INVESTIGATE AND SIMULATE DC/DC BUCK REGULATOR BY USING LTSPICE

MOHD SHARIMIN BIN RASHID

UNIVERSITI SAINS MALAYSIA

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by

MOHD SHARIMIN BIN RASHID

Thesis submitted in partial fulfilment of the requirements for the degree of Bachelor of Engineering (Electronics Engineering)

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Abbreviations

SMPS	Switching-Mode Power Supply
HSS	High Side Switch
LHS	Low Side Switch
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PWM	Pulse Width Modulation
EMI	Electromagnetic Interference
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction Mode
VCVS	Voltage Control Voltage Source
DC	Direct Current
S_1	Switch 1
S_2	Switch 2
C_o	transistor output capacitance, Farad
D	duty cycle
C	total capacitance, Farad
E	energy stored in capacitors, Joule
L	inductance, Henry
I_{in}	input current, Ampere
I_{out}	output current, Ampere

V_{in}	input voltage, V
V_{out}	output voltage, V
P_{in}	input power, Watts
P_{out}	output power, Watts
η	power efficiency
Fs	switching frequency
Dt	duty cycle
D1	diode 1
T	period

Abstract

This paper presents an investigation and simulation of DC/DC buck converter by using LTspice. Buck converter is a converter that is capable of lowering input voltage as an output voltage. Pulse Width Modulation (PWM) signal with constant duty cycle to drive the switch of the converter. Instead of using the conventional buck converter, this project will replace the normal diode to Schottky's diode and SMPS. The minimum size of inductor is calculated and the minimum value for the capacitor is calculated and simulated without affecting the circuit overall performance. The buck converter are made of several sub circuit such as comparator, voltage reference, SMPS and ramp voltage. Every sub-circuit are simulated separately and then as a whole. The author also present the simulation results and discussion (in Chapter 4) related to the theoretical aspects. Results shows that the DC/DC buck converter is able to maintain its load current at 1mA and load voltage of 1.32V at input voltage of 1.4V to 6V. The efficiency of the circuit according to the given limit of input voltage is more than 70%.

Abstrak

Penulisan ini membentangkan reka bentuk dan simulasi terhadap DC/DC penukar rendah dengan menggunakan perisian LTspice. Penukar rendah ini adalah penukar yang mampu menurunkan voltan tinggi yang masuk ke litar kepada produk voltan yang lebih rendah. *Pulse Width Modulation* (PWM) dengan kitar tugas yang tetap untuk memacu suis penukar. Daripada menggunakan penukar rendah yang biasa, projek ini telah menggantikan diod biasa kepada diod Schottky yang berada dilam litar penukar rendah. Kadar upaya minima saiz induktor dan upaya minima kapasitor telah diambil kira tanpa menjejaskan upaya sirkit. Penukar rendah telah dihasilkan dengan hasil gabungan komparator,rujukan voltan, SMPS dan voltan tanjakan. Setiap litar kecil di simulasi berasingan dan seterusnya secara menyeluruh. Penulisan juga membentangkan hasil simulasi dan diskusi di *Chapter 4* di mana berkenaan dengan aspek-aspek teori. Hasil simulasi menunjukkan DC/DC penukar rendah mampu mengekalkan *load current* di paras 1mA dan voltan keluar di 1.32V dalam linkungan voltan masuk dari 1.4V sehingga ke 6V. Kecekapan litar mengikut had voltan masuk adalah lebih dari 70%.

Chapter 1

Introduction

This chapter will review on the basic of a buck converter and its applications.

1.1 Research Background

In the foundations of circuit theory, every engineer especially from electronic and electrical courses is exposed to the three basic components that make up from a simple electronic circuit to a very complex electronic circuit. Those components are resistor, inductor and capacitor. As technology bloom worldwide, there are more electronic devices integrated for variation of usage such as transistors, diodes operational amplifiers and integrated circuits (IC).

As time escalated, nanotechnology (nanotech) is introduced to worldwide and results in smaller electronic circuits with the ability to accommodate a wide range of applications such as personal computer (laptops), mobile phone, audio and video systems. In short, electronic devices is something we have been using throughout our daily life. Powering up or charging up an electronic device is normally can be done in two ways.

Usually a consumer can get the power directly from Tenaga Nasional Berhad which is the local power provider and the other method is portable power source such as battery. Battery comes in many shapes and sizes and depending on the application, it could be an AA size alkaline battery, a polymer lithium-ion battery or a lead acid battery.

Due to high fast transient in battery voltage, a stable output operation is very demanding to operate with high efficiency. Thus, step-down (buck) DC/DC converter has its spot on electronic industrial market. With a buck regulator, power is stored in the inductor results in higher efficiencies. The highest efficiencies can be >97% with very low losses. With these nature, buck converter is able to extend a battery life.

For the sake of better understanding theoretical knowledge on custom design processes of IC, an investigation on DC converter regulator is selected for the final year project. The design is based on variety of the state-of-the-art published structures, designed and simulated result can achieve by using LTspice software from Linear Technology.

1.2 Problem Statement

Analog technology has been successfully engage in controlling voltage regulator, especially DC/DC converter. Apart from being successful, analog technology been having trouble to run buck converter operation (switching control). Digital technology is highly recommendable to replace the analog technology in order to improve its efficiency. This project will investigate the efficiency of the buck regulator by using control logic.

1.3 Objectives

The purpose of this project is to investigate and simulate a dc regulating circuit that is capable of regulating a certain range of input with a constant output by using a different type of DC/DC buck converter circuit. First is to study about the switching mode power supplies, ramp generator, operational amplifier and comparator at 100kHz switching frequency. Another purpose is to reduce the inductor size and capacitor size without affecting the circuit performance.

1.4 Research Scope

The purpose of this project is to investigate and simulate a load and line regulation at 1mA load current with 100kHz switching frequency. The proposed circuit consists of voltage reference circuit, switching transistors circuit, ramp generator circuit, operational amplifier circuits and comparator.

In crucial objective of this project is to investigate and simulate power regulator IC by using LtSpice. There are several considerations which would define the research scope.

a) Conceptual system design.

b) Subsystem design of all circuits.

c) Schematic design for all subsystem.

d) Netlist extraction of the schematic design to generate LTspice netlist.

e) Every subsystems are to be simulated by using LTspice and then the system as a whole.

f) Assessment of the results and further improvement or modification if required.

LTspiceXVII

- LTspice is a high performance SPICE simulator, schematic capture and waveform viewer with enhancements and models for easing the simulation of switching regulators.

1.5 Thesis Outline

The report is organized into 3 chapters which are the introduction, literature review and methodology.

Chapter 1 gives an overview of the project. It begins with a quick introduction to the research background, followed by the problem statement, project objectives, research scope and thesis outline.

Chapter 2 gives an overview on the prior work and literature review. Next, it introduces the theory of low dropout voltage regulator and the best topologies is chosen that offers low dropout voltage, small output droop, fast load regulation, and small silicon area in this project.

Chapter 3 describes the chosen circuitry and topologies and the project specification and methodology used.

Chapter 4 shows the simulation results of every sub-circuit and a circuit as whole as well as calculating the minimum inductor and capacitor size.

Chapter 5 gives you the conclusion of the circuit and future work that could be done.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents the information of the research before start this project. There are some concepts that will be a huge aid and need to apply to this project. A DC/DC voltage regulator need a high capacitance with good electrical properties is required to regulate output voltage effectively. Hence, this chapter will be discussing on every possibility of electronic devices and components that is necessary to satisfy the above conditions.

2.2 Capacitors

Capacitor is a passive electronic component that is capable of storing electrical energy by storing charges. It consists of two conducting plates often in the form of metallic plates separated by a non-conducting commonly known as dielectric. By applying a potential difference, electric charge is stored on the plates and energy is stored in the electric field. The effect of a capacitor is also known as capacitance. Capacitors are widely used in electronic circuits for blocking direct current while allowing alternating current to flow. In other words, they stabilize voltage and power flow [1].

2.2.1 Total Capacitance and Total Energy Stored

Capacitors can be connected in several ways which are series and parallel or combination of both. During circuit analysis, total capacitance, C is more concerned. Apart from that is the energy, E stored in the capacitors is also important for analysis."Large overshoots are caused by insufficient output capacitance, and large voltage ripple is caused by insufficient capacitance as well as a high equivalent series resistance (ESR) in the output capacitor [8]."

Capacitors in series :

$$C = \left(\frac{1}{C1} + \frac{1}{C2} + \cdots + \frac{1}{Cn}\right)^{-1}$$

Capacitors in parallel :

$$C = C_1 + C_2 + \ldots + Cn$$

Where,

$$E = \frac{1}{2} CV^2$$

E = Energy stored in capacitors, Joule

C = Total capacitance, Farad

V = Applied voltage, Volt

2.2.2 Types of Capacitors

Capacitors can be varies in the electronic market according its specification and capabilities. The common capacitors in the market are tantalum, ceramic, conductive polymer, aluminium electrolytic, electric double layer and lithium-ion capacitors.

Table 2.1 Types of capacitors

Type of capacitors	Capacitance range (Farad)	Description
Tantalum	0.1 - 680µF	• Either in a form of solid capacitor or electrolytic capacitor. • Used in electronic devices including portable telephones, pagers, personal computers, and automotive electronics.
Ceramic	0.1pF - 27.2µF	• Ceramic material acting as the dielectric • High capacity and small size at low price compared to other low value capacitor types
Conductive polymer	1.7µF - 3500µF	• Electrolytic capacitor • In between the positive and negative electrode, there are a dielectric medium and a solid electrolyte. • Since it is not liquid electrolyte, it will not dry out, leak, or burst.
Aluminium Electrolytic	0.1 µF - 68000µF	• Larger capacitance per unit volume than other types above
Electric double-layer	0.25F - 3000F	• Popularly named as supercapacitor or ultacapacitor. • Very high capacitance but with much lower working voltage.

		• Available in single cells or in modules.
Lithium ion	1100F-2200F	• Activated carbon is used as cathode while anode consists of carbon material which is pre-doped with lithium ion. • Higher working voltage and energy density than electric double layer.

2.2.3 Comparing of Capacitors

One of the main differences between capacitor types is the frequency band they are good for. For instance, ceramic and mica capacitors are good at very high frequencies and electrolytic capacitors have the highest capacitance per unit volume.

Table 2.2: List of compared capacitors

Name	PowerBurst	Ultimo	Illinois
Type	Electric double-layer	Lithium Ion Capacitor	Electric double-layer
Capacitance (Farad)	100	1100	100
Tolerance (%)	-20 to +20	-	-10 to +30
Voltage Rating (Volt)	2.7	3.8	2.7
Energy Density (Wh/kg)	-	12	4.82
Dimension (LxD or LxWxH in mm)	45x22	138x106x4.5	45x22
Operating Temperature (°C)	-40 to +65	-20 to +70	-40 to +65

2.3 Inductors

Inductor is a part of low-pass filter design in order to remove ripples at the output voltage of buck converter. It has two main tasks:

1) "Limiting the current slew rate through power switches" which yields limiting in the peak current. This action reduces power loss in the circuit [9].
2) The main advantage of employing inductor in switching mode power supply is "Storing energy" [9].

2.4 MOSFETs

MOSFET (Metal-Oxide-Semiconductor Field Effect Transistor) is a voltage controlled device that only requires a small input current to run or operate. To be more precise, a power MOSFET is designed to handle a large amount of voltage or power. The switching speed of MOSFET is very high and the switching time are in the order of nanoseconds. There are two types of MOSFETs, known as n-channel MOSFET and p-channel MOSFET. From these two types of MOSFETs, each of it is available in either enhancement-mode or depletion-mode. In comparison, enhancement-mode MOSFETs are used widely than depletion-mode MOSFETs. 8 A typical MOSFET comprises of three terminals which are drain (D), gate (G) and dource (S). Figure 2.1 below shows the types of MOSFET and its characteristics due to applied gate (G) voltage. The source (S) terminal for each MOSFET in the figure is grounded in the circuit and not labelled.

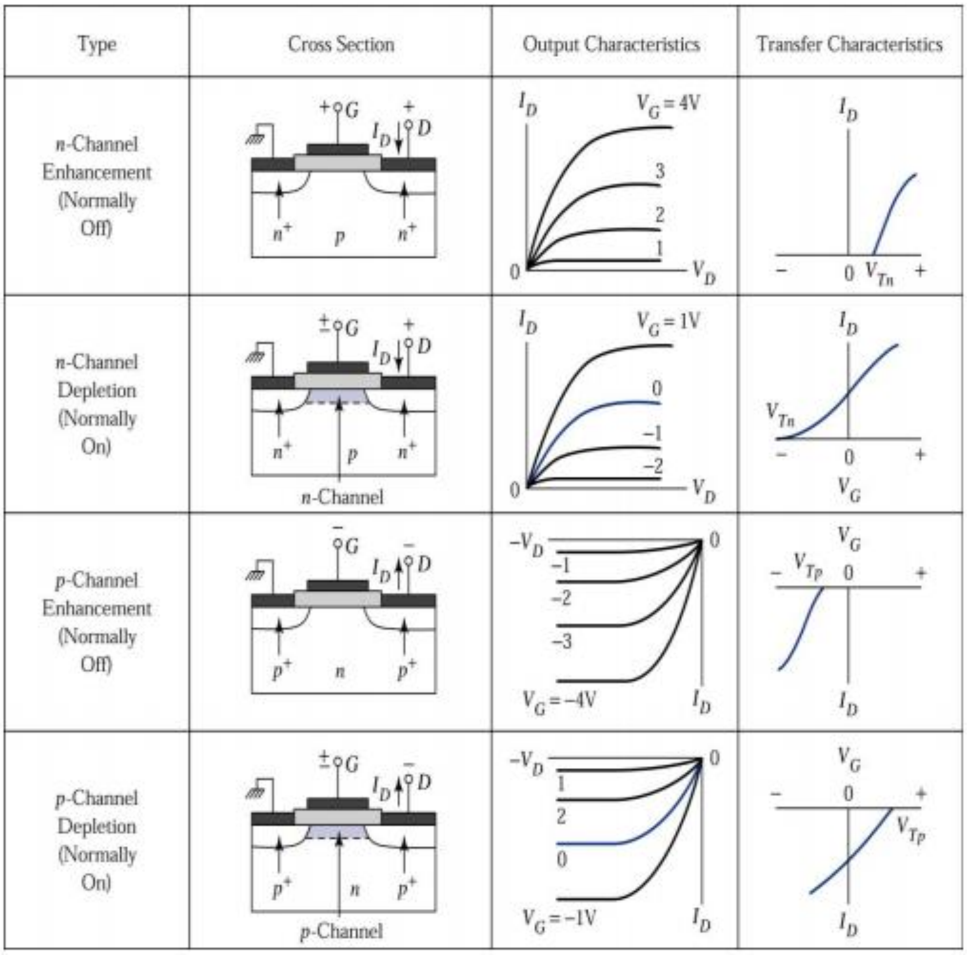

Figure 2.1 Types of MOSFET

Power MOSFET is widely used in low voltage (less than 200V) application or switch. Usually, it can be found in the most power supplies, DC-DC converter and low voltage controllers. The gate (G) of a MOSFET is like a programmable integrated circuit (PIC) or a timer because of its pulses behaviour.

2.5 Methods for DC/DC Conversion

There are several methods can be used in regulating the unregulated DC voltage to a desired regulated DC voltage regardless of any changes in input voltage. In this chapter we are highlighting on switched-mode power supply (SMPS) and linear regulators and explain both advantages and disadvantages.

2.5.1 Linear Regulator

Linear regulator is a type of regulator that has no switch. The regulated output voltage is solely based on the design of potential divider.

1) Linear regulator has two main parts which are variable resistance in series with output load [3].

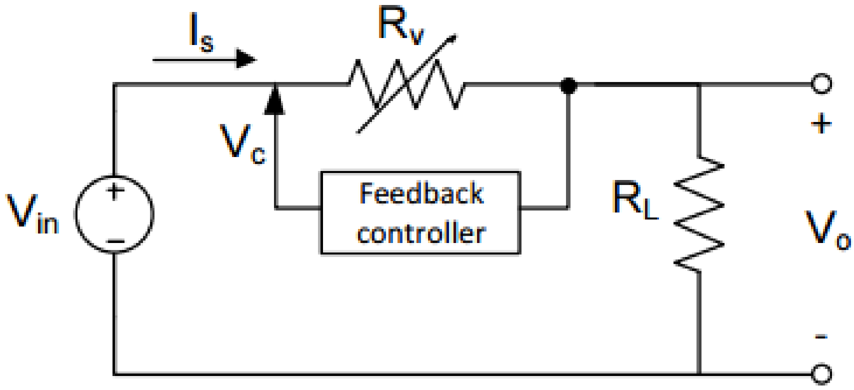

Figure 2.2 Diagram of a linear regulator [25]

2) Voltage controlled current source (VCCS) is the control part of the regulator. It sense the output voltage V_o and regulates the current source I_s to maintain a constant value of output voltage so that it is equal to the voltage reference V_{ref} .

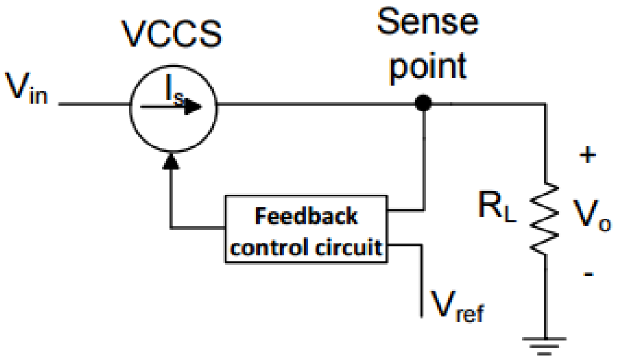

Figure 2.3 Simple linear regulator [10]

Linear regulator operates relentlessly which will results in lesser efficiency as compares to switching regulator. Moreover, it produces more heat than any regulators especially compared to SMPS. The greater the difference between input and output, more heat will produced which might requires an expensive heat-sinks.

2.5.2 Switching-Mode Power Supply

SMPS is widely known as switch DC/DC regulator. From its name, it uses switches (often are transistors) and as well very low loss components such as capacitors, inductors and transformers for regulating output voltage [3]. Same as linear regulator, SMPS also has two main parts which are the control part and power stage. In order to get a better regulation of output voltage, most of the work is done by designing control part.

The typical switch in SMPS is MOSFET which is as a power switch for stabilizing output voltage. Unlike linear regulator, the switch in SMPS is not continuously and they operates under specific frequency. With that features, SMPS is good for extending a battery life by reducing power loss.

SMPS can be design as a step-down converter and as a step-up converter of DC input voltage. Common characteristic of SMPS is its capabilities to suppress large ripples due to switching.

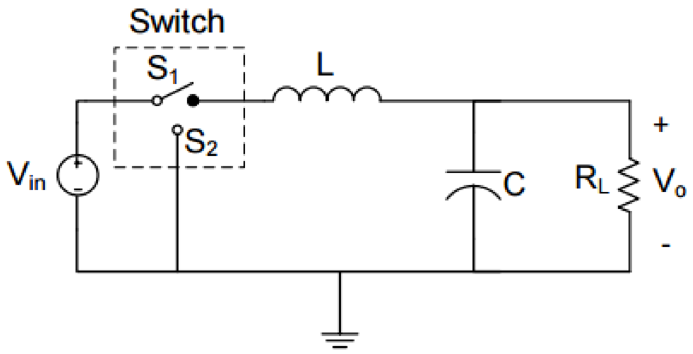

Figure 2.4 Switching-mode power supply

2.6 Linear Regulator vs Switching Regulator

The following judgements are about why the switching regulator is a better choice than linear regulator.

1) High voltage efficiency

Due to potential divider concept that been used by linear regulator, the circuit will heat up and need a heat-sink to regulate its temperature. While SMPS uses switching method (based on duty cycle) to regulate extra power loss. The power loss is lesser compared to linear regulator.

Power efficiency for both linear regulator and SMPS can be expressed by using the following equation 2.1.

$$\varepsilon = \frac{Pout}{Pin} = \frac{Vout.Iout}{Vin.Iin}\ \% \qquad \text{(Eq. 2.1)}$$

P_{out} = Output power

P_{in} = Input power

V_{out} = Output voltage

V_{in} = Input voltage

I_{out} = Output current

I_{in} = Input Current

Since I_{out} is equal to I_{in} ,($I_{out} = I_{in}$) for linear regulator thus, Eq. 2.1 can be simplified into new equation which is Eq. 2.2. for a linear regulator.

$$\varepsilon = \frac{Vout}{Vin} \% \qquad \text{(Eq. 2.2)}$$

The efficiency of a linear regulator is related to the power drop across resistor. Therefore the higher the power drop the lower the efficiency of a linear regulator which will be results in shortened battery life [30].

2) Versatility

SMPS can be a step-up (boost) regulator and step-down (buck) regulator. This is due to the energy stored inside the output inductor. If it has greater power than the input it is a boost regulator whereas if the stored energy is low and has lower power than the input it is called a buck regulator. Unlike linear regulator which only able to step-down the input voltage.

3) SMPS liabilities

Since the SMPS has a complicated feedback control loop for energy management despite of being smaller than a linear regulator, it causes drawbacks for SMPS in terms of overall cost of the power supply and makes it more expensive than a linear regulator.

Due to high efficiency is switching because of the fast transitions of current and voltage it will invites an interference (noise). Rapid voltage changes at the inductor node leads to radiated electric fields, while fast-changing inductor current produces magnetic fields [30]. An extra LC filter is needed to filter out the ripples at output voltage.

2.7 DC/DC Buck Converter

As the name suggests, the step-down or buck converter converts a higher input voltage into a stabilized lower output voltage. Switch controller block and power block are two main parts of buck converter's circuit. "It can operate in Continuous Conduction Mode (CCM) or in Discontinuous Conduction Mode (DCM), depending on the waveform of the inductor current [5]". Figure 2.6 given below is a simplified circuit diagram with the main current and voltage waveforms.

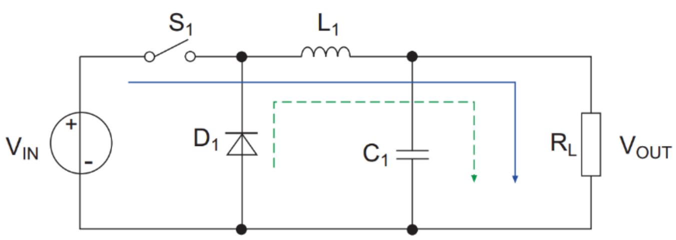

Figure 2.5 Simple buck converter

——— Current Flow, S_1 closed

- - - - - Current Flow, S_1 open

$$V_{OUT} = V_{IN} \frac{t_{ON}}{T} = \delta V_{IN}, \quad \textit{valid when } V_{IN} > V_{OUT}$$

The most straightforward way to understand this circuit is to assume that L1 and C1 are combining into a low pass filter. When switch S1 is closed, the potential difference from L1 is charging up the capacitor. If S1 is then opened, the energy stored in the magnetic field of the inductor will discharge into the capacitor and load [10]. This will results in decreasing voltage level at the load. The average output voltage is then the mark ratio of the PWM control signal multiplied by the input voltage.

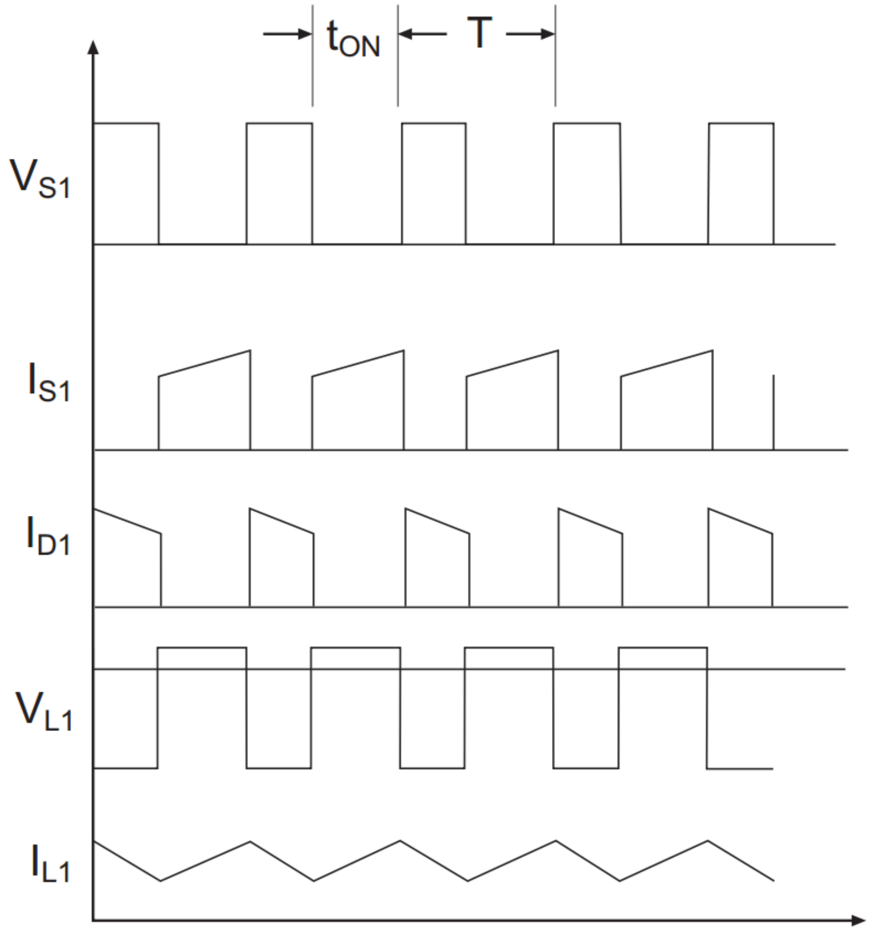

Figure 2.6 Buck Regulator Simplified Schematic and Characteristics

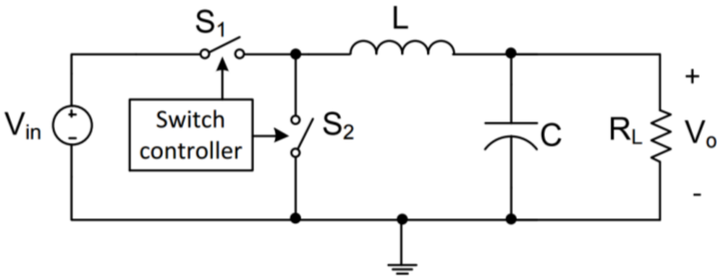

Figure 2.7 Buck converter circuit with replacement of diode

For this buck converter, it has two switches which are S1 and S2 which is for high side switch (HSS) and low side switch (LSS) respectively. As for the HSS, p-channel MOSFET (PMOS) is more preferable than n-channel MOSFET (NMOS) due to complication to drive the voltage supply [5]. The LSS is to improve its efficiency during conversion of power. The diode from Figure 2.6, D1 is replaced by NMOS for LSS. Figure below is an illustration of the model

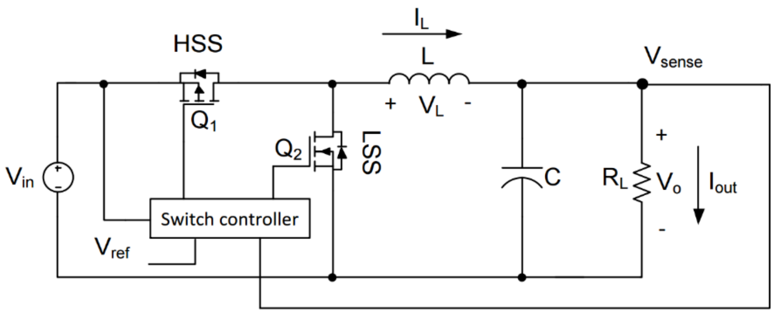

Figure 2.8 Buck converter schematic

This process is accomplished by sensing the output voltage of the circuit by means of a negative feedback loop which adjusts the duty cycle to control on and off state of the MOSFET switches under specified frequency [5].

2.8 Description of Subsystems of Buck Converter

2.8.1 Switch Controller

The pulse-width modulation (PWM) generator is the major part in DC/DC converters as it operates as the power switch for the circuit.

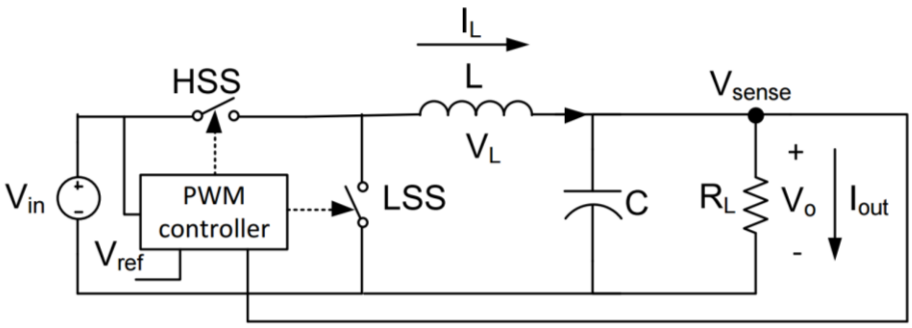

Figure 2.9 PWM buck converter schematic

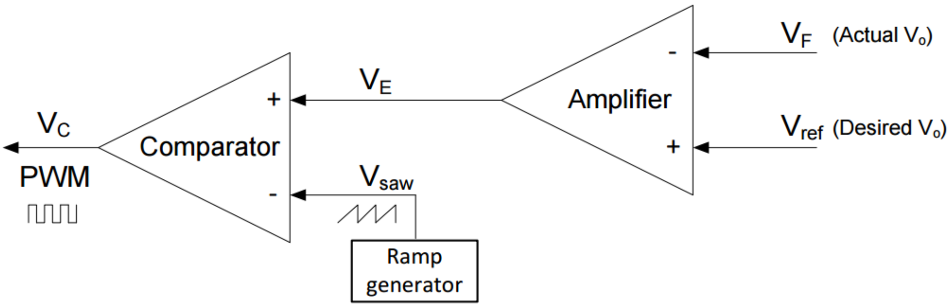

Figure 2.10 PWM generator configuration [5]

When the circuit output voltage changes, V_E also changes and thus causes the comparator threshold to change. Consequently, the output pulse width (PWM) also changes. This duty cycle change then moves the output voltage to reduce the error signal to zero, thus completing the control loop [11]. V_{ref} is high error amplifier reduces V_E to keep on the HSS for a most time of each period in order to adjust output voltage [12].

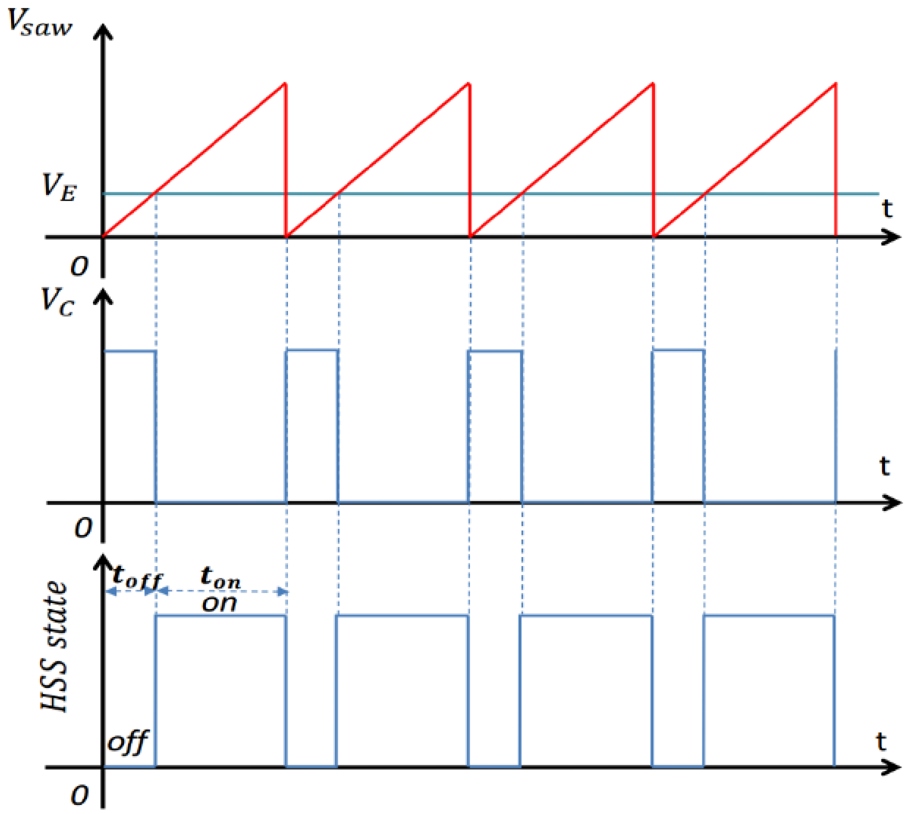

Figure 2.11 Duty cycle waveform when V_{ref} *is low*

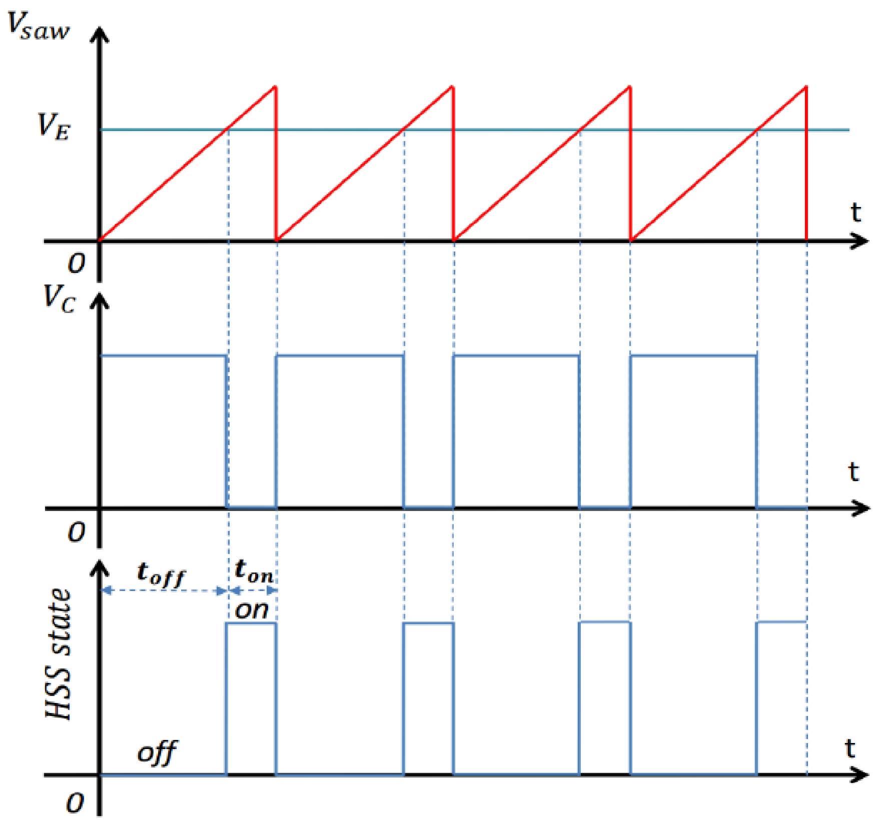

Figure 2.12 Duty cycle waveform when V_{ref} is high

2.9 Duty Cycle Calculation for Buck Converter

Assume that both HSS and LSS are ideal and the other elements are lossless;

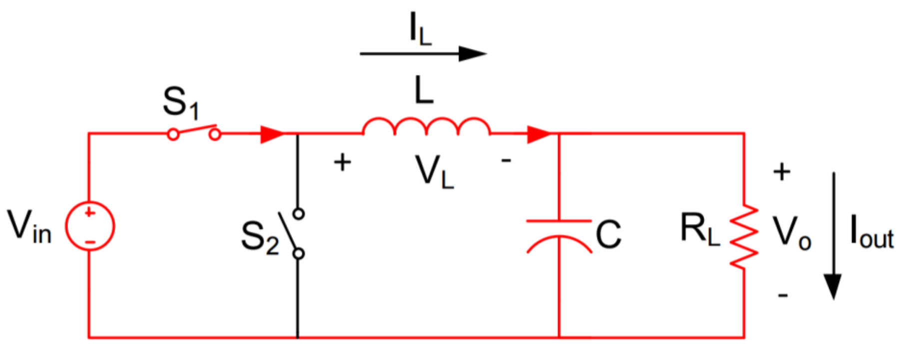

Figure 2.13 Buck converter configuration (on-state) [13]

As shown in Figure 2.14, when the high side MOSFET conducts (during on-state) the path is provided to supply inductor and load. On the other hand, since the low side MOSFET is switched OFF (cut-off state) by PWM controller part thus there is no current flow through it and in this condition inductor current increases linearly and voltage "Vin – Vo" appears across the inductor [13]. Energy stored in inductor can be described as:

$$E = \frac{1}{2} L \, . \, I_L^2 \qquad \text{Eq 2.9}$$

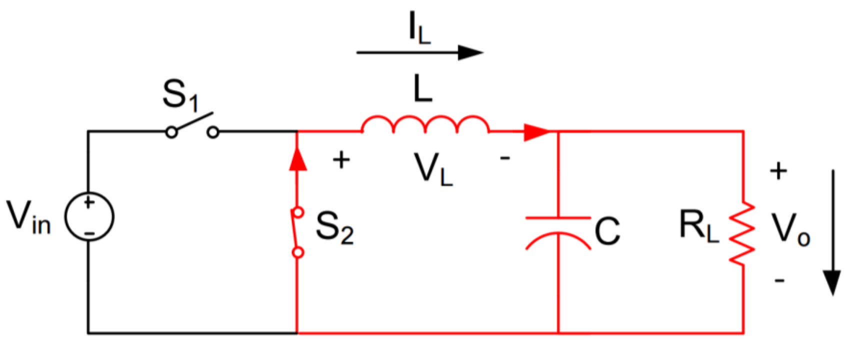

Figure 2.14 Buck converter configuration (off-state) [13]

According to Figure 2.15, when the high side switch is turned off (during off-state) and low side one is turned on a path will be provided to discharge energy which is stored in inductor, so the inductor current decreases and voltage "-Vo" appears across the inductor [13].

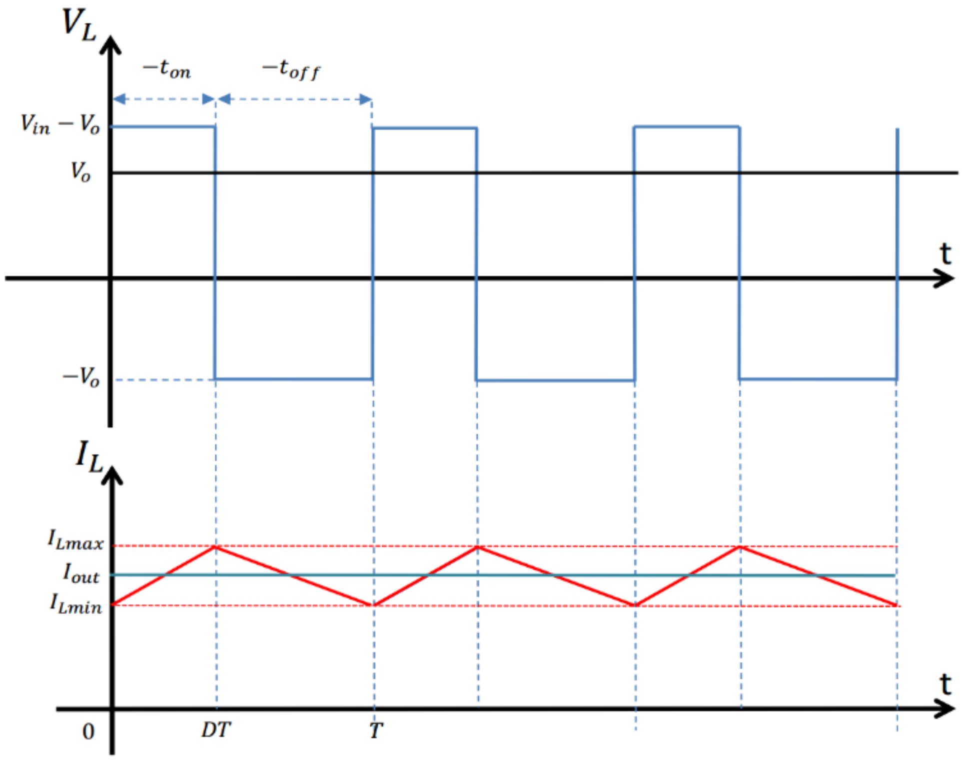

Figure 2.15 Inductor voltage and current waveforms in “on & off” states [13]

Energy stored in inductor at the end of cycle is equal to energy which is stored at the start of cycle. Therefore, we can conclude that the equation for the duty cycle is:

$$D = \frac{Vo}{Vin} \qquad \text{Eq 2.10}$$

2.10 Integrated Circuit Voltage Regulator

LTC3642 is a DC/DC step-down regulator with high efficiency. It uses the Burst Mode operation where the load current is supplied by the output capacitor. It has a very small cycle time that minimizes the supply current hence improves the efficiency greatly.

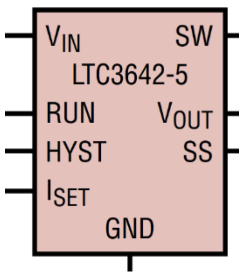

Figure 2.16 LTC3642 Configuration [7]

2.10.1 Main Control Loop

The feedback comparator will compare the output voltage with reference voltage. If the output voltage is greater than the reference, the comparators is disabled. As the load discharges the output capacitor, the output voltage decreases until the comparator enables burst cycles.

During the burst cycle, HSS is turned on and the inductor is starting to ramp up until it exceeds the comparator threshold. Once HSS exceeded the threshold, it will turned off and LSS will turns on. Inductor current will ramp down until the current is close to zero. The process of burst cycle will repeat if the output voltage is still lesser than the reference voltage by 800mV.

2.10.2 Start-Up and Shutdown

Pin 5 run control input. A voltage on this pin above 1.2V enables normal operation. Forcing this pin below 0.7V shuts down the LTC3642, reducing quiescent current to approximately 3µA [7].

2.10.3 Inductor Selection

Input voltage, output voltage and peak current will determine the switching frequency of LTC3642. A good choice of inductors can be made through this equation :

L = $\left(\frac{Vout}{f.Ipeak}\right).\left(1-\frac{Vout}{Vin}\right)$ Where f is the frequency and $Ipeak$ is the peak current.

Chapter 3

Methodology

3.1 Background

Based on discussion on Chapter 2, it is a compulsory to understand on the needed components to design an energy storage system. The better the design is, the better the efficiency in using power. According to the selected converter, it provides an idea to approach the best power supply system.

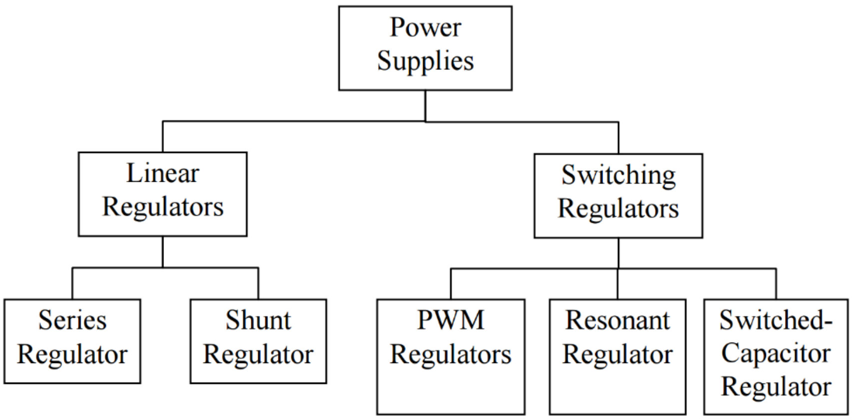

Figure 3.1 Classification of power supply [5]

The best category for the switching DC/DC regulator and IC voltage regulator is PWN regulator as the other 4 categories is not covered in research scope as they are not suitable for proposed design. Series regulator and shunt regulator from linear regulator both possessed low efficiency in regulating output voltage due to bad heat dissipation through active device. Meanwhile, the resonant regulator requires a transformer and switched-capacitor is more complicated design with more than 1 capacitors.

Through the eliminating processes, the PWM regulator is selected for the power supply of DC/DC buck converter. Due to the characteristic of capacitor that will experience decrease of voltage across it as it discharges current, in order to prolong operating time.

3.2 Specifications of Design

There are a lots of factor need to be taken into consideration for designing DC/DC converters such as stable operation (not to be broken easily due to operation failure such as abnormal switching or burnout), high efficiency, small output ripple, good load-transient response [4]. These properties can further upgrade to some level by modified the DC/DC converter external parts. These four properties will be determine a converter its application. For instance faster transient response can be achieved by increasing frequency but on the other hand higher frequencies causes lower efficiency therefore always there is trade-off between transient response of the system and efficiency of converter.