, the fuzzy controller and PID controller yielded comparable performances [15].

2.2 Theories

2.2.1 Introduction to Buck-Boost Converter

In continuous conduction mode, the buck-boost converter assumes two states per switching cycle. The ON State is when transistor (mosfet or IGBT) is ON and diode is in OPEN circuit mode. The OFF State is when transistor (mosfet or IGBT) is OFF and diode is CLOSE circuit mode. A simple linear circuit can represent each of the two states where the switches in the circuit are replaced by their equivalent circuit during each state. The circuit diagram for each of the two states is shown in figure 2.2.

The duration of the ON state is $D \times T_S = T_{ON}$ where D is the duty cycle, set by the control circuit, expressed as a ratio of the switch ON time to the time of one complete switching cycle, Ts. The duration of the OFF state is called $TOFF$. Since there are only two states per switching cycle for continuous conduction mode, $TOFF$ is equal to $(1-D) \times T_S$. The quantity $(1-D)$ is sometimes called D'. These times are shown along with the waveforms in figure 2.1.

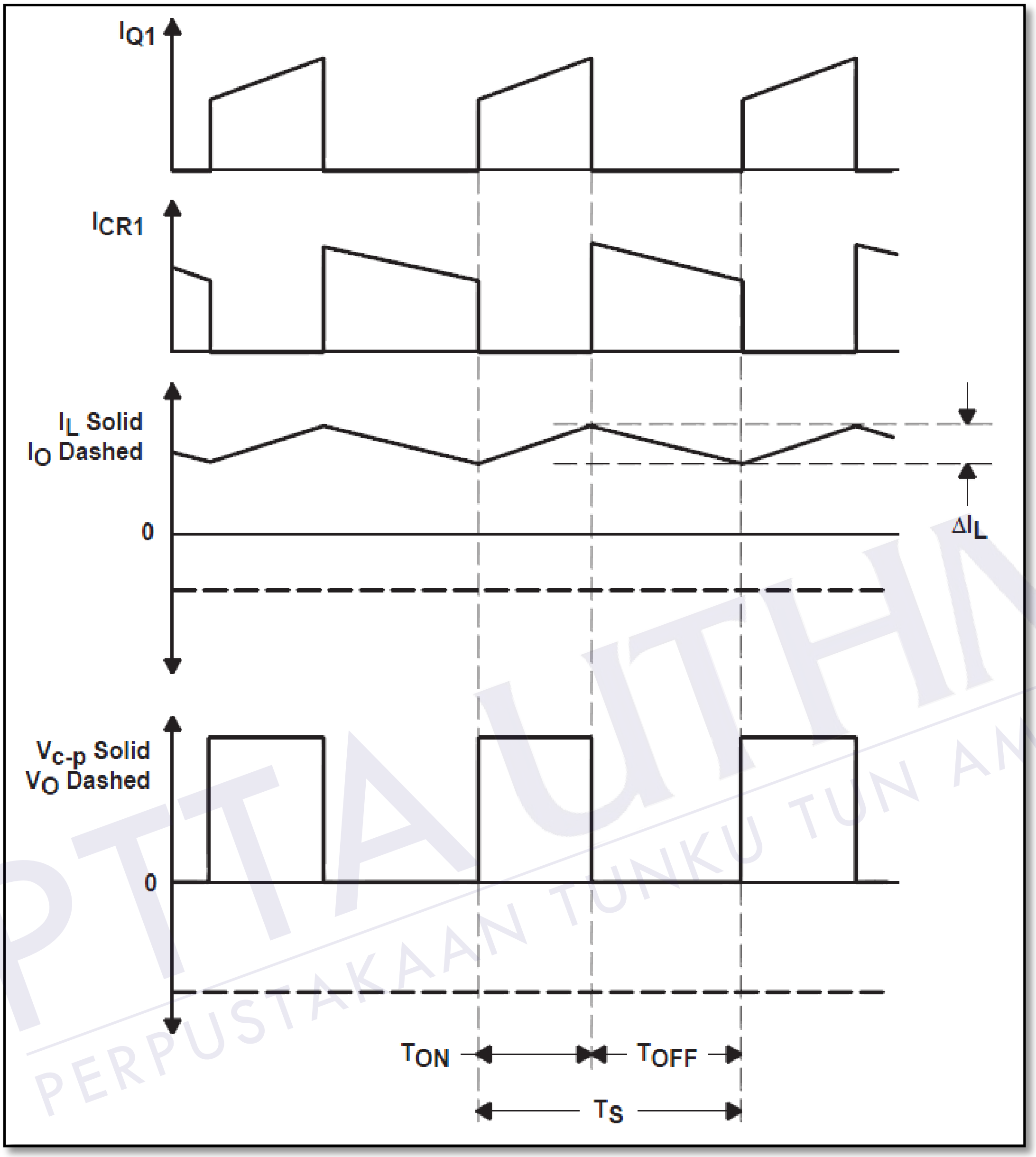
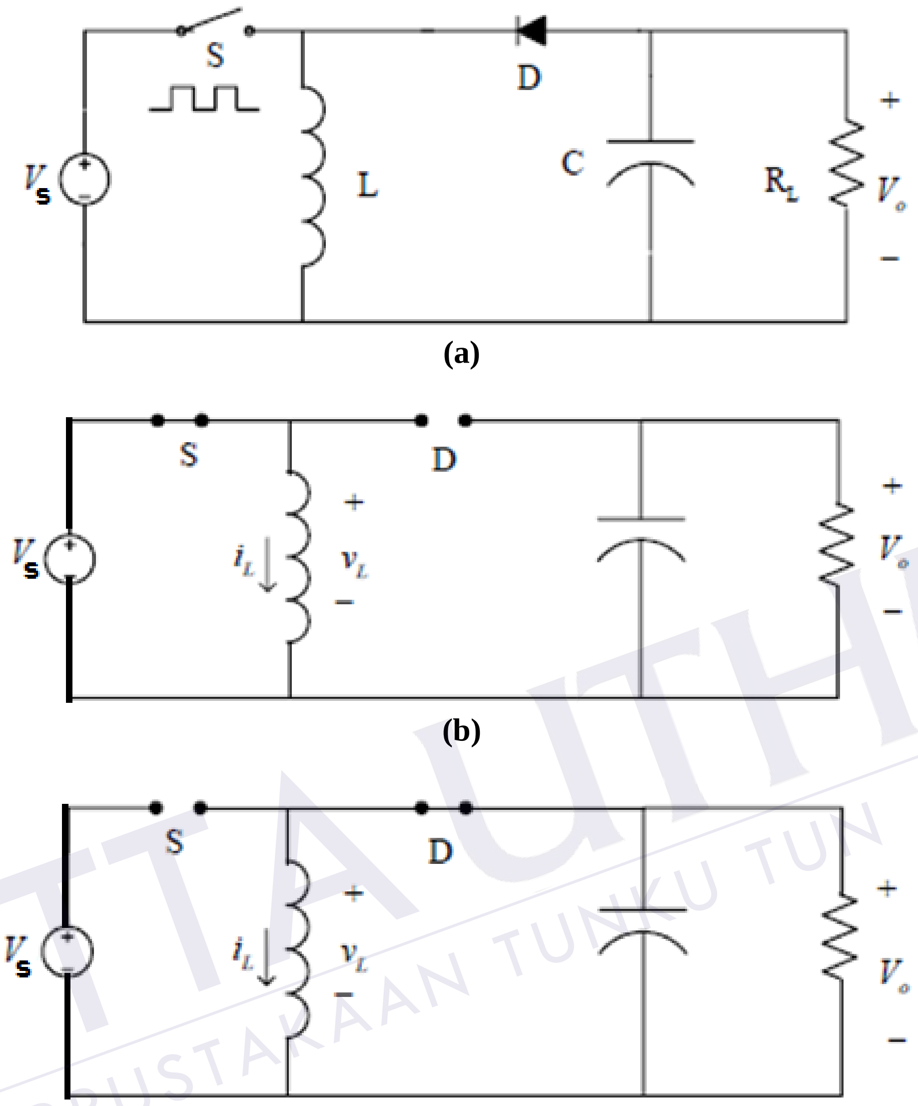


Figure 2.1: Continuous Mode Buck-Boost Power Stage Waveforms

2.2.1.1 Buck-Boost Converter Formula

The equivalent circuit for buck-boost converter in two switching modes; closed and opened is shown in figure 2.2.



(a)

(b)

(c)

Figure 2.2: Buck-Boost converter (a) Basic Circuit (b) Circuit when switch is closed (c) Circuit when switch is opened

Buck-boost analysis when the switch is closed;

$$V_L = V_s = L\frac{\partial i_L}{\partial t} \tag{2.1}$$

$$\frac{\partial i_L}{\partial t} = \frac{V_S}{L} \tag{2.2}$$

The rate of change for the inductor current is a linearly constant, so equation 2.2 can be expressed as

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_S}{L}$$

$$\therefore\ \Delta \boldsymbol{i}_{\boldsymbol{L}\,(\boldsymbol{closed})} = \frac{\boldsymbol{V_s DT}}{\boldsymbol{L}} \tag{2.3}$$

Buck-boost analysis when the switch is opened;

$$V_L = V_O = L\frac{\partial i_L}{\partial t} \tag{2.4}$$

$$\frac{\partial i_L}{\partial t} = \frac{V_O}{L} \tag{2.5}$$

The rate of change for inductor current is constant, thus the change in current at opened circuit is

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_O}{L}$$

$$\therefore\ \Delta \boldsymbol{i}_{\boldsymbol{L}\,(\boldsymbol{opened})} = \frac{\boldsymbol{V_O(1-D)T}}{\boldsymbol{L}} \tag{2.6}$$

For steady-state operation, the net change in inductor current must be zero over one period of time. Voltage output can be determining using equation 2.3 and 2.6 in steady state operation.

$$\Delta i_{L\,(closed)} + \Delta i_{L\,(opened)} = 0$$

$$\frac{V_S DT}{L} + \frac{V_O(1-D)T}{L} \qquad = 0$$

Solving for V_{out}

$$\boldsymbol{V_O = -V_S\left[\frac{D}{1-D}\right]} \tag{2.7}$$

Equation 2.7 shows the output voltage produced using buck-boost converter method has an opposite polarity compared to input voltage. These converter can produced three stage of voltage depend on the duty cycle;

i. If the duty cycle is greater than 0.5 ($D > 0.5$), the output voltage will be higher than the input voltage (boost mode).

ii. If the duty cycle is equal to 0.5 ($D = 0.5$), the output will produce the same amount of voltage as input voltage.

iii. If the duty cycle is lower than 0.5 ($D < 0.5$), the output voltage will be lower than the input voltage (buck mode).

In the buck-boost converter, the source is never connected directly to the load. Energy is stored in the inductor when the switch is closed and transferred to the load when the switch is opened. Hence, the buck boost converter is also referred to as an indirect converter.

Assuming no power losses in the converter, power absorbed by the load must be equal with power supplied by the source,

$$P_O = P_S \tag{2.8}$$

$$\boldsymbol{\frac{{V_O}^2}{R} = V_S I_S} \tag{2.9}$$

Average source current is related to average inductor current as;

$$I_S = I_L D \tag{2.10}$$

Thus, equation 2.9 can be written as;

$$\frac{\boldsymbol{V_O}^{2}}{\boldsymbol{R}} = \boldsymbol{V_S I_L D} \tag{2.11}$$

Solving for I_L

$$\boldsymbol{I_L} = \frac{\boldsymbol{V_O}^{2}}{\boldsymbol{V_S R D}} = \frac{\boldsymbol{P_O}}{\boldsymbol{V_S D}} = \frac{\boldsymbol{V_S D}}{\boldsymbol{R\,(1-D)^2}} \tag{2.12}$$

For continuous current mode I_L must be greater than Δi_L.

Maximum and minimum inductor current;

$$I_{max} = I_L + \frac{\Delta i_L}{2} = \frac{V_S D}{R(1-D)^2} + \frac{V_S D T}{2L} \tag{2.13}$$

$$I_{min} = I_L - \frac{\Delta i_L}{2} = \frac{V_S D}{R(1-D)^2} - \frac{V_S D T}{2L} \tag{2.14}$$

For continuous current, the inductor current must remain positive. Therefore, in order to determine the boundary between continuous (CCM) and discontinuous current (DCM), I_{min} in equation 2.14 is set to zero.

$$\frac{V_S D}{R(1-D)^2} - \frac{V_S D T}{2L} = 0$$

Thus, the value of the inductor that determines the boundary between the CCM and DCM is

$$L_{min} = \frac{(1-D)^2 R}{2f} \tag{2.15}$$

The output voltage ripple for the buck boost converter;

$$|\Delta Q| = \left[\frac{V_O}{R}\right] DT = C\Delta V_O \tag{2.16}$$

Solving for ΔV_O

$$\Delta V_O = \frac{V_O DT}{RC} = \frac{V_O D}{RCf} \tag{2.17}$$

Thus

$$\boldsymbol{r = \frac{\Delta V_O}{V_O} = \frac{D}{RCf}} \tag{2.18}$$

2.2.2 Introduction to switching

Two switching conditions taken place in the dc to dc converter;

i. power semiconductor devices switching (such as igbt, mosfet, scr)
ii. switching mode (continuous conduction mode and discontinuous conduction mode)

Power semiconductor devices is a physical component that needed in constructing dc to dc converter while switching mode can be achieved from calculation regarding the value of inductance in the dc to dc converter circuit.

2.2.2.1 Power semiconductor device

The range of power devices developed over the last few decades can be represented as a in figure 2.3 on the basis of their controllability and other dominant features.

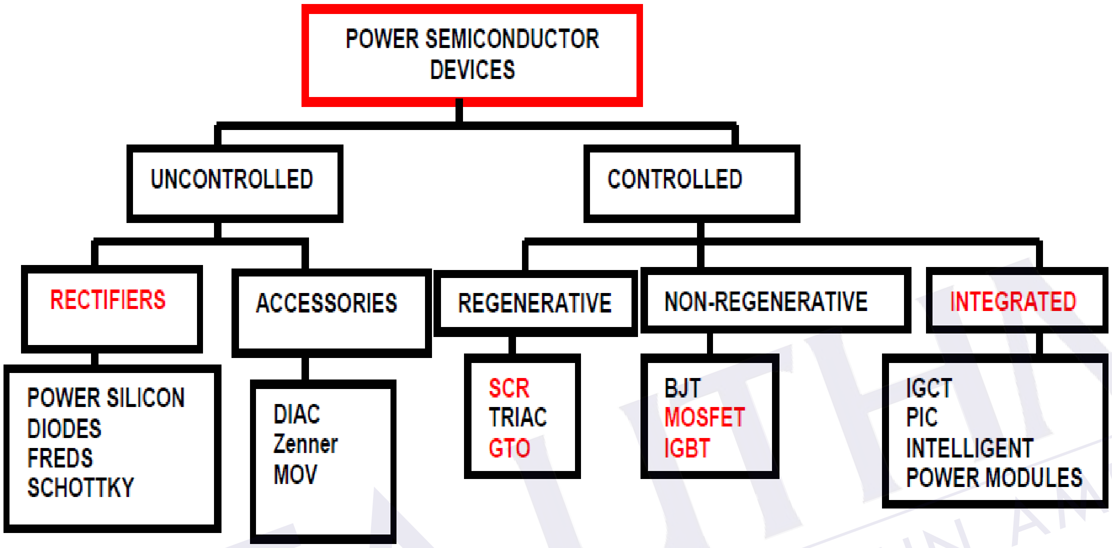


Figure 2.3: Power semiconductor device variety

In designing buck-boost converter, controlled with non-regenerative power semiconductor compenant is selected to be a switching device. Most of buck-boost converter designed only used either mosfet or igbt nowaday.

2.2.2.1.1 MOSFET *(Metal Oxide Semiconductor Field Effect Transistor)*

The Power MOSFET technology has mostly reached maturity and is the most popular device for lighting ballast type of application where high switching frequencies are desired but operating voltages are low. For low frequency applications, where the currents drawn by the equivalent capacitances across its terminals are small, it can also be driven directly by integrated circuits. At high current low voltage applications the MOSFET offers best conduction voltage specifications as the internal resistance is current rating dependent. However, the inferior features of the inherent anti-parallel diode and its higher conduction losses at power frequencies and voltage levels restrict its wider application.

2.2.2.1.2 **IGBT** *(Insulated Gate Bipolar Transistor)*

It is a voltage controlled four-layer device with the advantages of the MOSFET driver and the Bipolar Main terminal. The switching times can be controlled by suitably shaping the drive signal. This gives the IGBT a number of advantages: it does not require protective circuits, it can be connected in parallel without difficulty, and series connection is possible without snubbers. The IGBT is presently one of the most popular devices in view of its wide ratings, switching speed of about 100 KHz, an easy voltage drive and a square safe operating area devoid of a second breakdown region.

2.2.2.2 Switching mode

As mention in introduction to swiching, the CCM and DCM can be achieved from calculation regarding the value of inductance in the dc to dc converter circuit (refer to equation 2.15).

When the current through the inductor can fall to zero, the condition is known as *discontinuous conduction mode* (DCM) operation. When the inductor current never falls to zero, or when the power supply employs synchronous rectification, the condition is said to be in *continuous conduction mode* (CCM). Figure 2.4 shows the inductor current in CCM and DCM condition.

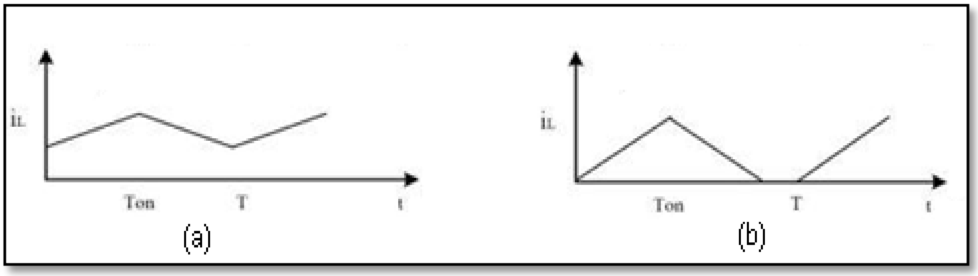


Figure 2.4: Inductor current (a) continuous conduction mode ($I_L > \Delta i$)
(b) discontinuous conduction mode ($I_L < \Delta i$)

2.2.2.2.1 Advantages of DCM

i. The CCM boost, buck-boost, and flyback topologies have a right half planes zero **(**RHPZ) in their control to output transfer function. The right half plane zero is nearly impossible to compensate for in the compensation loop. As a result, the control loop in these CCM converters is typically made to cross over at a frequency much lower than the RHPZ frequency resulting in lower transient response bandwidths. The DCM version of the boost, buck-boost, and flyback converters do not have a right half plane zero and can have higher loop crossover frequency allowing higher transient response bandwidths.

ii. In the buck, boost, buck-boost, and all topologies derived from these, the input to output and control to output transfer functions contain single pole responses while operating in DCM. Converters with only single pole transfer functions are easier to compensate than converters having a double pole response.

2.2.2.2.2 Disadvantages of DCM

i. In DCM, the inductor current reaches zero while in non-synchronous operation, the end of the inductor connected to the switch (also called the freewheel end), must immediately transition to the voltage at the other end of the inductor. However, there will always be inductive and capacitive parasitic elements which will cause severe ringing if damping is not implemented. This ringing can produce undesirable noise at the output of the power supply.

ii. Boost, buck-boost, and derived topologies are commonly operated only in DCM to avoid the adverse effects of the RHPZ described earlier. However, to achieve the same power in DCM as in CCM, the peak and RMS currents are substantially higher resulting in greater losses in the conduction paths and greater ringing because the energy stored in inductances is proportional to the square of the current. Energy stored that is not delivered to the output causes ringing and losses.

iii. In DCM, the inductance must be much smaller in value to allow the current to fall to zero before the start of the next cycle. Smaller inductance results in higher RMS and peak inductor currents. Because the RMS and peak currents are greater in DCM than in CCM, the transformers must be sized larger to accommodate greater flux swings and copper and core losses. DCM has a physically larger transformers and inductors required for same power output as CCM.

2.2.3 Introduction to PID controller

Proportional-integral-derivative (PID) control: Over 90% of the controllers in operation today are PID controllers (or at least some form of PID controller like a P or PI controller). This approach is often viewed as simple, reliable, and easy to understand.

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.

Conventional PID controllers have been extensively used in industry, due to their effectiveness for linear systems, ease of design and inexpensive cost. Despite their effectiveness for linear systems, conventional PID controllers are not suitable for nonlinear systems and higher-ordered and time-delayed systems, not to mention complex and vague systems that require expert knowledge. For these reasons, it is worth developing fuzzy-logic-based controllers which have the capability to handle not only linear, as well as indistinct defined systems [11].

2.2.4 Introduction to Fuzzy Logic controller

Since its introduction in 1965 by Lotfi Zadeh (1965) [8], the fuzzy set theory has been widely used in solving problems in various fields, and recently in educational evaluation. Fuzzy control is a practical alternative for a variety of challenging control applications since it provides a convenient method for constructing nonlinear controllers via the use of heuristic information. Figure 2.3 shows the structure of the fuzzy logic controller.

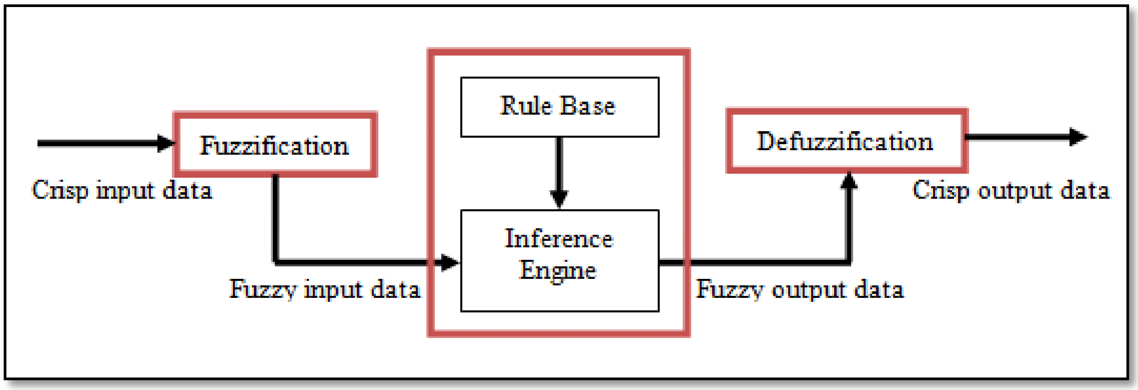


Figure 2.5: Structure of the fuzzy logic controller

Fuzzy logic works by executing rules that correlate the controller inputs with the desired outputs. Generally the key aspects of fuzzy logic comprises of fuzzy sets, membership functions, linguistic variables and fuzzy rules:

i. A rule-base (a set of If-Then rules), which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control.

ii. An inference mechanism (also called an "inference engine" or "fuzzy inference" module), which emulates the expert's decision making in interpreting and applying knowledge about how the best way to control a plant.

iii. A fuzzification interface, which converts controller inputs into information that the inference mechanism can easily use to activate and apply rules.

iv. A defuzzification interface, which converts the conclusions of the inference mechanism into actual inputs for the process.

2.2.4.1 Fuzzification

Fuzzification is a process of making a crisp quantity fuzzy. Before this process is taken in action, the definition of the linguistic variables and terms is needed. Linguistic variables are the input or output variables of the system whose values are words or sentences from a natural language, instead of numerical values. A linguistic variable is generally decomposed into asset of linguistic terms. Example, in the air conditioner system, Temperature (T) is linguistic variable represents the temperature of a room. To qualify the temperature, terms such as "hot" and "cold" are used in real life. Then, Temperature (T) = {too cold, cold, warm, hot, too hot} can be the set of decomposition for the linguistic variable temperature. Each member of this decomposition is called a linguistic term and can cover a portion of the overall values of the temperature. To map the non-fuzzy input or crisp input data to fuzzy linguistic terms, membership functions is used.

2.2.4.2 Membership Function

The membership function is a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs that are define functional overlap between inputs, and ultimately determines output response.

The “shape” of the membership function is an important criterion that has to be considered. There are different shapes of membership functions such as triangular, Gaussian, trapezoidal, generalized bell and sigmoidal. The triangular shape is the most popular and widely used membership function. The degree of membership function is normally lies in the range [0 1]. Figure 2.4 shows the definitions and graphs of these membership functions.

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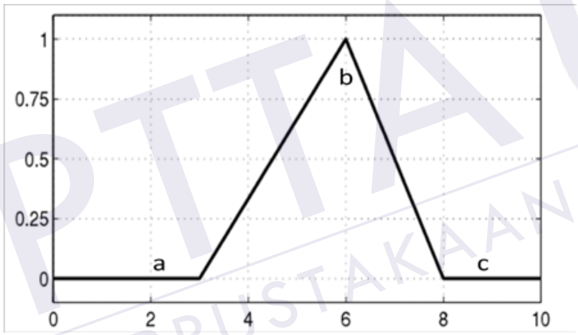

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Triangular membership function

$$trimf(x;a,b,c)=\begin{cases} 0 & x\le a \\ \dfrac{x-a}{b-a} & a\le x\le b \\ \dfrac{c-x}{c-b} & b\le x\le c \\ 0 & c\le x \end{cases}$$
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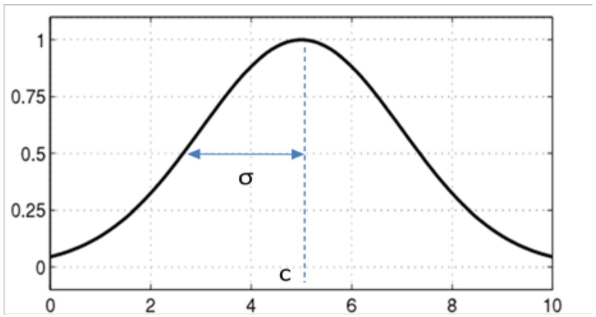

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Gaussian membership function

$$gaussmf(x;\sigma,c)=e^{\frac{-(x-c)^2}{2\cdot\sigma^2}}$$
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Figure 2.6: Different types of membership function

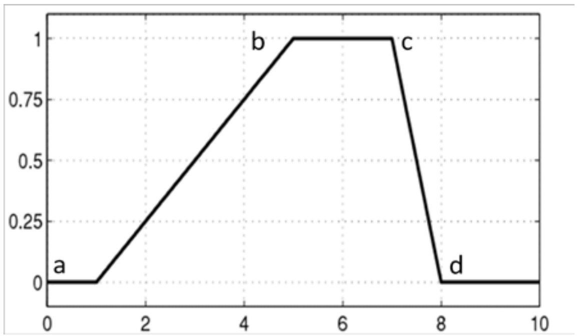
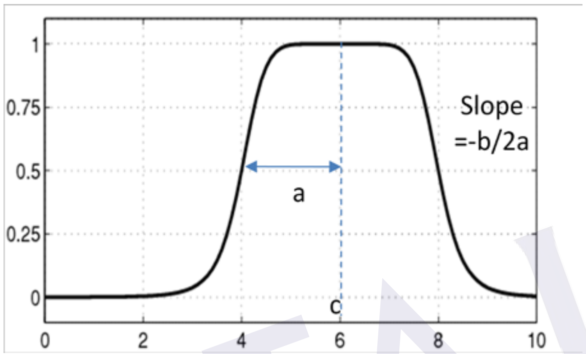
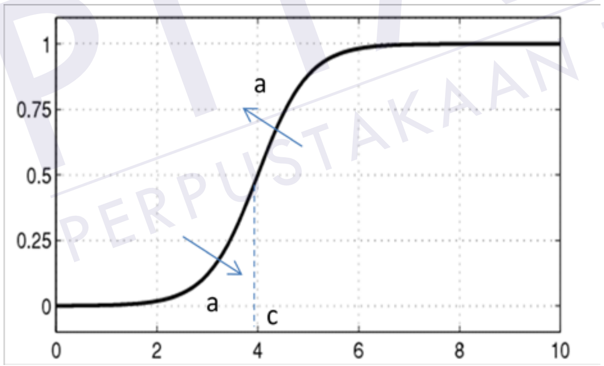
	Trapezoidal membership function $trapmf(x;a,b,c)=\left\{\begin{cases} 0 & x\le a \\ \frac{x-a}{b-a} & a\le x\le b \\ 1 & b\le x\le c \\ \frac{d-x}{d-c} & c\le x\le d \\ 0 & d\le x \end{cases}\right\}$
	Generalized bell membership function $gbellmf(x;a,b,c)=\frac{1}{1+\left\|\frac{x-c}{a}\right\|^{2b}}$
	Sigmoidal membership function $sigmf(x;a,c)=\frac{1}{1+e^{-a(x-c)}}$

Figure 2.6(continued): Different types of membership function

The membership functions classify the element in the set, whether it is discrete or continuous. The membership function in the continuous form is a mathematical function, possibly a program. In the discrete form the membership function and the universe are discrete points in a list (vector). The discrete representation is more convenient for certain application.

Although triangular membership function consisting of simple straight line segments and very easy to implement in fuzzy control but the Gaussian membership function facilitate obtaining smooth and continuous output.

2.2.4.3 Fuzzy Rules

In a fuzzy logic control system, a rule base is constructed to control the output variable. The primary goal of fuzzy systems is to formulate a theoretical foundation for reasoning about imprecise propositions, which is termed *approximate reasoning* in fuzzy logic technological systems. Fuzzy sets and fuzzy operators are the subjects and verbs of fuzzy logic. These if-then rule statements are used to formulate the conditional statements that comprise fuzzy logic. A single fuzzy if-then rule assumes the form if x is A then y is B where A and B are linguistic values defined by fuzzy sets on the ranges (universes of discourse) X and Y, respectively. The if-part of the rule "x is A" is called the antecedent or premise, while the then-part of the rule "y is B" is called the consequent or conclusion [9]. A fuzzy rule is a simple IF-THEN rule with a condition and conclusion. Rules are usually expressed in the form of:

If variable IS set THEN action
For example, a simple temperature regulator that uses a fan has the following rules:
IF temperature IS very cold THEN stop fan
IF temperature IS cold THEN turn down fan
IF temperature IS normal THEN maintain level
IF temperature IS hot THEN speed up fan

The procedures of fuzzy logic control are where A set of input data from an array of sensors is fed into the control system. The values of input variables undergo a process termed as “fuzzification,” which converts the discrete values into a range of values. Fuzzified inputs are evaluated against a set of production rules. Whichever production rules are selected will generate a set of outputs. Output data are “defuzzified” as distinctive control commands [7].

2.2.4.4 Inference engine

In general, inference is a process of obtaining new knowledge through existing knowledge. In the context of fuzzy logic control system, it can be defined as a process to obtain the final result of combination of the result of each rule in fuzzy value. There are many methods to perform fuzzy inference method and the most common two of them are Mamdani and Takagi-Sugeno-Kang method.

Mamdani method was proposed by Ebrahim H.Mamdani as an attempt to control a steam engine and boiler in 1975. It is based on Lofti Zadeh’s 1973 paper on fuzzy algorithms for complex system and decision processes. This method uses the minimum operation R_c as a fuzzy implication and the max-min operator for the composition. Suppose a rule base is given in the following form;

IF input x = A AND input y = B
THEN output z = C

2.2.4.5 Defuzzification

Defuzzification is performed to converts the fuzzy output of the inference engine to crisp using membership functions analogous to the ones used by the fuzzifier. There are many different methods for defuzzification such as Centroid of Gravity (COG), Mean of Maximum (MOM), Weighted Average, Bisector of Area (BOA), First of Maxima and Last of Maxima. There is no systematic procedure for choosing a good defuzzification strategy, but the selection of defuzzification procedure is depends on the properties of the application.

Centroid of Gravity (COG) is the most frequent used and the most prevalent and physically appealing of all defuzzification methods. The basic equation of Centroid of Gravity (COG) is;

$$u_o = \frac{\int_u \mu_u(u)udu}{\int_u \mu_u(u)du} \tag{2.19}$$

Where u_o is control output obtained by using Centroid of Gravity (COG) defuzzification method.

2.2.5 Controller analysis

In order to investigate the effectiveness of Gaussian fuzzy logic controller (GFLC), another controller needs to be designed. PID controller performance in term of maximum overshoot ratio, peak time (tp), settling time (ts) and voltage deviations are used as benchmark to investigate the effectiveness of Gaussian fuzzy logic controller.

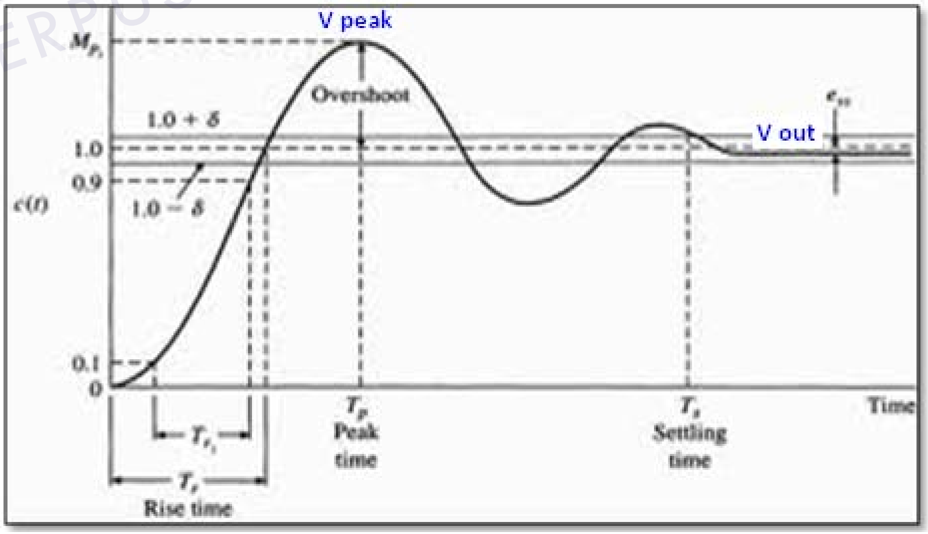


Figure 2.7: Waveform specifications

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