DEVELOPMENT OF A NON-PULSATING BUCK-BOOST CONVERTER WITH CONTINUOUS CURRENT MODE (CCM)

MOHD SHARIF BIN ZAKARIA

A thesis submitted in
fulfillment of the requirement for the award of the
Degree Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JULY, 2013

ABSTRACT

This master report presents a voltage tracking of dc-dc buck-boost converter. The dc-dc Buck converter is designed to tracking the output voltage with three mode of operation. This master report consists open loop control, closed loop control with PID controller. The Buck-Boost converter has some advantages compare to the others type of dc converter. However the nonlinearity of the dc-dc Buck-Boost converter characteristics, cause it is difficult to handle by using conventional method such as open loop control system.. In order to overcome this main problem, a close loop control system using proportional-integral-differential (PID) controller is developed. The effectiveness of the proposed method is verified by develop simulation model in MATLAB-Simulink program. The simulation results show that the proposed proportional-integral-differential (PID) controller produce significant improvement control performance compare to convational converter for voltage tracking output for dc-dc Buck-Boost converter.

ABSTRAK

Laporan master ini membentangkan kaedah mengesan voltan keluaran penukar Buck-Boost. Penukar Buck-Boost direka untuk mengesan voltan keluaran dalam 3 mod operasi. Laporan ini merangkumi rekabentuk penukar jenis kawalan gelung buka dan gelung tertutup dengan pengawal PID. Penukar Buck-Boost mempunyai banyak kelebihan berbanding berbanding dengan penukar arus terus yang lain. Walau bagaimanapun, ciri-ciri tidak linear penukar Buck-Boost menyebabkan ia sukar untuk dikawal seperti dalam sistem gelung buka. Bagi menangani masalah utama ini, sistem gelung tertutup dengan pengawal PID direkabentuk. Keberkesanan cara yang disarankan ini dibuktikan dengan membangunkan model simulasi dalam program MATLAB-Simulink. Keputusan simulasi menunjukkan bahawa pengawal PID yang dicadangkan itu menghasilkan peningkatan prestasi kawalan jika dibandingkan dengan penukar konvasional untuk mengesan voltan keluaran pengawal penukar Buck-Boost arus terus.

CONTENTS

LIST OF TABLE

LIST OF FIGURE

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol

$v0$	Output voltage
$vcon$	Control voltage
$Vref$	Reference voltage
kp , kI	Proportional gain and integral gain of P-I controller
$k1$	Voltage reduction factor
$vramp$	Sawtooth or Ramp voltage
VU ,VL	Upper and Lower threshold voltages
q	Switching signal
h	Switching hypersurface
$iref$	Reference current
C	Capacitor
CCM	Continuous Conduction Mode
ce	Change of Error
D	Duty Cycle
DC	Direct Current
DCM	Discontinuous Conduction Mode
e	Error
Fs	Frequency Switching
GUI	Graphical User Interface
KD	Derivative gain
KI	Integral gain
KP	Proportional gain
L	Inductor
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation
R	Resistor
S	Switch
V_{C} -	Voltage (Calculation)
V_{o} -	Output Voltage
V_{s} -	Input Voltage
Kth	switching cycle
V_{ref}	Reference output
ZE	Zero

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

DC-DC converters are electronic devices used to change DC electrical power efficiently from one voltage level to another. The advantages over AC because DC can simply be stepped up or down. 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 back into the supply, and this feature results in energy saving for transportation system with frequent stop; and also are used, in DC voltage regulation.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 converters. 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 [1].

Basically, the DC-DC converter consists of the power semiconductor devices which are operated as electronic switches and classified as switched-mode DC-DC converters. Operation of the switching devices causes the inherently nonlinear characteristic of the DC-DC converters. Due to this unwanted nonlinear characteristics, the converters requires a controller with a high degree of dynamic response. Pulse Width Modulation (PWM) is the most frequently consider method among the various switching control method. In DC-DC voltage regulators, it is important to supply a constant output voltage, regardless of disturbances on the input voltage.

Controller for the PWM switching control is restraining to Proportional-Integral-Differential (PID) controller. This controller often applied to the converters because of their simplicity. However, implementations of this control method to the nonlinear plants such as the power converters will undergo from dynamic response of the converter output voltage regulation. In general, PID controller produces long rise time when the overshoot in output voltage decreases [2].

Nowadays, the control systems for many power electronic appliances have been increasing widely. Crucial with these demands, many researchers or designers have been struggling to find the most economic and reliable controller to meet these demands. The idea to have a control system in dc-dc converter is to ensure desired voltage output can be produced efficiently as compared to open loop system. [2]

In this project, MATLAB/Simulink is used as a platform in designing the PID logic controller. MATLAB/Simulink simulation model is built to study the dynamic behavior of DC-DC converter and performance of proposed controller.

1.2 PROBLEM STATEMENTS

Buck-Boost DC-DC converters is capable to step-down and step-up the input voltage to produce fixed output voltage. Problem with higher current ripple will influenced and decreased the output voltage regulation and efficiency of the converter.

The switching technique of the converter causes the converter system to be nonlinear system. Nonlinear system requires a controller with higher degree of dynamic response. A Proportional-Integral-Differential (PID) controller has an advantage in term of simple structure and low cost even though PID controllers unable to adapt to the external disturbances and internal variations parameters and suffer from dynamic response of the system [7].

1.3 PROJECT OBJECTIVES

The objectives of this project are;

i) To model and analyze a DC-DC Buck-Boost converter without controller (open loop) and simulate using MATLAB Simulink.

ii) To design PID Controller to control the switching of DC-DC Buck-Boost Converter and simulate using MATLAB Simulink.

iii) To analyze the voltage output for DC-DC Buck-Boost converter between open loop and PID controller.

1.4 PROJECT SCOPES

The scopes of this project is to simulate the proposed method of voltage tracking of DC-DC buck-boost converter using PID controller with MATLAB Simulink software. Analyses of the converter will be done for improving performance DC-DC buck-bosst converter using PID in continuous current mode (CCM) only.

1.5 THESIS OVERVIEW

This project report is organized as follows;

i) Chapter 1 briefs the overall background of the study. A quick glimpse of study touched in first sub-topic. The heart of study such as problem statement, project objective, and project scope and project report layout is present well through this chapter.

ii) Chapter 2 covers the literature review of previous case study based on PID controller background and development. Besides, general information about Buck-Boost Converter and theoretical revision on CCM mode system also described in this chapter.

iii) Chapter 3 presents the methodology used to design open loop Buck-Boost Converter without and with PID controller. All the components that have been used in designing Buck-Boost Converter are described well in this chapter.

iv) Chapter 4 reports and discuss on the results obtained based on the problem statements as mentioned in the first chapter. The simulation results from

Open loop and PID controller will be analyzed with helps from set of figures and tables.

v) Chapter 5 will go through about the conclusion and recommendation for future study. References cited and supporting appendices are given at the end of this project report.

CHAPTER 2

LITERATUR REVIEW

2.1 INTRODUCTION

The switched mode dc-dc converters are some of the simplest power electronic circuits which convert one level of electrical voltage into another level by switching action. These converters have received an increasing deal of interest in many areas. This is due to their wide applications like power supplies for personal computers, office equipments, appliance control, telecommunication equipments, DC motor drives, automotive, aircraft, etc.
The commonly used control methods for dc-dc converters are pulse width modulated (PWM) voltage mode control, PWM current mode control with proportional (P), proportional integral (PI), and proportional integral derivative (PID) controller. [3]

2.2 DC-DC CONVERTER

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 ratio. Like transformer, it can be used to step down or step up a dc voltage source. (Muhammad H. Rashid, 2004) [1]

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 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. (Muhammad H. Rashid, 1993) [1]

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 (Rashid, M. H., 2007) [1]

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.
Because there is a small power loss in those states (low voltage across a switch in the on state, zero current through a switch in the off state), switching regulators can achieve high efficiency energy conversion.

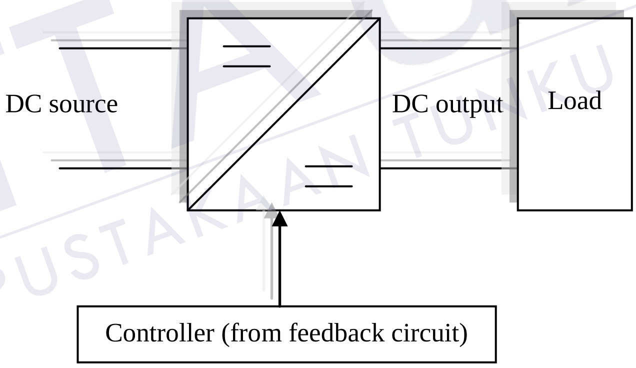

Figure 2-1: General DC-DC converter block diagram

2.3 FUNCTION OF DC-DC CONVERTER

The DC-DC converter has some functions. These are:

i) Convert a DC input voltage Vs into a DC output voltage Vo.

ii) Regulate the DC output voltage against load and line variations.

iii) Reduce the AC voltage ripple on the DC output voltage below the required level.

iv) Provide isolation between the input source and the load (if required).

v) Protect the supplied system and the input source from electromagnetic interference (Rashid, M. H., 2007) [1]

The DC-DC converter is considered as the heart of the power supply, thus it will affect the overall performance of the power supply system. The converter accepts DC and produces a controlled DC output.

2.4 DC-DC CONVERTER SWITCHING

There are two switching condition that need to be applied, that is when ON and OFF as shown in Figure 2-2.

When ON,
Output voltage is the same as the input voltage and the voltage across the switch is 0V.

When OFF,
Output voltage = 0V and current through the switch = 0A. In ideal condition, power loss = 0W since output power equal to input power.

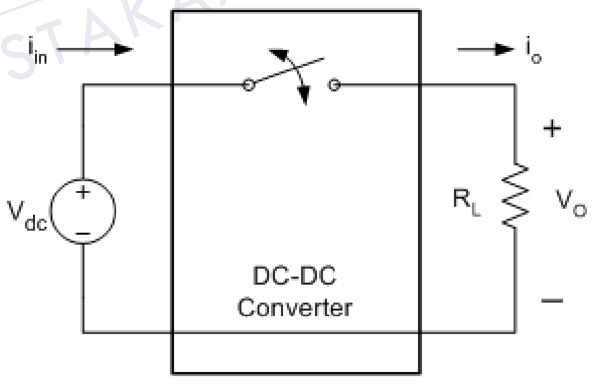

Figure 2-2 : Switching of DC-DC converter.

ON and OFF resulting in pulse as shown in Figure 2-3 where switching period, T , is a one full cycle (360°) of a waveform ranging from t_{ON} to t_{OFF} pulse.

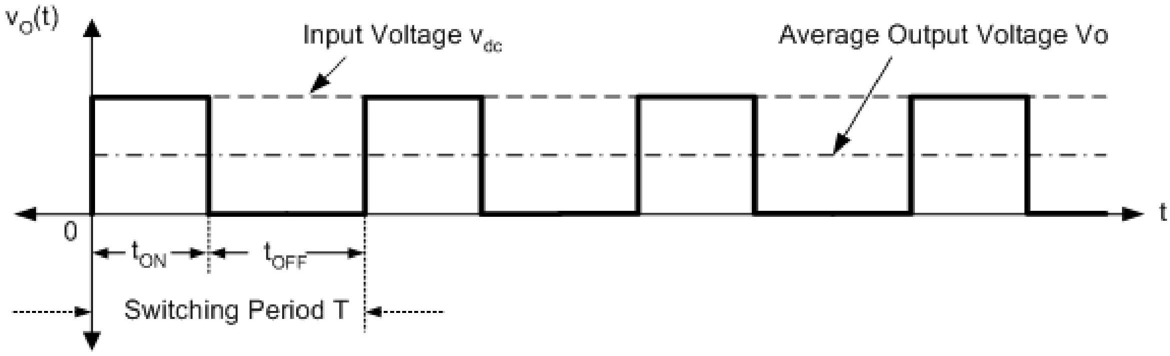

Figure 2-3 : Switching pulse

Thus, duty cycle, D, which depends on t_{ON} and range of duty cycle is $0 < D < 1$. If switching frequency, f_s, is given,

$$D = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T} = t_{on} f_s \qquad (2.1)$$

Average DC output voltage,

$$\overline{V}_0 = \frac{1}{T}\int_0^T v_o(t)\,dt = \frac{1}{T}\int_0^{DT} V_i\,dt = V_i D \qquad (2.2)$$

There are two modes of operation in DC-DC converters based on inductor current, i_L,

i) Continuous Conduction Mode (CCM), when $i_L > 0$.

ii) Discontinuous Conduction Mode (DCM) when i_L goes to 0 and stays at 0 for some time.

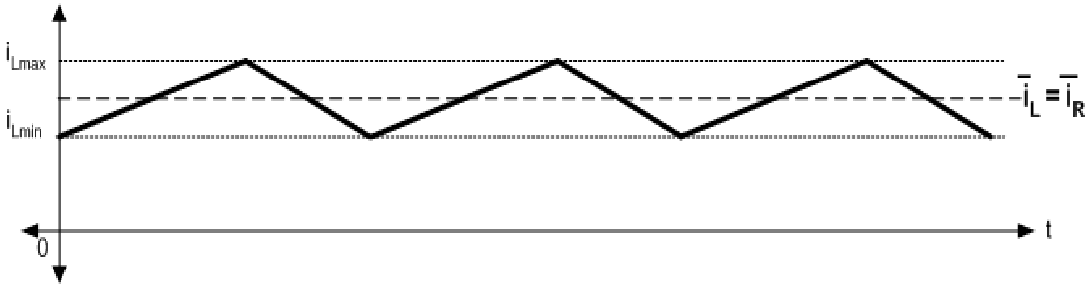

Figure 2-4 : Continuous Conduction Mode.

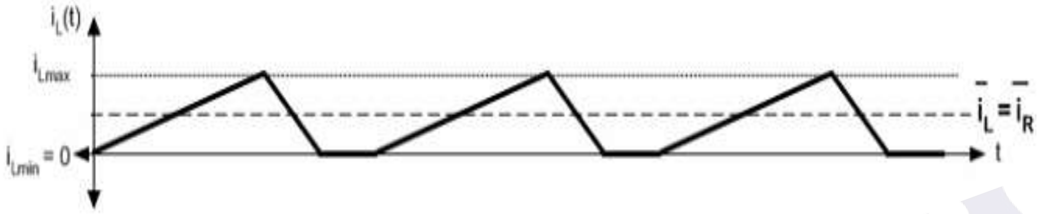

Figure 2-5 : Discontinuous Conduction Mode.

In steady state and periodic operation, inductor charges and discharges with V_{avg} DC voltage across inductor in one period = 0. Thus, inductor looks like a short circuit as shown in Figure 2-6.

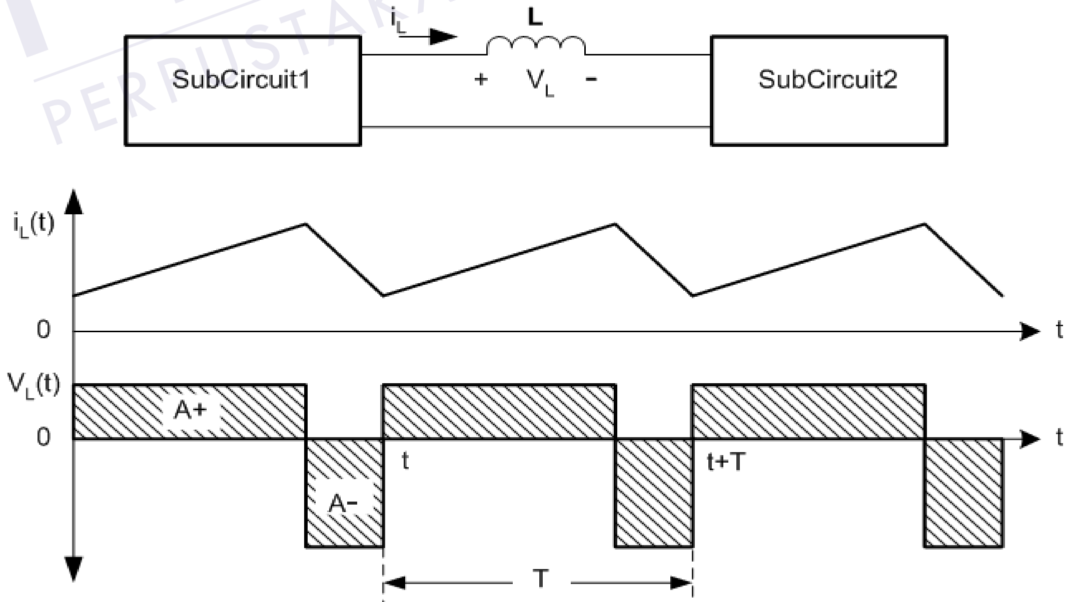

Figure 2-6 : Inductor current and voltage during short circuit.

2.5 THE OPERATION OF BUCK-BOOST CONVERTER

A buck-boost converter provides an output voltage that may be less than or greater than the input voltage hence the name „‟buck-boost‟‟‟; the output voltage polarity is opposite to that of the input voltage. This converter is also known as an inverting regulator. The circuit arrangement of a buck-boost convertor is shown in Figure 2-7.

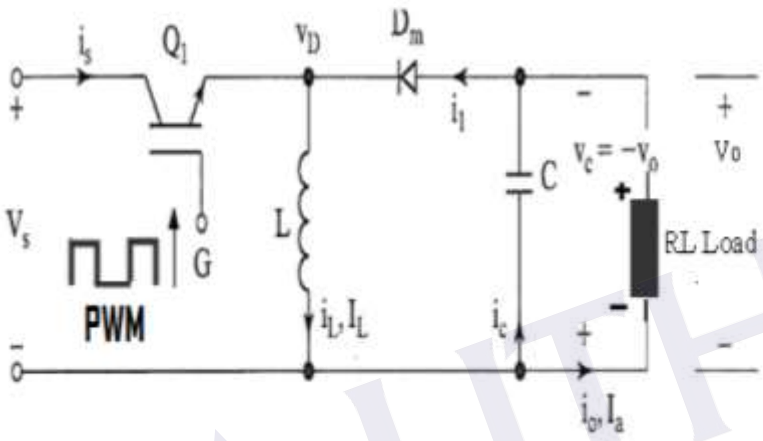

Figure 2-7 : Buck-Boost converter diagram

The circuit operation divided into two modes. During mode 1, transistor Q1 is turned on and diode D_m is reversed biased. The input current, which rises, flows through inductor L and transistor Q1. During mode 2, transistor Q1 is switched off and the current, which was flowing through inductor L, would flow through L, C, D_m, and the load. The energy stored in inductor L would be transferred to the load and inductor current would fall until transistor Q1 is switched on again in the next cycle. The wave-forms for steady-state voltages and currents of buck boost converter are shown in Figure 2-8

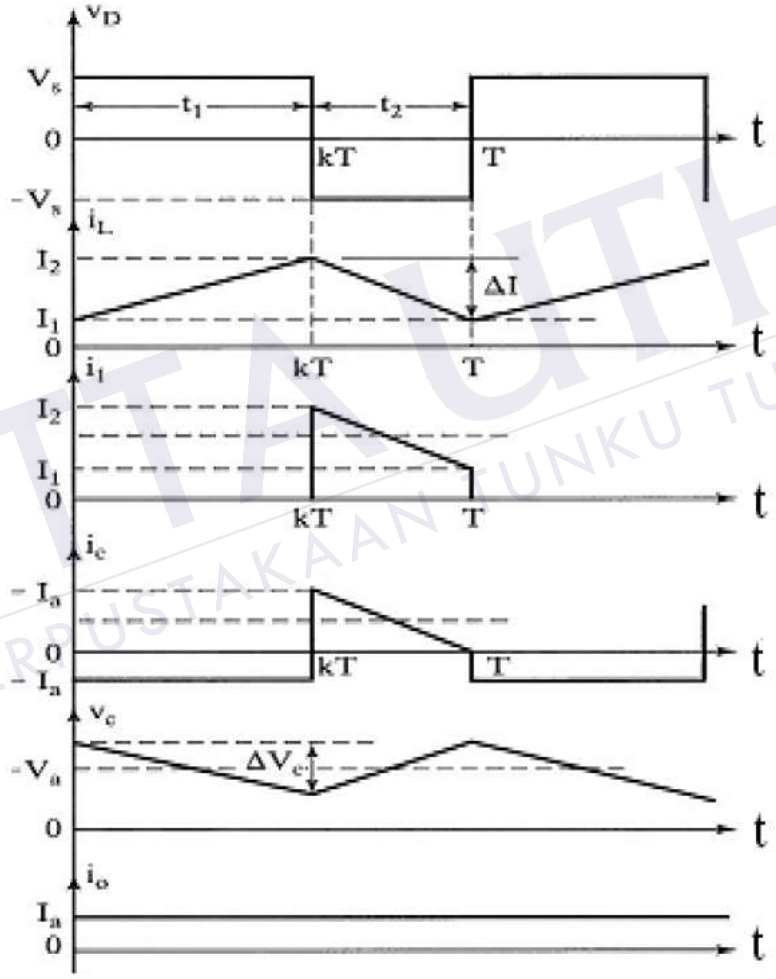

Figure 2-8 : waveforms of buck boost converter

The rate of change of inductor current is a constant, indicating a linearly increasing inductor current. The preceding equation can be expressed as

$$\Delta i_L/\Delta t = \Delta i_L/DT = V_s/L \tag{2.3}$$

Solving for Δi_L when the switch is closed

$$(\Delta i_L)_{closed} = V_s DT/L \tag{2.4}$$

Analysis for the switch open.When the switch is open; the current in the inductor cannot change instantly, resulting in a forward-biased diode and current into the resistor and capacitor. In this condition, the voltage across the inductor is

$$v_L = V_O = L\, di_L/d_t$$
$$di_L/dt = V_O/L \tag{2.5}$$

Again the rate of change of inductor current is constant, and the change in current is

$$\Delta i_L/\Delta t = \Delta i_L/(1-D)T = V_0/L \tag{2.6}$$

Solving for Δi_L,

$$(\Delta i_L)_{open} = V_0(1-D)T/L \tag{2.7}$$

For steady-state operation, the net change in inductor current must be zero over one period using Eqs.2.2 and 2.5,

$$(\Delta i_L)_{closed} + (\Delta i_L) = 0$$
$$V_s DT/L + (1-D)/L = 0 \tag{2.8}$$

Solving forV_O,

$$V_O = -(D/(1-D)) \tag{2.9}$$

Equation 2.7 shows the output voltage has opposite polarity form the source voltage. Output magnitude of the buck boost converter can be less than the source greater than the source, depending on the duty ratio of the switch. If D > 0.5, the output is larger than the input, and if D < 0.5, output is smaller than the input.

Note that the source is never connected directly to the load in the buck boost converter.

Energy is stored in the inductor when the switch is closed and transferred to the load when switch is open. Hence, the buck boost converter is also referred to as an indirect converter.

Power absorbed by the load must be the same as that supplied by the source,
Where

$$P_O = P_O^2/R \quad (2.10)$$

$$P_S = V_S I_S \quad (2.11)$$

$$V_O^2/R = V_S I^S \quad (2.12)$$

Average source current is related to average inductor current by

$$I_S = I_L D$$

Resulting in

$$V_O^2/R = V_S I_L D \quad (2.13)$$

Substituting for V_O using Eqe 2.7 and solving for

$$I_L = V_O^2/V_S DR = P_O/V_S D = V_S D/(1-D)^2 \quad (2.14)$$

Maximum and minimum inductor current is determined using Eqe 2.2 and 2.12

$$I_{max} = I_L + \Delta i_l/2 = V_S D/(1-D)^2 + V_S DT/(2L) \quad (2.15)$$

$$I_{min} = I_L - \Delta i_l/2 = V_S D/(R(1-D)^2 + V_S DT/2L \quad (2.16)$$

For continuous current, the inductor current must remain positive. To determine the boundary between continuous and discontinuous current I_{min} is set to zero in Eqe 2.14,

$$(LF)_{min} = (1-D)^2 R/2 \quad (2.17)$$

Or

$$L_{min} = (1-D)^2 R/2f \quad (2.18)$$

When F is switching frequency in hertz

Output voltage ripple

The output voltage ripple for the buck boost converter is computed from the capacitor current waveform

$$|\Delta Q| = (V_O/R) = C\Delta V_O \quad (2.19)$$

Solving for ΔV_O,

$$V_O = V_O DT/RC = V_O D/RCF \quad (2.20)$$

$$\Delta V_O/V_O = D/RCF \quad (2.21)$$

2.6 PID CONTROLLER

Most of the control techniques for DC motor controller 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. A proportional integral derivation controller (PID Controller) is a generic control loop feedback mechanism widely used in industrial control system. A PID is most commonly used feedback controller. 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. [4]

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 [3]. 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. Derivative can be a bad thing with a noisy signal. 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.

CHAPTER 3

METHODOLOGY

3.1 CIRCUIT DIAGRAM

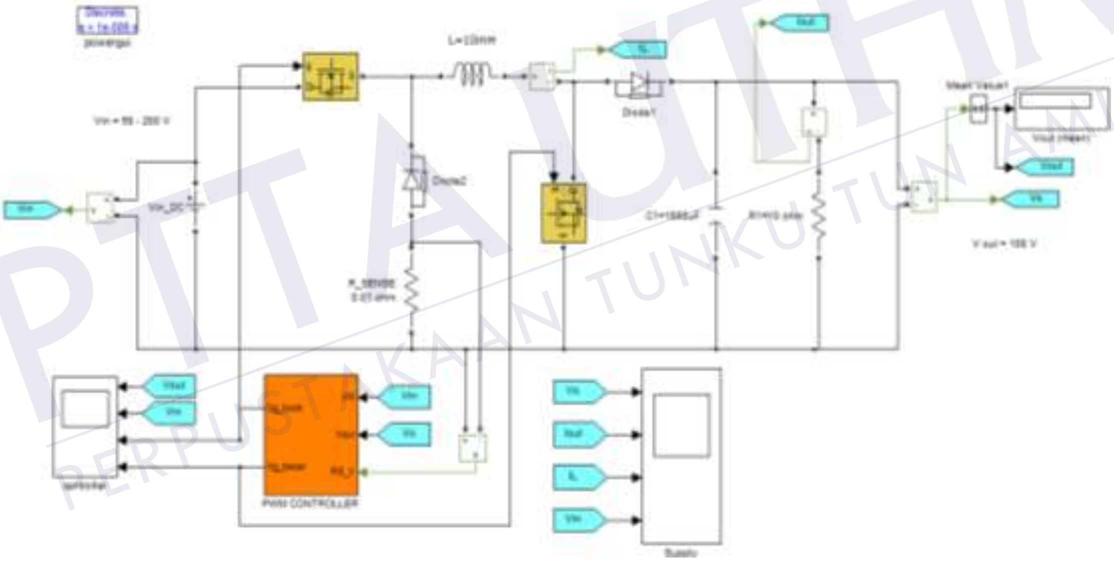

Figure 3-1 Buck-Boost Converter Circuit

Figure 3-1, show the circuit diagram used for simulation using Matlab/Simulink in this projec. Two MOSFET switch used to turn on/off the switching. The MOSFET also act as selector to select operation of converter either Buck Converter or Boost Converter depending on input givent.

For above circuit, if the input less then 100V it will operate as Boost Converter where give the higher output then supply input. If the input supply more then 100V up to 200V max, the circuit will operate as Buck Converter where output will reduced to targeted 100V. The converter parameter for the circuit is;

Table 1 : Circuit Parameter

No	Item	Parameter
1	Input Voltage (Vin)	50 – 200V
2	Output Voltage (Vout)	100V ±5%
3	Power (Pout)	1000W
4	Frequency (f)	10kHz
5	Inductor (L)	10 mH
6	Capacitor (Cout)	1000 μF
7	Rsense	0.01 Ω
8	Rsense	10 Ω

3.2 THE CONTROLLER

Traditional PWM controller where use switching on/off the MOSFET, may not good enought to perform in the current converter where the application required power converter to respond to demand. Figure 3-2, show the controller used for converter.

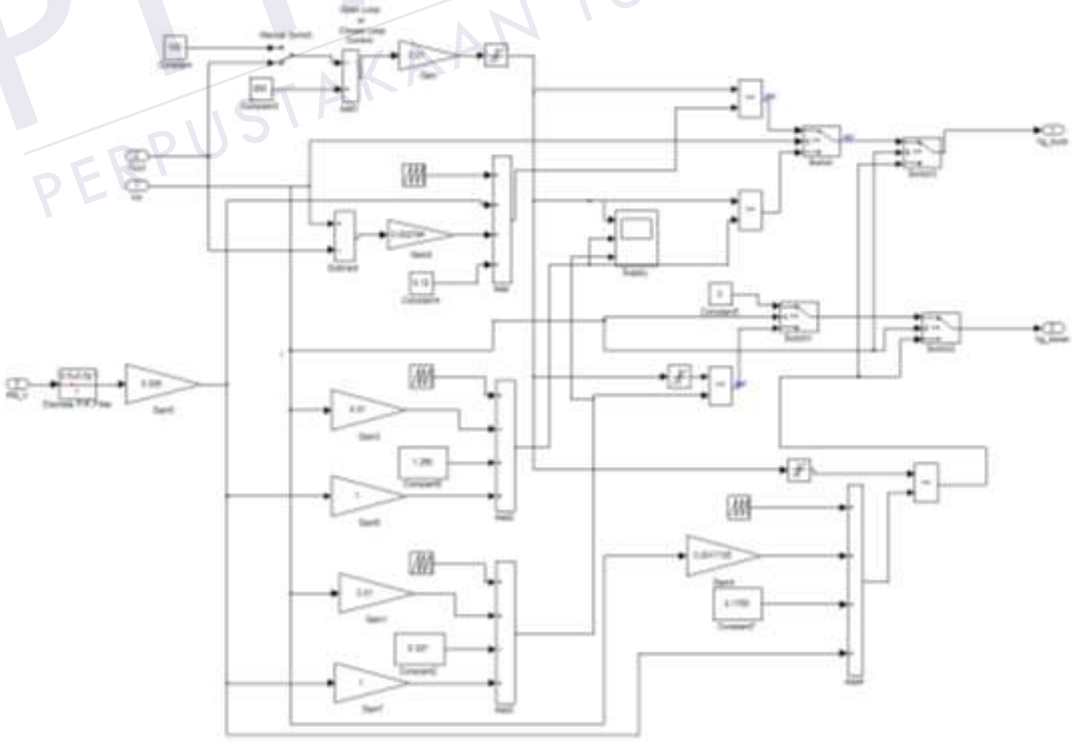

Figure 3-2 : PID Controller used for analysis

3.3 BUCK CONVERTER

The operation of the buck converter is fairly simple, with an inductor and two switches (usually a transistor and a diode) that control the inductor. It alternates between connecting the inductor to source voltage to store energy in the inductor and discharging the inductor into the load.

The buck converter, shown in Figure 3-3, converts the unregulated source voltage Vin into a lower output voltage Vout. The NPN transistor shown in Figure 1 works as a switch. The ratio of the ON time (*tON*) when the switch is closed to the entire switching period (T) is defined as the duty cycle D = to/T. The corresponding PWM signal is shown in Figure 3-5 .

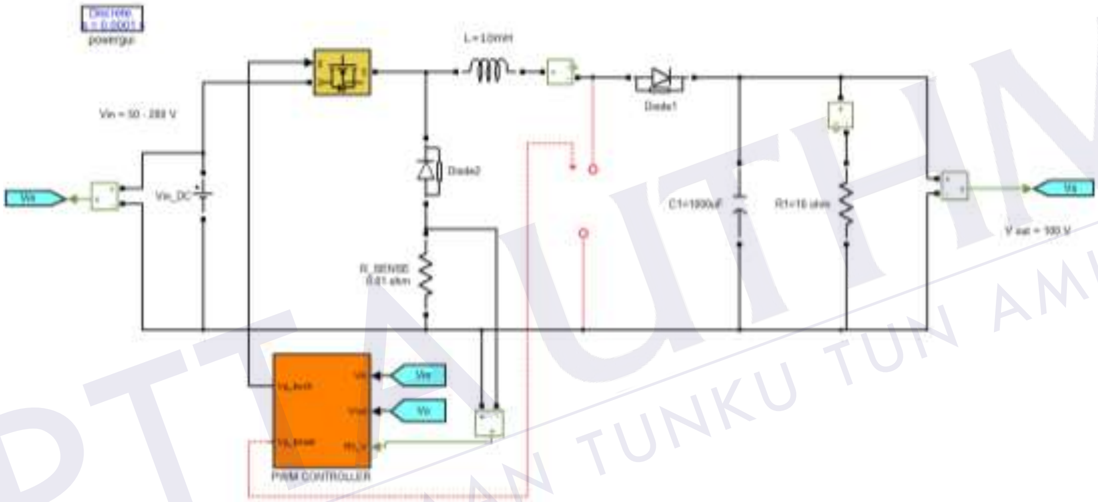

Figure 3-3 : Buck Converter Circuit

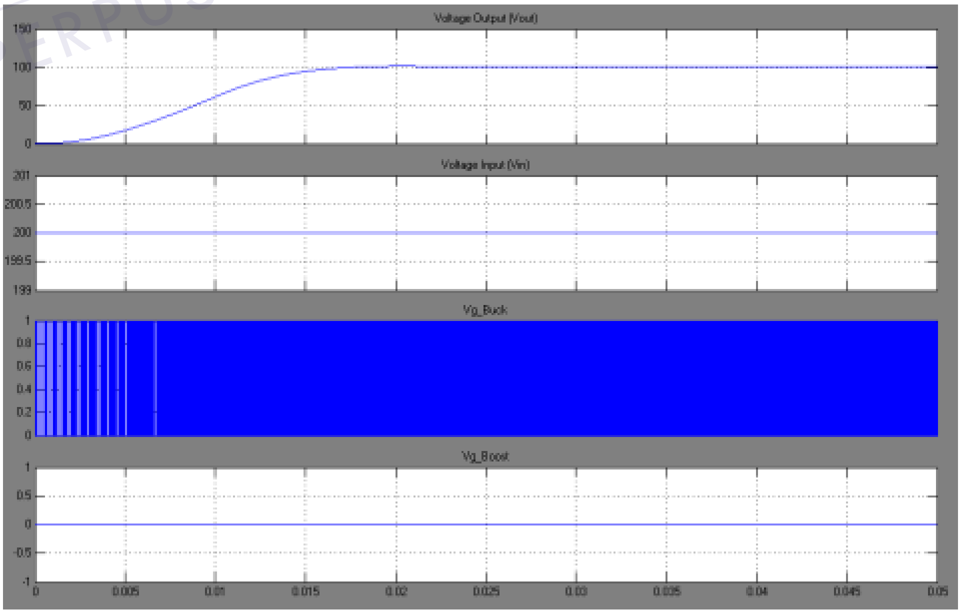

Figure 3-4 The Graph of Vout, Vin, Vg-Buck and Vg-Boost During Buck Operation

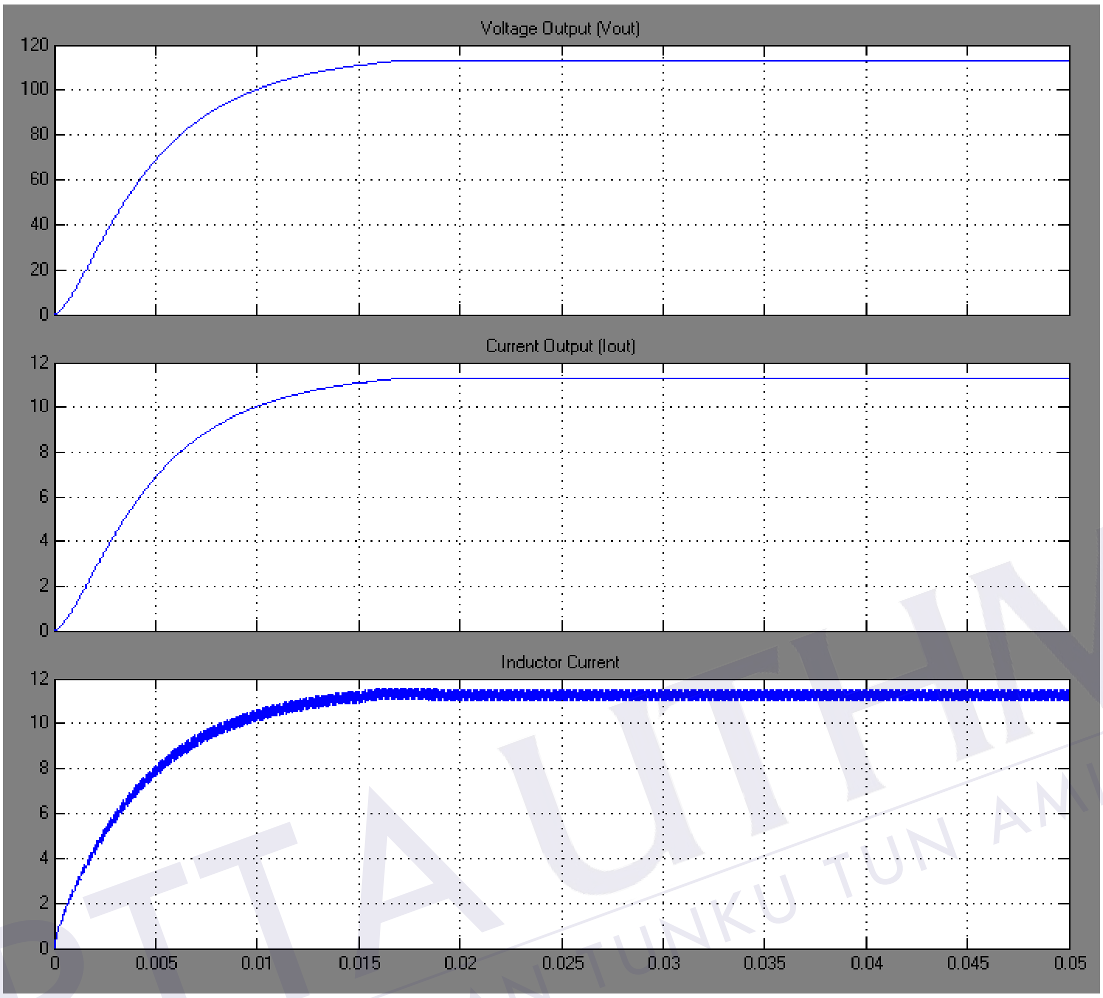

Figure 3-5 : Buck Operation - Voltage and Current Respond

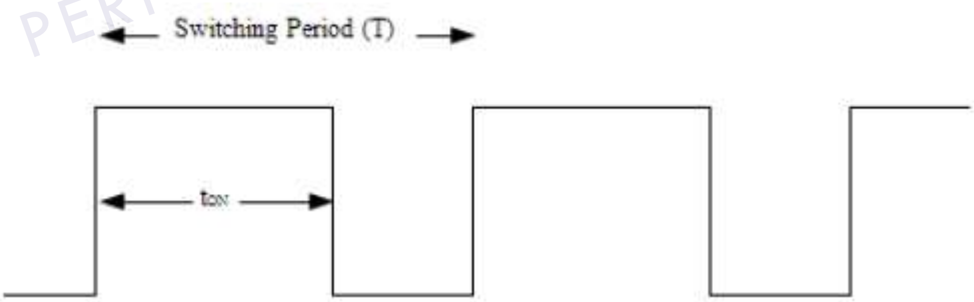

Figure 3-6 : PWM signal to control the switches in the DC-DC converter

The equivalent circuit in Figure 3-7 is valid when the switch is closed. The diode is reverse biased, and the input voltage supplies energy to the inductor, capacitor and the load. When the switch is open as shown in Figure 3-8, the diode conducts, the capacitor supplies energy to the load, and the inductor current flows through the capacitor and the diode [2]. The output voltage is controlled by varying the duty cycle. On steady state, the ratio of output voltage over input voltage is D, given by *Vout/ Vin.*

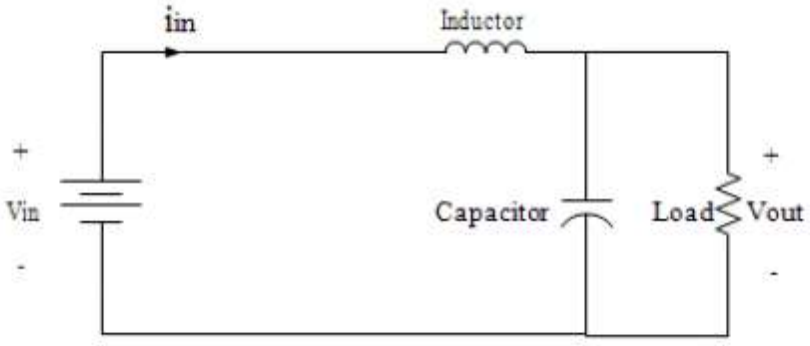

Figure 3-7 : Equivalent circuit of the buck converter when the switch is closed

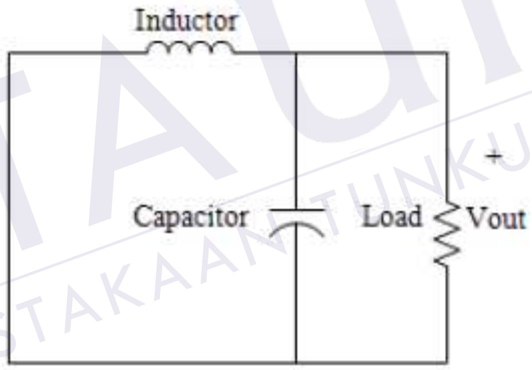

Figure 3-8 : Equivalent circuit of the buck converter when the switch is open

A buck converter is a step-down DC to DC converter. Its design is similar to the step-up boost converter, and like the boost converter it is a switched-mode power supply that uses two switches (a transistor and a diode), an inductor and a capacitor.

The buck converter reducing the dc voltage, using only nondissipative switches, inductors, and capacitors. The switch produces a rectangular waveform $v_s(t)$ as illustrated in Figure 3-5. The voltage $v_s(t)$ is equal to the dc input voltage V_g when the switch is in position *1*, and is equal to zero when the switch is in position 2.

In practice, the switch is realized using power semiconductor devices, such as transistors and diodes, which are controlled to turn on and off as required to perform the function of the ideal equal to the inverse of the switching period T_s, generally lies in the range of switching speed of the semiconductor devices.

The duty ratio D is the fraction of time which the switch spends in position 1, and is a number between zero and one. The complement of the duty ratio, D', is defined as (1-D) [2].

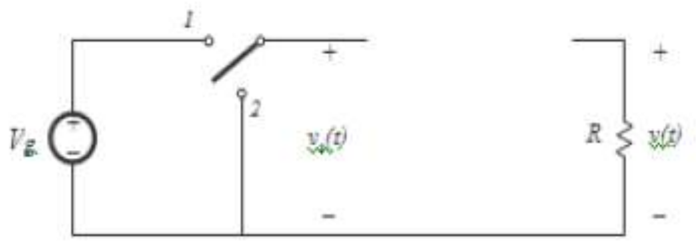

Figure 3-9 : Ideal switch, (a) used to reduce the voltage dc component

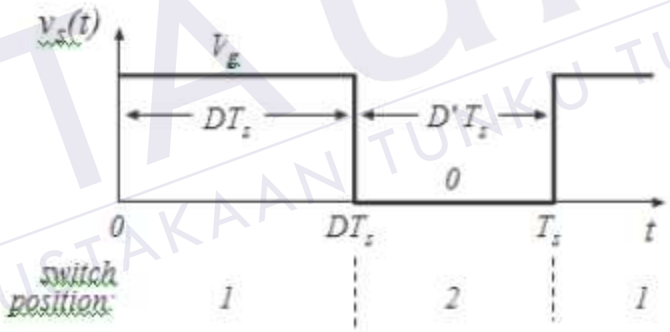

Figure 3-10 : (b) its output voltage waveform vs(t).

The switch reduces the dc component of the voltage: the switch output voltage $v_s(t)$ has a dc component which is less than the converter dc input voltage V_g. From Fourier analysis, we know that the dc component of $v_s(t)$ is given by its average value $<v_s>$, or

$$< Vs> = \frac{1}{Ts}\int_0^{Y} Vs(t)dt \qquad (3.1)$$

As illustrated in Figure 3-11, the integral is given by the area under the curve, or DT_sV_g. The average value is therefore

<Vs> = $\frac{1}{Ts}(DTsVg) = DVg$ (3.2)

So the average value, or dc component, of *vs(t)* is equal to the duty cycle times the dc input voltage *Vg*. The switch reduces the dc voltage by a factor of *D*.

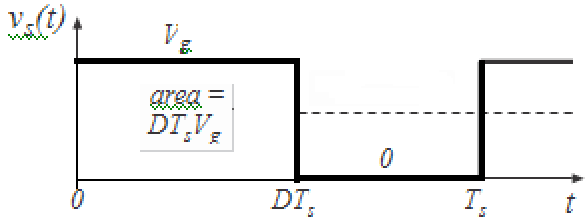

Figure 3-11 : Output voltage dc component by the switching period.

What remains is to insert a low-pass filter as shown in Figure 3-12. The filter is designed to pass the dc component of *vs(t)*, but to reject the components of *vs(t)* at the switching frequency and its harmonics. The output voltage *v(t)* is then essentially equal to the dc component of *vs(t):*

V<Vs>=DVg (3.3)

The converter of Figure 3-11 has been realized using lossless elements. To the extent that they are ideal, the inductor, capacitor, and switch do not dissipate power. For example, when the switch is closed, its voltage drop is zero, and the current is zero when the switch is open. In either case, the power dissipated by the switch is zero. Hence, efficiencies approaching 100% can be obtained. So to the extent that the components are ideal, we can realize our objective of changing dc voltage levels using a lossless network.

The network of Figure 3-12 also allows control of the output. Figure 3-13 is the control characteristic of the converter. The output voltage, given by equation (3.3), is

plotted vs. duty cycle. The buck converter has a linear control characteristic. Also, the output voltage is less than or equal to the input voltage. Feedback

systems are often constructed which adjust the duty cycle D to regulate the converter output voltage. Inverters or power amplifiers can also be built, in which the duty cycle varies slowly with time and the output voltage follows [3].

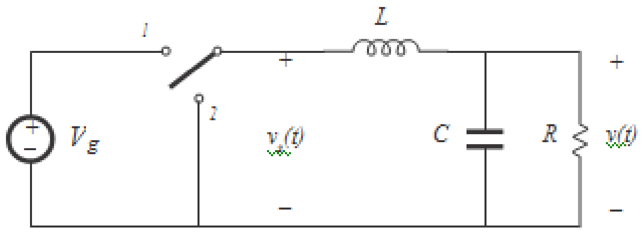

Figure 3-12 : Insertion of low-pass filter, to remove switching harmonics and pass only the dc component of *vs(t)* to the output.

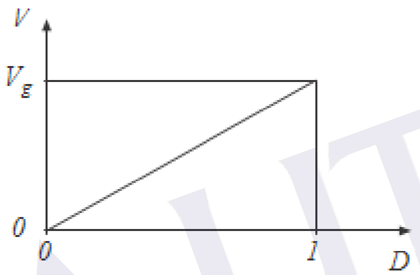

Figure 3-13 : Buck converter dc output the voltage V vs. duty cycle D.

3.4 MODE OF OPERATION

The operation of dc-dc converters can be classified by the continuity of inductor current flow. So dc-dc converter has two different modes of operation that are

(a) Continuous conduction mode (CCM) and

(b) Discontinuous conduction mode (DCM).

A converter can be design in any mode of operation according to the requirement.

3.4.1 CONTINUOUS CONDUCTION MODE

When the inductor current flow is continuous of charge and discharge during a switching period, it is called Continuous Conduction Mode (CCM) of operation shown in figure 2.12(a). The converter operating in CCM delivers larger current than in DCM.

3.4.2 DISCONTINUOUS CONDUCTION MODE

When the inductor current has an interval of time staying at zero with no charge and discharge then it is said to be working in Discontinuous Conduction Mode (DCM) operation and the waveform of inductor current is illustrated in figure 3-10(c). At lighter load currents, converter operates in DCM. The regulated output voltage in DCM does not have a linear relationship with the input voltage as in CCM.

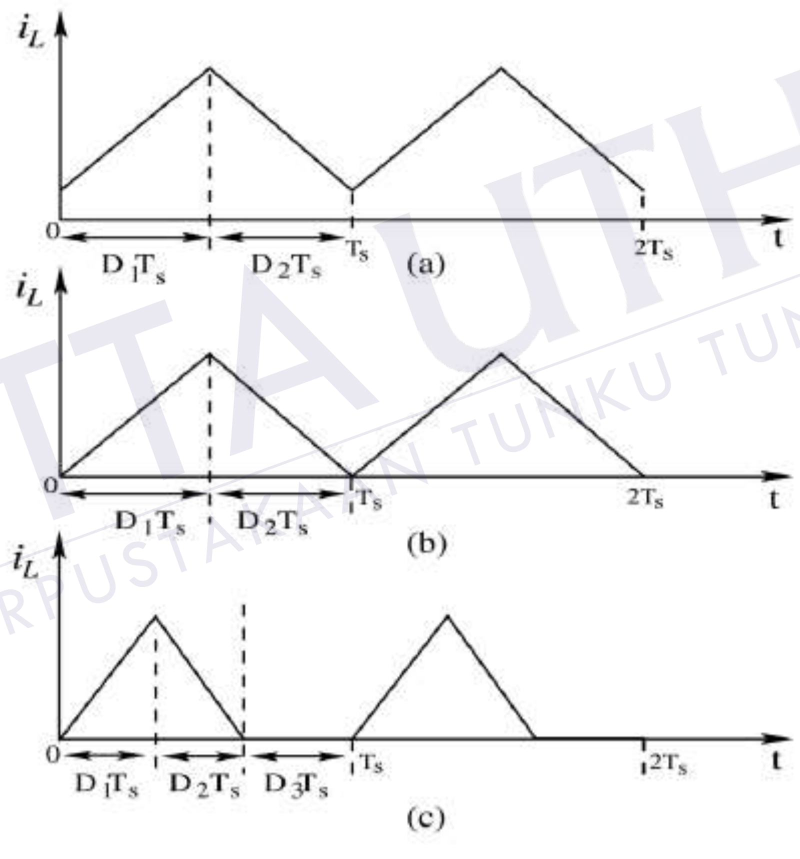

Figure 3-14 : Inductor current waveform of PWM converter
(a) CCM (b) boundary of CCM and DCM (c) DCM

REFERENCES

[1] H. R. Muhammad, Power Electronics Circuit, Devices and Applications, Florida: Computer Engineering University of West Florida, 2004.

[2] U. R. Mohan, dalam *Power Electronics Converter Application and Design*, John Wiley & Son, Inc, 2003, pp. 231-303.

[3] J. a. R. L.Guo, "PID Controller Modification to Improve Steady-State Performance of Digital Controller for Buck and Boost Converters," dalam *Conference Proceeding of IEEE Applied Power Electronics Conference and Exposition, pp. 381-388, Feb 2002*, 2002.

[4] S. H. B. Jamali, "Voltage Tracking of DC-DC Boost Converter Using Gaussian Fuzzy Lofic Controller," Universiti Tun Hussein Onn Malaysia, Batu Pahat, 2012.

[5] A. S. Weddell, "Photovoltaic Sample-and-Hold Circuit Enabling MPPT Indoors for Low-Power Systems," *IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS*, vol. 59, p. 1196, 6 June 2012.

[6] N. Abd Malek, A. R. Abd Rahman, H. B. Hasini dan M. N. Mohd Jaafar, "An Improved Solar PV System for Malaysian Rural Electrification," dalam *2010 IEEE Student Conference on Research and Development (SCOReD 2010),*, Putrajaya, Malaysia, 2010.

[7] G. Y. a. P. A.Perry, "A New Design Method for PI-Like Fuzzy Logic Controller for DC-DC Converters," dalam *35th Annual IEEE Power Electronics Specialists Conference*, Aache, German, 2004.

[8] M. K. K. T. a. P. S. M. Ahmed, "Implementing Sliding Mode Control for Buck Converter," dalam *IEEE 34th Annual Power Electronics Specialist Conference, Vol. 2, pp. 634-637m June 2003*, 2003.

[9] G. a. D.Divan, "Discreat Time Integral Sliding Mode Control for Discreate Pulse Modulated Converters," dalam *21st Annual IEEE Power Electronics Specialist Conference, pp.67-73, June 1990*, 1990.

[10] Z. H. G. a. X. Q.Hu, “Application of Sliding Mode Control in Control of Power Electronics Converters,” dalam *Proceeding 5th International Conference on Electrical Machines and System, Vol.42, No.2, pp.117-122, April 2001*, 2001.

[11] Y. a. A. W.Gao, “Discreat-Time variable Structure Control System,” dalam *IEEE Transaction on Industrial Electronics, Vol.42, No.2, pp.117-122, April 1995*, 1995.

[12] J. O. a. M. J.Matas, “Discreat Sliding Mode Control of Boost Converter for Output Coltage Tracking,” dalam *8th International Conference on Power Electronics and Variable Speed Drives, pp.351-354, Sep 2000*, 2000.

[13] L. a. G. P.Mattevelli, “General Purpose Sliding Mode Controller for DC/DC Converter Application,” dalam *24th Annual IEEE Power Electronics Specialist Conference, pp.609-615, June 1993*, 1993.

[14] M. N. M.A, “Voltage Tracking of A DC-DC Converter Using Neural Network Control,” Universiti Tun Hussein Onn Malaysia; Master's Thesis, 2012.

[15] S. H. Jamali, “Voltage Tracking of DC-DC Converter Using Gaussian Fuzzy Logic Controller,” Universiti Tun Hussein Onn Malaysia, Master's Thesis, Batu Pahat, Johor, 2012.