STUDY OF DC-DC BOOST CONVERTER EFFICIENCY USING CAPACITOR AS ENERGY INPUT

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A project report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor (Hons.) of Electrical and Electronic Engineering

Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"STUDY OF DC-DC BOOST CONVERTER'S EFFICIENCY USING CAPACITOR AS ENERGY INPUT"** was prepared by **FOO SHIN LOONG** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor (Hons.) of Electrical and Electronic Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature : _______________________

Supervisor : Mr Lau Kean Hong

Date : _______________________

Specially dedicated to
my beloved mother, father, sisters
and my soulmate, Tan Ying Ying.

ACKNOWLEDGEMENTS

Foremostly, I would like to thank everyone who had contributed to the successful completion of this project. I would like to express my gratitude and appreciation my research supervisor, Mr Lau Kean Hong for his advice, guidance and his patience throughout the development of the research. The other person would be Mr. Ng Mow Song, who has also played a vital role in the early part of our project.

In addition, I would also like to express my gratitude to my loving parent and friends who had helped and given me encouragement throughout the one year duration on this final year project. The first would be my project partner, Choong Pak Wai. We encouraged each other to strive for the success of the project. At times of failure, not only we had given ourselves a break time, the time was used for discussions and improvements on our previous design. This approach that has been implemented by us has proven to complete our project module by module, though at particular time, we were actually focusing on few modules.

Next, I would like to sincerely thank my friends who were from the UTAR EV Team, as they had permitted us to place and store our devices at their cabin. Without their help, we would have to walk into the university compound daily, carrying plenty of stuffs. Apart from that, I would like to convey my deepest gratitude to Mr. Ho K.W, who has never been tired of fabricating the PCBs for me. As for the rest of my friends, who are not named here, rest assured that I am thankful to them as well. Well, what matters the most is the thought, rather than the action.

STUDY OF DC-DC BOOST CONVERTER'S EFFICIENCY USING CAPACITOR AS ENERGY INPUT

ABSTRACT

This thesis focuses on designing a PWM boost DC-DC converter with variable duty ratio that uses a supercapacitor as the input source. In order to accomplish that, a thorough understanding on DC-DC converters and supercapacitors is required. This research covers the use of supercapacitors as a potential energy storage alternative, the operating principles of DC-DC converters, the performance of current IC regulators, the comparison of conventional batteries, and the specifications of potential target applications. The design, analysis, simulations and experimental results of a boost converter with supercapacitors as the input source are implemented and conducted. The future of supercapacitor as the primary energy source for powering electric vehicle (EV) is discussed.

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LIST OF SYMBOLS / ABBREVIATIONS

Ah	ampere-hour
C_O	transistor output capacitance, Farad
C_{Total}	total capacitance, Farad
D	duty cycle
E	energy stored in capacitors, Joule
L	inductance, Henry
I_I	input current, Amp
I_O	output current, Amp
J	energy, Joule
$M_{V\,DC}$	DC voltage transfer function, V_O/V_I
R_F	diode forward resistance, ohm
R_L	load resistance, ohm
V	applied voltage, Volt
V_{DS}	drain to source voltage, Volt
V_F	threshold voltage of diode, Volt
V_C	capacitor voltage, Volt
V_{CC}	supply voltage to 555 timer, Volt
V_I	input voltage, Volt
V_O	output voltage, Volt
V_∞	steady state voltage, Volt
W	power, Watt
f_s	switching frequency, hertz
η	efficiency of converter
f_s	switching frequency, hertz
r_C	ESR of filter capacitor C, ohm
r_L	ESR of inductor L, ohm

r_{DS}	MOSFET on-resistance, ohm
t_H	on-time, second
t_L	off-time, second
t_{on}	switched-on time, second
t_{off}	switched-off time, second
t_r	regulation time, second

AC	Alternating Current
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction Mode
DCM	Direct Current Resistance
DC	Direct Current
ELDC	Electric Double Layer Capacitor
EMI	Electromagnetic Interference
ESR	Equivalent Series Resistance
FCX FCEV	Fuel Cell eXperimental Fuel Cell Electric Vehicle
FES	Faculty of Engineering and Science
IC	Integrated Circuit
IMA	Integrated Motor Assist
LED	Light Emitting Diode
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
PIC	Programmable Integrated Circuit
PM	Permanent Magnet
PWM	Pulse Width Modulation
UART	Universal Asynchronous Receiver and Transmitter
UPS	Uninterrupted Power Supply
UTAR	Universiti Tunku Abdul Rahman

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CHAPTER 1

INTRODUCTION

1.1 Background

In the fundamentals of circuit theory, every electrical and electronic engineer is exposed to the knowledge of three basic components that make up a simple electronic circuit. The components are namely resistor, inductor and capacitor. As technology advances, more and more electronic devices are incorporated into electronic circuits, such as transistors, diodes and integrated circuits (IC).

Through time, electronic circuits become smaller and have the ability to cater a wide range of applications such in laptops, mobile phones, audio systems and video systems. In brief, electronic devices are something that we see and utilise in our daily life. Powering up the electronic devices is normally done through two means. The first way is to obtain it directly from the power supply provided by the local power utility company, which is Tenaga Nasional Berhad in our case. The latter method would be relying on portable power source, which we normally call 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.

Up to a few years ago, capacitor has never been considered as a potential device for energy storage. However, recent breakthroughs in capacitor improvements have significantly raise the possibility of using capacitors as an alternative in energy storage. Those breakthroughs comprise of the invention of electric double layer capacitor (EDLC) commonly known as supercapacitor or ultracapacitor and the lithium ion capacitor, where both are having very high capacitance, long life cycles but low working voltage when compared to conventional capacitors. In addition, scientists have succeeded on using carbon nano-tubes to increase the rate of charge/discharge of the supercapacitor (Bleicher, 2010).

Hence, it is now possible for supercapacitor to be used as a battery just like a typical AA size battery, as a temporary power supply (uninterrupted power supply), in hybrid vehicle to smoothen load changes and in any application where there is concern for energy storage.

1.2 Aim and Objectives

This final year project is dedicated on designing efficient energy storage system using capacitor. It aims to explore on green energy using capacitor to power up electronic devices with high efficiency. In order to achieve the stated aim, below are the objectives that we intend to fulfill.

1. **To provide a regulated output voltage.** Similar to conventional capacitors, the voltage of the capacitor increases as it charges, and vice versa. Therefore, there is a need for a regular circuit to provide a stable output voltage.
2. **High efficiency over a range of output current.** As different electronic circuits consume different amount of current, the proposed energy storage system should exhibit high efficiency over a range of output current to minimise power losses.
3. **Suitable for target applications.** The proposed energy storage system should provide adequate power to its target application.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Efficient energy storage system using capacitors would require a high capacitance capacitor with good electrical properties and a DC-DC converter to provide a regulated output voltage. Hence, this chapter will discuss every possible electronics device that is necessary to satisfy the conditions above.

2.2 Capacitors

Capacitor is a passive electronic component that can store electrical energy by storing charges. It consists of two conducting plates separated by a non-conducting, insulator material commonly known as dielectric. By applying a potential difference across the two conducting plates, electric charge is stored on the plates and energy is stored in the electric field.

2.2.1 Total Capacitance and Energy Stored in Capacitors

When there are two or more capacitors connected either in series, parallel, or combinations of both, the total capacitance, C_{Total} is more concerned in circuit analysis. Apart from that, the energy, *E* stored in the capacitors is also of equivalent importance.

When connected in series:

$$\frac{1}{C_{Total}} = \frac{1}{C_1} + \frac{1}{C_2} + ... + \frac{1}{C_N} \tag{2.1}$$

When connected in parallel:

$$C_{Total} = C_1 + C_2 + ... + C_N \tag{2.2}$$

$$E = \frac{1}{2} C_{Total} V^2 \tag{2.3}$$

where

C_{Total} = total capacitance, Farad

E = energy stored in capacitors, Joule

V = applied voltage, Volt

2.2.2 Types of Capacitors

Below describes the few types of the commercial capacitors available in the market. This includes tantalum, ceramic, conductive polymer, aluminium electrolytic, electric double layer and lithium-ion capacitors.

Table 2.1: Types of Capacitors

Type	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 Capacitor	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.

Working voltage can be increased by connecting the capacitors in series. However, this would reduce the total capacitance, C_{Total}. The solution is then to connect the capacitors already in series, parallel with each other. This connection is called bank connection, and do note that each capacitor's energy capacity would still be the same.

2.2.3 Comparisons of Capacitors

Figure 2.1: PowerBurst® Electric Double Layer Capacitor

With reference to both Figure 2.1 and Table 2.1, it is shown that an electric double layer capacitor has almost the same physical appearance of an electrolytic capacitor. However, electrolytic capacitor having roughly half the size of the 15 F electric double layer capacitor shown in Figure 2.1, will only have a capacitance of about 2200μF. As compared in Table 2.2 below, the most promising high energy density capacitor would be the Ultimo capacitor.

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 Power MOSFETs

MOSFET (Metal-Oxide-Semiconductor Field Effect Transistor) is a voltage controlled device and only requires a small input current to operate. More specifically, a power MOSFET is designed to handle a large amount of power. The switching speed is very high and therefore, the switching times are of the order of nanoseconds.

There are two types of MOSFETs, namely 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.

A typical MOSFET comprises of three terminals which are drain (D), gate (G) and dource (S). Figure 2.2 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.

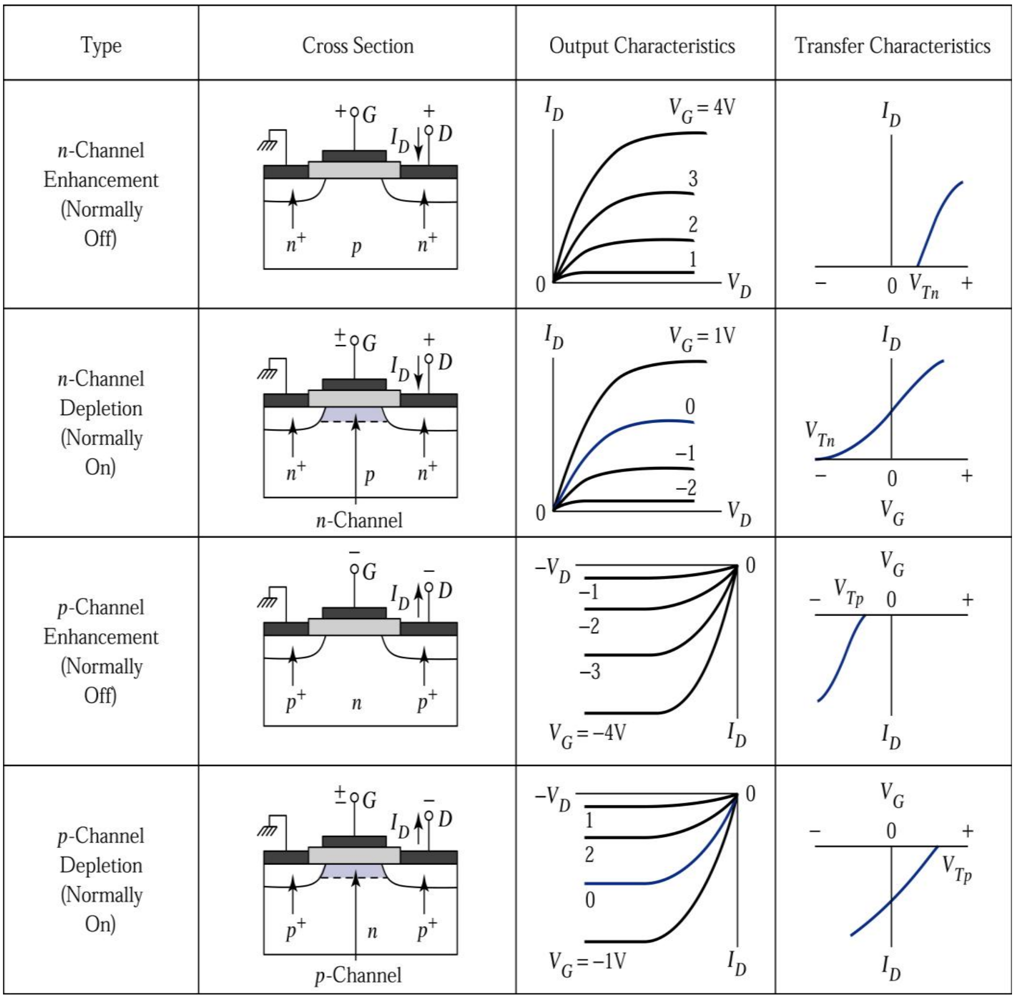


Figure 2.2: Types of MOSFET

A power MOSFET is an important component in DC-DC regulators, as it is responsible for the on-off switching in the regulator circuits. The gate (G) voltage will be normally driven by a device that can produce pulses such as programmable integrated circuit (PIC) or a timer.

2.4 Diodes

A diode is a device that conducts current in only one direction. It is made from a semiconductor material connected to two electrical terminals. When the diode is forward-biased with an applied voltage that is higher than then barrier potential, then current shall conduct across the diode.

Apart from the normal diodes used for rectification (one direction current flow), there are also other special purpose types diodes such zener diodes and varactor diodes which have their own applications in electronic devices.

Meanwhile, Schottky diode is a special semiconductor diode with a low forward voltage drop and a very fast switching action. While standard silicon diodes have a forward voltage drop of about 0.7V, Schottky diodes has forward-bias voltage drop at in the range 0.15V to 0.45V.

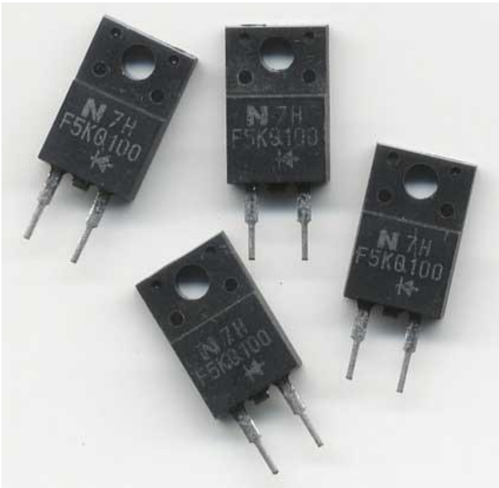


Figure 2.3: Schottky Barrier Diode (F5KQ100, 5.5A 100V).

2.5 Programmable Integrated Circuits (PIC)

Programmable Integrated Circuits (PIC), more commonly known as microcontroller, its difference with a normal microprocessor found in personal computers and laptops is that microcontroller has its own memory, and input-output modules such as timer, analog-to-digital conveter (ADC) and serial input-output interface.

$$Microcontroller = Microprocessor + Input/Output + Memory \qquad (2.4)$$

Basically, a PIC only requires an external power supply and clocking support from an oscillator to function. In order to program the PIC, the two most used methods are by using assembly language (machine instructions) or high level language (plain English-like) such as C. Programming with assembly language word requires assembler while high level language would need a compiler.

The PIC is by far the most suitable device to be used for switching on-off of the power MOSFET and the diode in the DC-DC regulators using pulse width modulation (PWM). However, the power consumption of the PIC will be of question since it would be powered up by normal AAA size battery.

2.6 DC-DC Converters

Every single active electronic circuit, regardless whether it is digital or analog, requires power supplies. The power supply that is supplied by our local energy provider is in alternating current (AC) form, and when such electronic circuit would require direct current (DC) supply voltage, the source would normally be derived from a battery or from the AC supply voltage using a transformer, rectifier and filter.

Here we would be focusing on regulated DC supply voltage. It simply implies that given a fluctuating DC supply voltage as input, the output voltage would be maintained within a narrow range of the desired nominal voltage in spite of load current and temperature variations. In order to accomplish this, DC-DC converters which is a type of voltage regulator, will be used.

2.6.1 Buck PWM DC-DC Converters

A typical buck PWM dc-dc converter is shown below in Figure 2.4. It consist of a power MOSFET used as a controllable switch using PWM, a diode D1, an inductor L, and a filter capacitor C. V_I refers to the input voltage and V_O is the regulated output voltage on resistor R_L representing a DC load.

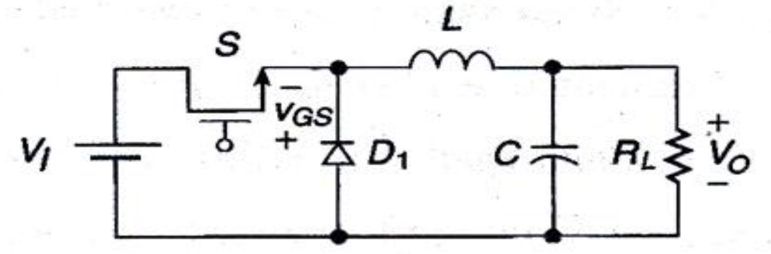


Figure 2.4: Buck PWM DC-DC Converters.

A buck PWM converter is a step down converter where the output voltage is lower than the input voltage. It can be operated in either continuous conduction mode (CCM) or discontinuous conduction mode (DCM). In CCM, the inductor current flows during the entire cycle, whereas in DCM the inductor current falls to zero, remains at zero for a period of time and then starts to increase. Conductions losses and device stresses are higher on DCM compared to CCM.

The power MOSFET will be turned on and off by a PWM, which is characterised by its duty cycle, D and switching frequency, f_s

$$D = \frac{t_{on}}{T} = \frac{t_{on}}{t_{on} + t_{off}} = f_s t_{on} \tag{2.5}$$

$$M_{V\,DC} = D \; (For\ a\ lossless\ converter) \tag{2.6}$$

Below is the equivalent circuit of the buck converter with parasitic resistances and the diode offset voltage that will be used to calculate the efficiency of the converter.

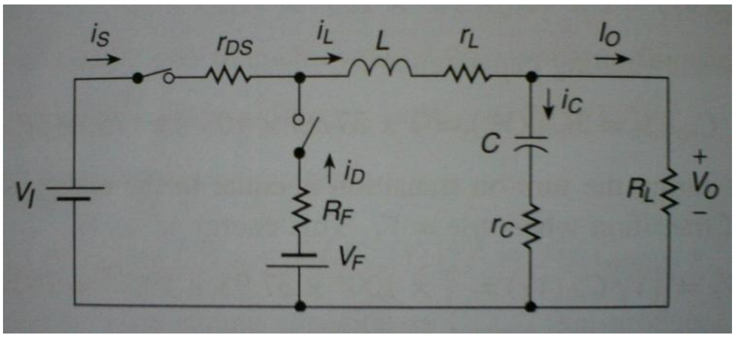


Figure 2.5: Equivalent circuit of the Buck converter

$$\eta(CCM) = \frac{1}{1 + \frac{Dr_{DS} + (1-D)R_F + r_L}{R_L} + \frac{(1-D)V_F}{V_O} + \frac{f_s C_O R_L}{M_{V\,DC}^2} + \frac{r_C R_L (1-D)^2}{12 f_s^2 L^2}} \qquad (2.7)$$

where

η = efficiency of converter

r_{DS} = MOSFET on-resistance, ohm

f_s = switching frequency, hertz

D = duty cycle ratio

L = inductance, Henry

r_C = ESR of filter capacitor C, ohm

R_F = diode forward resistance, ohm

R_L = load resistance, ohm

r_L = ESR of inductor L, ohm

V_F = threshold voltage of diode, V

V_I = input voltage, V

V_O = output voltage, V

C_O = transistor output capacitance, assuming linear, Farad

$M_{V\,DC}$ = DC voltage transfer function, V_O/V_I

Assuming other parameters are constant except for load resistance, it can be shown that as load resistance increases, efficiency increases (Kazimierczuk, 2008).

2.6.1.1 Improvements for Buck Converters

The disadvantage of the buck converter shown in Figure 2.4 is the pulsating input current waveform. The input current flows when the switch is closed and is abruptly interrupted when the switch is open. In order to obtain a continuous input current, a second-order L-C low pass filter can be added at the input of the converter.

Next is the buck converter with synchronous rectifier. The diode in Figure 2.4 will be replaced by an n-type or p-type MOSFET with an external Schottky diode connected to both MOSFET in parallel. This circuit, as shown in Figure 2.6 is a good application for input voltage V_O of 2V or less, switching frequency f_s of 300 kHz or less and output current I_O in between 10 to 100 A.

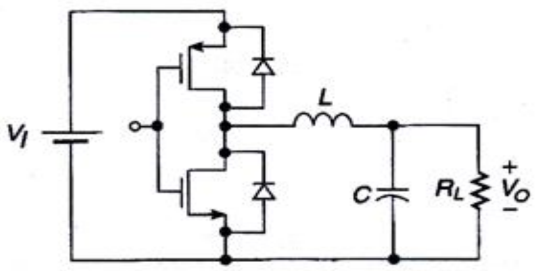


Figure 2.6: Buck Converter with CMOS synchronous rectifier.

2.6.2 Boost PWM DC-DC Converter

A typical boost PWM dc-dc converter is shown below in Figure 2.7. It consist of a power MOSFET used as a controllable switch using PWM, a diode D, an inductor L, and a filter capacitor C. V_I refers to the input voltage and V_O is the regulated output voltage on resistor R_L representing a DC load.

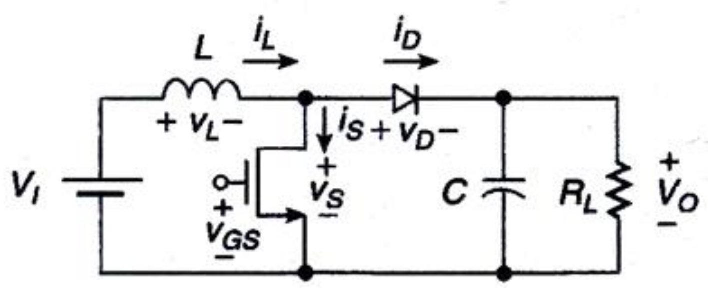


Figure 2.7: Boost PWM DC-DC Converters.

A boost PWM converter is a step up converter where the output voltage is higher than the input voltage. It can be operated in either continuous conduction mode (CCM) or discontinuous conduction mode (DCM). Similar to buck converter, duty cycle, *D* and switching frequency, f_s of a boost converter is given by equation (2.5). However, the DC transfer function for a lossless buck converter is given by

$$M_{V\,DC} = \frac{1}{1-D} \tag{2.8}$$

Below is the equivalent circuit of the boost converter with parasitic resistances and the diode offset voltage that will be used to calculate the efficiency of the converter.

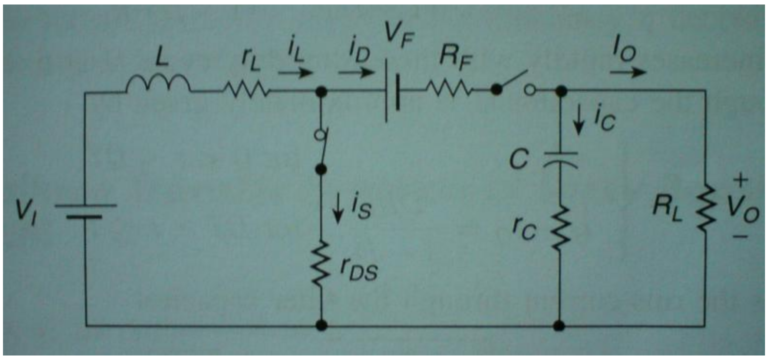


Figure 2.8: Equivalent circuit of the Boost converter

$$\eta(CCM) = \frac{1}{1 + \dfrac{r_L + Dr_{DS}}{(1-D)^2 R_L} + \dfrac{R_F + Dr_C}{(1-D)R_L} + \dfrac{V_F}{V_O} + f_s C_O R_L} \tag{2.9}$$

where

η = efficiency of converter

r_{DS} = MOSFET on-resistance, ohm

f_s = switching frequency, hertz

D = duty cycle ratio

L = inductance, Henry

r_C = ESR of filter capacitor C, ohm

R_F = diode forward resistance, ohm

R_L = load resistance, ohm

r_L = ESR of inductor L, ohm

V_F = threshold voltage of diode, V

V_I = input voltage, V

V_O = output voltage, V

C_O = transistor output capacitance, assuming linear, Farad

Assuming other parameters are constant except for load resistance, it can be shown that as load resistance increases, efficiency decreases (Kazimierczuk, 2008).

2.6.3 Buck-Boost PWM DC-DC Converter

A typical buck-boost PWM dc-dc converter is shown below in Figure 2.9. It consist of a power MOSFET used as a controllable switch using PWM, a diode D, an inductor L, and a filter capacitor C. V_I refers to the input voltage and V_O is the regulated output voltage on resistor R_L representing a DC load. The output voltage is inverting.

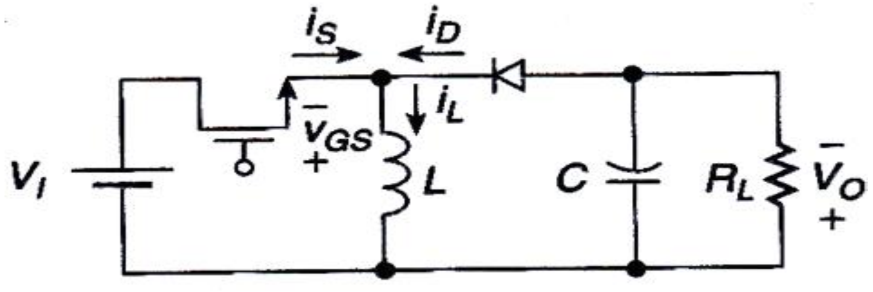


Figure 2.9: Buck-Boost PWM DC-DC Converters.

A buck-boost PWM converter can either be used as a step up or step down converter. It can be operated in either continuous conduction mode (CCM) or Discontinuous Conduction Mode (DCM). Similar to buck converter, duty cycle, D and switching frequency, f_s of a boost converter is given by equation (2.5). However, the DC transfer function for a lossless buck converter is given by

$$M_{V\,DC} = \frac{D}{1-D} \tag{2.10}$$

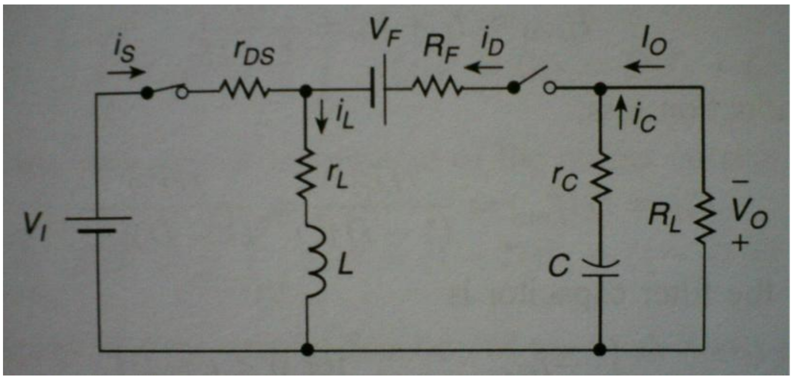


Figure 2.10: Equivalent circuit of the Buck-Boost converter

$$\eta(CCM) = \frac{1}{1 + \frac{r_L + Dr_{DS}}{(1-D)^2 R_L} + \frac{R_F + Dr_{DS}}{(1-D)R_L} + \frac{V_F}{V_O} + \frac{f_s C_O R_L (1+M_{V\,DC})^2}{M_{V\,DC}^2}} \tag{2.11}$$

where

η = efficiency of converter

r_{DS} = MOSFET on-resistance, ohm

f_s = switching frequency, hertz

D = duty cycle ratio

L = inductance, Henry

r_C = ESR of filter capacitor C, ohm

R_F = diode forward resistance, ohm

R_L = load resistance, ohm

r_L = ESR of inductor L, ohm

V_F = threshold voltage of diode, V

V_I = input voltage, V

V_O = output voltage, V

C_O = transistor output capacitance, assuming linear, Farad
$M_{V\,DC}$ = DC voltage transfer function, V_O/V_I

The efficiency of a buck-boost converter is dependent on the duty cycle ratio. When duty cycle is very close to zero, conduction losses are low but switching loss is high. On the other hand, when duty cycle is close to one, the conduction losses are high, therefore reducing efficiency (Kazimierczuk, 2008).

2.6.3.1 Improvements for Buck-Boost Converters

Apart from buck-boost converter, there is also boost-buck converter. Boost-buck converter is more commonly known as Ćuk converter, in honour of its inventor. Since the normal buck-boost converters produce inverting output, a non-inverting buck-boost converter can be obtained by cascading the buck and boost converters. Another way is to use a four-transistor (MOSFET) non-inverting buck-boost converters.

2.7 Integrated Circuit Voltage Regulators

Generally, DC-DC converters mentioned above are preferred for applications where the output power is more than 10W and the output voltage is more than 5V. When it comes to lower input voltage and requirement of output current that is typically 1A or less, IC regulator would be the better choice of use. Note that the integrated circuit (IC) voltage regulators being discussed here are switching regulators.

Since there are varieties of IC available from the market, it is for feasible to set a reference value for the requirement of the IC from selected vendors and manufacturers. Hence, we would prefer the criteria listed below to be met by the ICs.

i) Input voltage, V_I should be between 0.8 to 5V
ii) Output voltage, V_O should be between 3 to 5V

iii) Output current, I_O should be around 0.1 to 0.5A

iv) Efficiency to be at least 85% or more

The criteria is designated such because the working voltage of electric double layer and lithium ion capacitors are quite low. Lower V_I means the capacitors can discharge more energy before the lower threshold is reached. On the other hand, selection of V_O and I_O are made for low power applications like MP3 players, LED lights and to power up PIC circuits.

Below are the tables comparing on the efficiency of voltage regulators produced by Maxim Integrated Products, Advanced Analogic Technologies and Linear Technology.

Table 2.3: Specifications of Advanced Analogic Technologies AAT1218

Manufacturer	Advanced Analogic Technologies
Model	AAT1218
Input voltage (V)	0.5 to 5
Output voltage (V)	2.5 to 5.5
Output current (mA)	Up to 1000
Efficiency at Output of 3.3V	

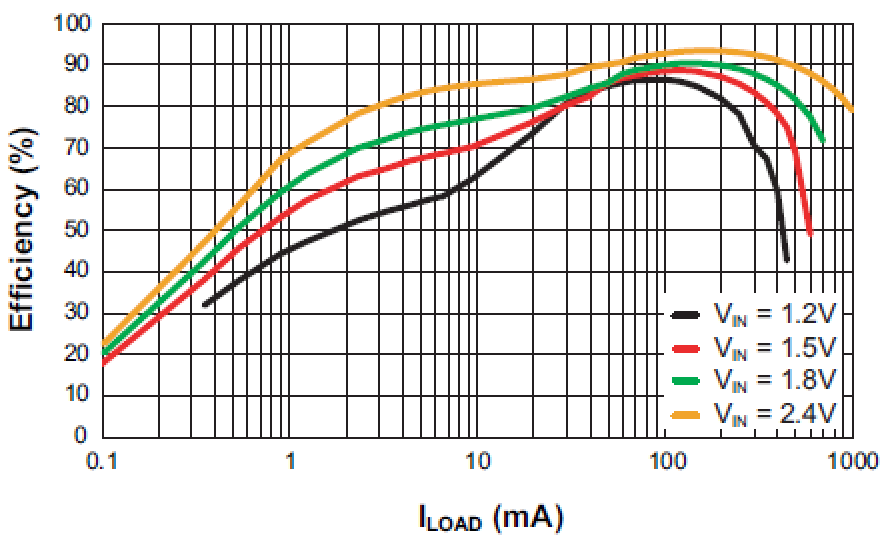


Table 2.4: Specifications of Maxim Integrated Products MAX1674

Manufacturer	Maxim Integrated Products
Model	MAX1674
Input voltage (V)	0.7 to 5.5
Output voltage (V)	2 to 5.5
Output current (mA)	Up to 1000
Efficiency at Output of 3.3V	

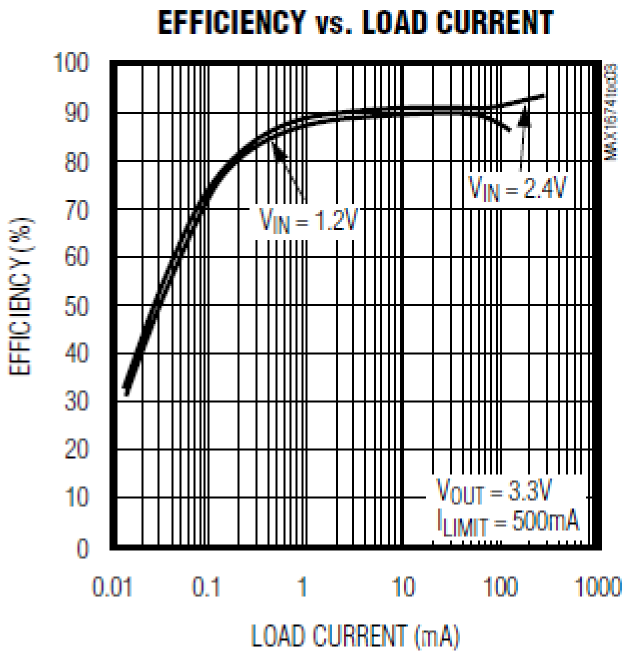
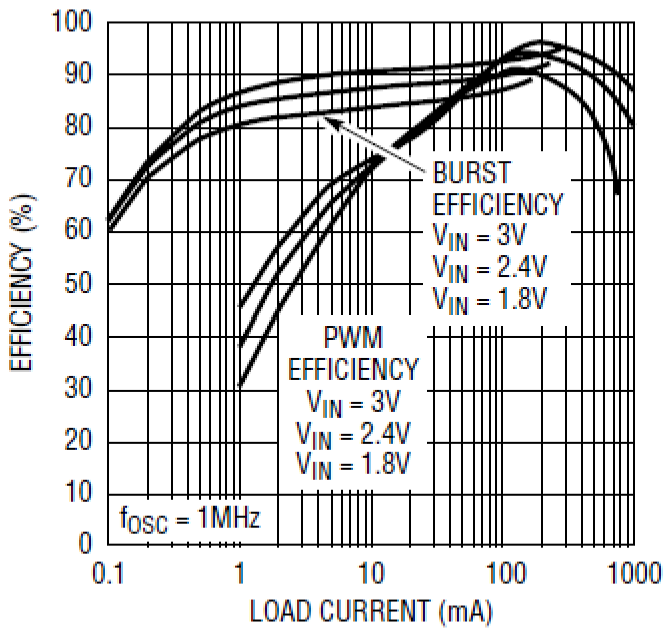


Table 2.5: Specifications of Linear Technology LTC3422

Manufacturer	Linear Technology
Model	LTC3422
Input voltage (V)	0.5 to 4.5
Output voltage (V)	2.25 to 5.25
Output current (mA)	Up to 1000
Efficiency at Output of 3.3V	
	

As seen from the three graphs shown in Table 2.3, 2.4 and 2.5, all the three ICs will almost reach peak efficiency when it is running at 100mA. Furthermore, with the reduction of input voltage, there will only be a small drop of efficiency. Hence, producing an output voltage of 3.3V and output current of 100mA will be a good reference point for using IC voltage regulator in our case study.

Among the three ICs being compared, it is shown that the Maxim's MAX1674 IC would be best choice provided that our device application would consume less than 500mA. Though the other 2 ICs provide a wider range of output, do note that their efficiency drop drastically when (as low as 50% when V_I = 1.2V for Analogic Tech) the output current is around 500mA. Furthermore, MAX1674 IC provides a quite constant, high efficiency throughout an output current of 1 to 100mA range, which the other two ICs are not capable of.

Hence, it is deduced that MAX1674 IC is the most suitable IC when the target application is on a regulated output voltage of 3.3V, with a relatively constant high efficiency at 1 to 100mA output current and a current limit of 500mA.

2.8 Comparison of Technologies

Supercapacitors and lithium ion capacitor, both a subcategory of capacitor will be discussed here for future potential. There are possibilities for these capacitors to compete with conventional batteries to be used in daily consumer electronics, in electric or hybrid vehicles to supplement as secondary energy source and application in uninterruptable power supply (UPS). But before that, the characteristics of such capacitors have to be examined, which will then be followed by discussion of present technology as benchmark.

2.8.1 Capacitor Testing

Every single electronic component, which is identical to each other, is manufactured through the same process. However, due to microscopic differences of the material, the produced components will have variance, or more commonly termed as tolerance value. Tolerance is the allowable range where the actual value of a component can deviate from its nominal value.

Figure 2.11: Specification BMOD0140-E048 Supercapacitor

Specification	Design Spc.	Measured	
Voltage	48.6		V
Hi Pot ($1 \leq 2$mA)	2500V		V
DC ESR (mΩ)	≤ 8	6.67	
Initial Capacitance (F)	≥ 140	171.79	

In the journal written by (A. B. Cultura II, 2008) entitled "Performance Evaluation of a Supercapacitor Module for Energy Storage Applications", the authors had performed performance evaluation of the BMOD0140-E048 Supercapacitor manufactured by Maxwell Technologies Company. Note that from Figure 2.11, the measured capacitance is 171.79F while the nominal value is stated as 140F.

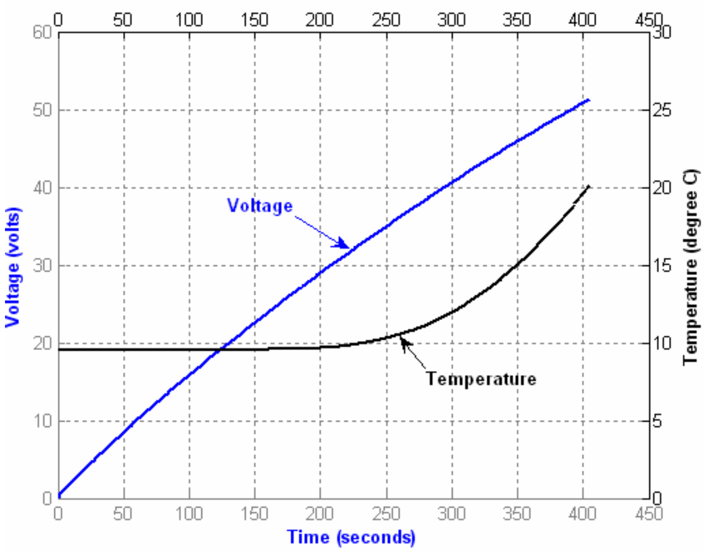


Figure 2.12: Charge profile of supercapacitor

Apart from measuring the actual capacitance of the supercapacitor module, few tests were conducted as well. In Figure 2.12, it show the graph that relates the temperature changes with time when the module is charged up to to 51.8V at costant 20A. From the result here, it important to understand the effect of temperature rise when the supercapacitor is charged to the rest of the circuit which may be sensitive to temperature difference and limiting the curent that flows into capacitor to prevent capacitor breakdown.

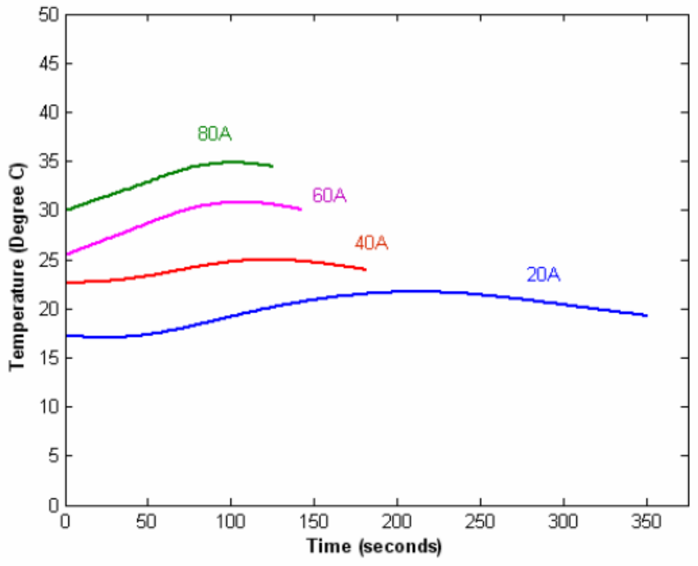


Figure 2.13: Discharge profile of supercapacitor

Discharging the supercapacitor at different amount of current will also affect its operating temperature of the supercapacitor as well. For example, when discharging at 80A, the temperature range is between 30°C to 34.8°C as shown in Figure 2.13.

2.8.2 Battery

A battery is defined as one or more electrochemical cells that convert stored chemical energy into electrical energy. There are two types of batteries, the first is primary batteries or disposable batteries, which are designed to be used once and discarded when they are exhausted. The latter would be secondary batteries or rechargeable batteries, which can be recharged and used finite times. The focus would be on secondary batteries as capacitors can be turned into rechargeable batteries.

Table 2.6: Comparison of Batteries and Capacitors

Parameters	NiCd	NiMH	Lead Acid	Li-Ion	EDLC	LIC
Energy Density (Wh/kg)	45-80	60-120	30-50	150-190	2-9	11-14
Cycle Life	100-200	200-300	<100	150-300	>100000	>100000
Fast Charge Time	1 Hr	2 -4 Hr	8-16 Hr	1.5-3 Hr	<1 Hr	<1 Hr
Overcharge Tolerance	moderate	low	High	low	low	low
Self-Discharge (per month)	20%	30%	5%	10%	>30%	<5%
Nominal Voltage	1.25	1.25	2	3.7	2.7	3.8
Toxicity	Highly Toxic	Low Toxicity	Highly Toxic	Low Toxicity	None	None

Nickel cadmium (NiCD), nickel metal hydride (NiMH) and lithium ion (Li-Ion) batteries can be found in a variety of consumer electronics, ranging from remote controls, handphone, digital cameras, laptops, music players and GPS devices. Li-Ion is more popular in laptops and mobile phones usage, and all the three mentioned batteries can be found in electric vehicle.

Lead acid battery, the oldest type of rechargeable battery, can be found in every motor vehicle, which includes fuel-combustion engine cars, electric cars and hybrid-electric cars. EDLC and ILC are electric double layer capacitor and lithium ion capacitor respectively. As can be seen from Table 2.6, capacitor holds the advantage of having a very long cycle life and short charging time but losses in term of energy density, which in fact prevented it from being a suitable alternative for electric or hybrid vehicles. However, with the recent improvements in capacitor technology, there is hope and possibility for capacitor to emerge as a reliable energy storage system.

2.8.3 Electric and Hybrid Vehicles

With reference to the above, one electric and one hybrid vehicle will be discussed and both are manufactured by Honda.

2.8.3.1 Honda Fuel Cell eXperimental Fuel Cell Electric Vehicle (FCX FCEV)

Honda's FCX Clarity FCEV is family of hydrogen fuel cell automobiles manufactured by Honda. Though the 2008 model (Clarity) and 2006 model (Concept) incorporate a compact lithium-ion battery that serves as a supplemental power source in the two FCX models, but the 2002 model uses supercapacitors instead.

Table 2.7: Specifications of FCX 2002

Powertrain		
Drive method		Front-wheel drive
Motor	Type	AC synchronous electric motor (permanent magnet)
	Max. output (kW [PS])	80 [109]
	Max. torque (N·m [kg·m])	272 [27.7]
Fuel cell stack	Type	Honda PEMFC (Proton Exchange Membrane Fuel Cell)
	Max. output (kW)*	86
Ultra-capacitor	Electrostatic capacity (F)*	9.2

(Source : http://world.honda.com/FuelCell/FCX/specifications/)

As can be seen from Table 2.7, the ultracapacitors (ELDC) also serve as supplemental power source in the 2002 model, and by assuming it has the same working voltage of 288V as the lithium-ion battery in the 2008 model, it could actually store up to 381.5kJ. The simplest connection to obtain 9.2 F at 288V is to connect 125 ultracapacitors in series, each with a rating of 2.3V and 1150F.

Compared to the technology at that time, the working voltage of an EDLC was 2.3V. Now, it is 2.7V and up to 3000F for EDLC; 3.8V and up to 3300F for LIC. From here, there is an improvement of 17.39% in working voltage and 160.8% in term of capacitance per cell for the supercapacitors (ELDC). In summary, Honda may have taken out the supercapacitors from their electric vehicles, but supercapacitors are improving with time. Hence, in the future, green energy car manufacturers will likely utilise supercapacitors again.

2.8.3.2 Honda Insight Hybrid Vehicle

The 2010 model incorporates integrated motor assist (IMA) which is powered by a flat, NiMH battery pack located below the cargo floor between the rear wheels. The 84 module battery is manufactured by Panasonic and provides a nominal system voltage of 100.8V with a nominal capacity of 5.75Ah that makes a total of 579.6Wh. The battery is recharged automatically by scavenging engine power, when needed, and by regenerative braking when the car is decelerating. The power management electronics, battery modules, and cooling system are all self-contained within the IMA battery pack.

It is highly possible to replace the NiMH with ultracapacitor module. However, the low energy density may prove to be a disadvantage. For example, the PBM module by Tecate Group has a maximum energy density of only 4.69Wh/kg for a 64.8V, 15.53kg module, which corresponds to only 72.83Wh.

2.8.4 Uninterruptable Power Supply (UPS)

As described by (Drew, 2008) in his Design Note 450, it opened a possibility to use supercapacitor for power ride-through applications, or basically a form of uninterruptable power supply (UPS). UPS is defined as an electrical apparatus that provides emergency power to a load when the input power source, typically the utility mains fails to do so. The source of power for the UPS can be of standby generator for high power or emergency power system consisting of batteries and associated electronic circuitry for low power users.

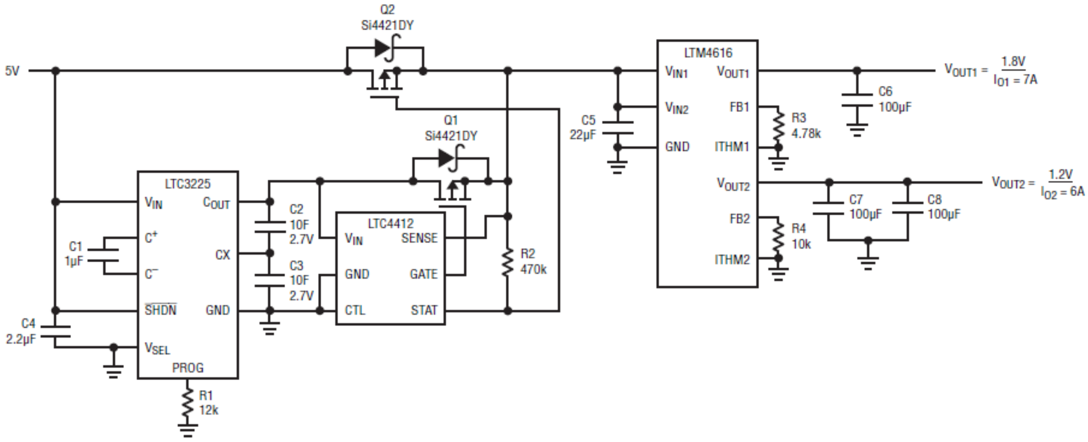


Figure 2.14: 5 V Ride-Through Application Circuit

As shown in Figure 2.14**,** the circuit above operates with a 5V input voltage while producing dual output of 1.8V, 7A (12.6W) and 1.2, 6A (7.2W) which makes a total output power of 19.8W through LTM4616. Meanwhile the LTC3225 is a charge-pump-based supercapacitor charger that is used to charge the supercapacitors at 4.8V, 150mA and balancing the voltages across two supercapacitors C2 and C3 with a rating of 10F, 2.7V.

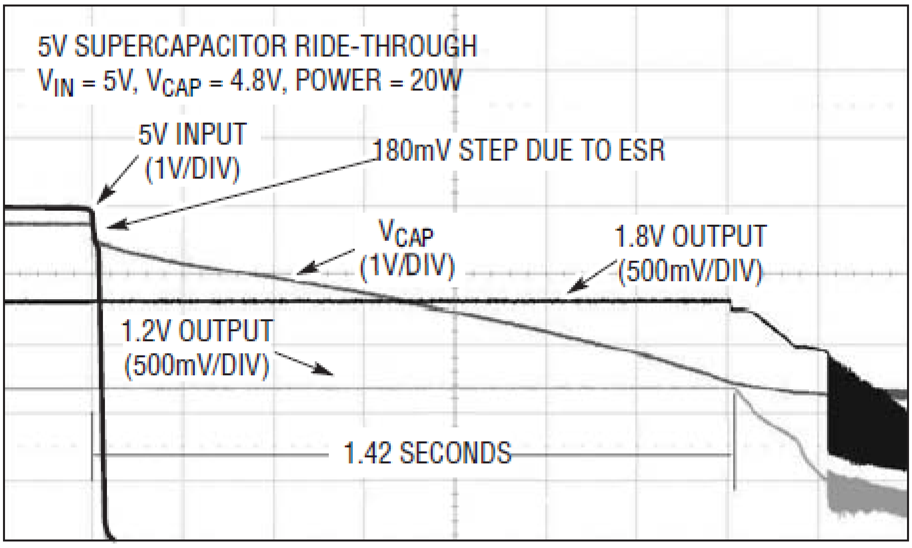


Figure 2.15: Timing Diagram

When the input voltage of 5V that acts as the main supply is removed, the supercapacitors and the rest of the circuit will function as the UPS, providing the output power. As shown in Figure 2.15, the charged supercapacitors at 4.8V will firstly experience 180mV drop due to the capacitors' ESR. Next, for the rest 1.42 seconds, it is able to produce 19.8 W, before shutdown when the supercapacitors' voltage reaches 2.4V.

Total energy produced = 19.8 W x 1.42 s = 28.116 J
Energy used from supercapacitors = 0.5 x 5 F x $(4.8^2\text{-}2.4^2)$ *= 43.2 J*
Efficiency = 65.08%

Though with only an efficiency of roughly 65%, is has opened an opportunity to use supercapacitors rather than conventional batteries for low power UPS, as supercapacitors have life cycles greater than 500,000 cycles, while batteries are having only a few hundred cycles. Besides focusing in increasing efficiency, improvement can be done through increasing the number of supercapacitors used, to cater for longer duration and higher output power.

2.9 Summary

This whole chapter has discussed every possible electronics device that is necessary to design a DC-DC converter which is able to provide a regulated output voltage. With the information conveyed earlier in this chapter, it is sufficient to design a basic DC-DC converter, but the development of the DC-DC converter will not be restricted by the information within this chapter. In a more specific statement, this chapter will present a broader view on how an energy storage system using capacitor as energy input can be designed.

The 3 basic DC-DC converters that have been mentioned explain the way how a fluctuating input voltage will be regulated, either through voltage step up or step down. The suitability of the converter is highly dependent on the working characteristics of the input source, which is in this case, capacitor. The selection of the most appropriate converter will be discussed in Chapter 3.

In addition to that, a few IC voltage regulators have been discussed in this chapter. As these devices are commercially sold and possess relatively high efficiency, it will become a good benchmark for the hardware that will be self-designed in Chapter 3. With a self-designed hardware, there is versatility in choosing the input and output parameters of the hardware. In comparison to the IC Voltage regulators, the input voltage is limited to a particular range and so does the output current.

The capacitor testing is basically a partial reprint of the findings by the authors of the journal entitled "Performance Evaluation of a Supercapacitor Module for Energy Storage Applications". Through the journal, it can be observed that fast current charging onto or discharging from the supercapacitor will tremendously increase the temperature of the supercapacitor. Here, the few issues that may pose problem to the self-designed hardware are that high current charging might damage (short-circuit) the supercapacitor and whether the hardware would require a cooling system, if the current drawn out from the supercapacitor is relatively high. Maximum charging or discharging current rating, is product-dependent and can be referred from the datasheet.

Hence, current-limited charging process will be implemented, but without the design of a current-limiting circuit (Please refer to subchapter 4.2). As for temperature increase, it is relatively not important for this scaled-down prototype (supercapacitor discharge current, also equivalent to the inductor current, is less than 3A when output of 12V and 0.5A is produced).

This chapter also discussed on the usage of supercapacitors as supplemental power source in Honda FCX 2002, in line with our objective of powering the DC motor of an electric vehicle (EV), albeit at a scaled-down model. Back then, the technology development was not as good it is now. Hence, with some forecasting on the present technology, this will again open up the possibility for supercapacitors to be used in electric and hybrid vehicles in the near future.

Finally, for the uninterruptable power supply (UPS), it is dedicated in exploring the potential for capacitors to be an energy storage medium that can be utilised when there is power outage. Obviously, this will only be feasible if there is a bank of supercapacitors, each with high capacitance.

CHAPTER 3

METHODOLOGY

3.1 Background

As previously discussed in Chapter 2, it is necessary to understand the basic components needed for the energy storage system, the operating principles of a DC-DC converter and the choices of converters that can be used. It provides the idea on the approaches that can be taken to realise the best power supply system.

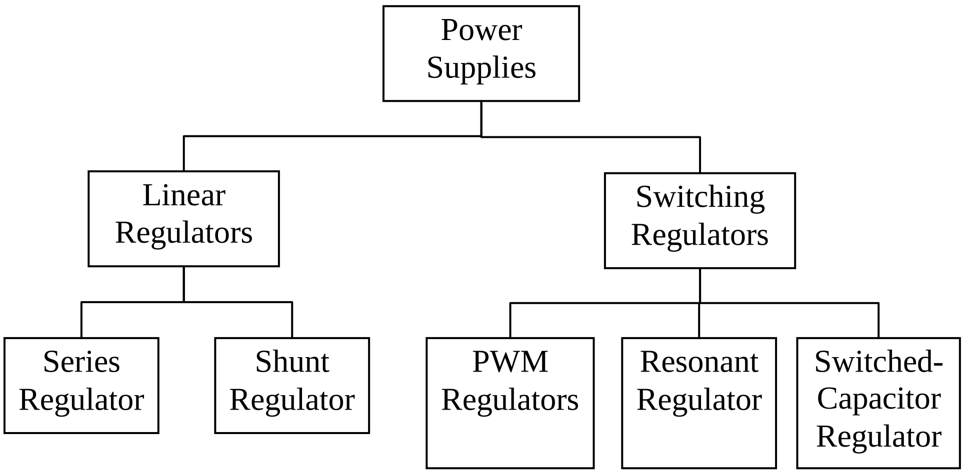


Figure 3.1: Classification of Power Supply (Kazimierczuk, 2008)

Foremostly, the DC-DC converters and integrated circuit voltage regulators belong to the PWM regulator category as shown in Figure 3.1. The other 4 categories of regulator (series, shunt, resonant and switched-capacitor) are not discussed because their circuit design is not suitable for the proposed methodology.

This is because both series and shunt regulators generally have lower efficiency compared to switching regulators, due to the heat dissipation through the active device to regulate output voltage. Meanwhile, resonant regulator would need a transformer and switched-capacitor regulator would require more than 1 capacitor in the design.

In short, the alternatives available now are from choosing buck converter, converter, buck-boost converter or IC regulator. Due to the characteristic of capacitor that will experience decrease of voltage across it as it discharges current, in order to prolong operating time, a step up (boost) converter is the better choice among the three mentioned converters. Consequently, the choices narrowed down now are either using a boost converter or an IC regulator.

3.2 Specifications of Hardware Design

The specifications of the hardware will be targeted for electric or hybrid vehicle applications. However, to design and construct the circuit in such a way that meets industrial standards; such as high working voltage and current, will be costly. Hence, the proposed hardware specifications would be as listed below.

i) Input voltage, V_I should be between 3 to 5.4V
ii) Output voltage, V_O should be at constant 12V
iii) Output current, I_O should be around 0.1 to 0.5A
iv) Efficiency to be at least 85% or more

With the specifications above, it is justified that the boost converter will be the best choice for the circuit design, considering the fact that IC regulators can only provide a maximum output voltage of 5V.

3.3 The Proposed Prototype Design

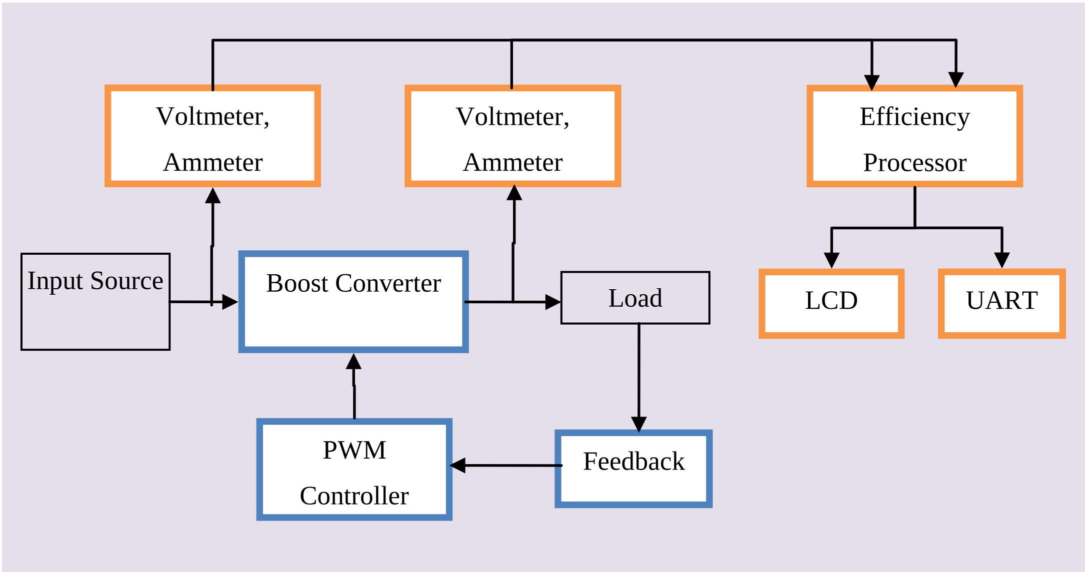


Figure 3.2: Topology of Proposed Prototype

The chosen boost converter will be an integral part of a larger system. Since the efficiency of the boost converter is of great significance, it is logical to include a power meter to measure the input and output side of the boost converter, to provide a real-time monitoring on the efficiency of the converter.

The proposed prototype in Figure 3.2 above shows the whole system. Since this project will be handled by 2 undergraduates, the job division will be clearly defined for each individual, as shown in Table 3.1.

Table 3.1: Job Division

Person In charge	Job Division	Sub-Component
Foo Shin Loong	Converter Design	Boost Converter
		PWM Controller
		Feedback
Choong Pak Wai	Measuring Device	Voltmeter
		Ammeter
		Efficiency Processor
		UART communication

3.4 PWM Waveform with Variable Duty Ratio

The author (Kazimierczuk, 2008, p. 99-105) has shown that a particular designated boost converter has a variable efficiency, η over a range of output current, I_O at fixed values of the input voltage, V_I as shown in Figure 3.3 for the output voltage, V_O equals to 400V. In addition, Figure 3.4 shows the duty ratio, D determines the specific output current, I_O at a fixed input voltage, V_I. For example, when V_I = 187V and an output current I_O = 0.155A is required, the duty ratio that best fits the designated converter is D = 0.55. But when V_I = 127V with the same output current (I_O = 0.155A), the duty ratio needed is D = 0.70.

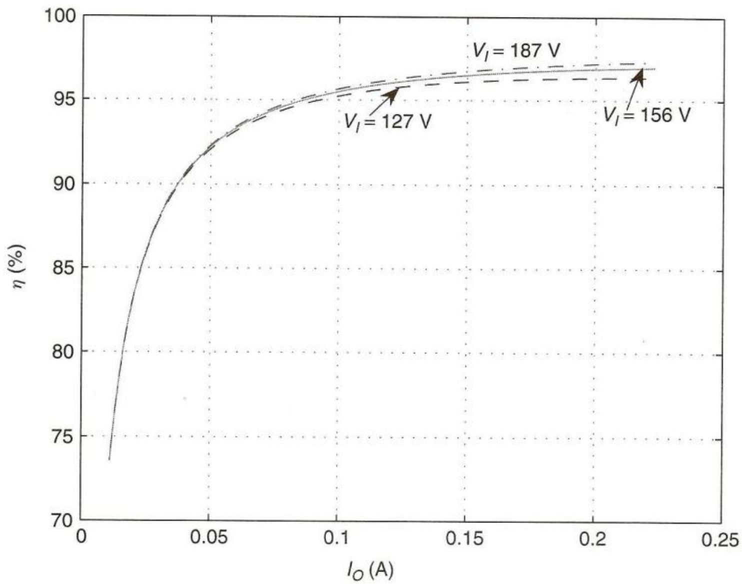


Figure 3.3: Graph of Efficiency against Output Current at Fixed Value of Input Voltage

Therefore, Figure 3.4 actually relates the required duty ratio with respect to the input voltage, to produce the constant output voltage of 400V. However, the design criterion that will be used in this methodology is to use the output voltage to relate to the duty ratio instead. This will be done through the use of the integrator, which will be discussed in subchapter 4.7.

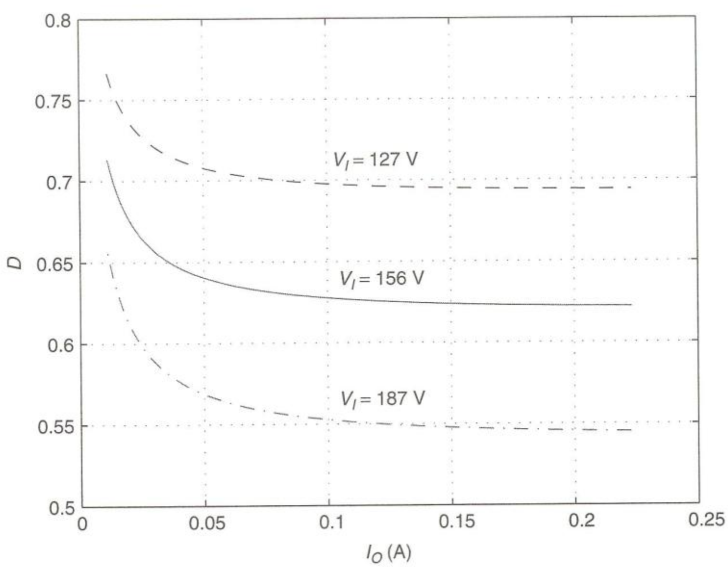


Figure 3.4: Graph of Duty Ratio against Output Current at Fixed Value of Input Voltage

3.5 Boost Converter Design

Most of the formulas that are related for the design of boost converter have been discussed in Chapter 2. Hence, the calculations on the design circuit will be based on the book *Pulse-width Modulated DC-DC Power Converter* by Kazimierczuk, M. K.

As the formulas would require a lot of parameters, it is impossible to measure every parameter using the university's lab facilities. An example would be the measurement of MOSFET on-resistance, r_{DS}. As this parameter is required in the calculations, we will assume the value from the datasheet to match the practical value of the device.

Apart from theoretical calculations, the MATLAB software will be used to simulate the results. The simulation results will provide the transient and steady-state response of the converter, at both input and output side. The analysis of the simulation will be discussed in the Chapter 4.

3.6 PWM Using 555 Timer

The PWM waveform will be produced by using two cascaded 555 timer; with the first timer generating a pulse of fixed frequency and the second timer modulating the generated pulse from the first timer.

By using a 555 timer and the formulas below, a fixed frequency pulse can be generated at the output. It will then be fed into the second 555 timer, as clock input.

$$t_H = 0.693(R_A + R_B)C \tag{3.1}$$

$$t_L = 0.693(R_B)C \tag{3.2}$$

$$period = t_H + t_L \tag{3.3}$$

$$frequency = 1/\ period \tag{3.4}$$

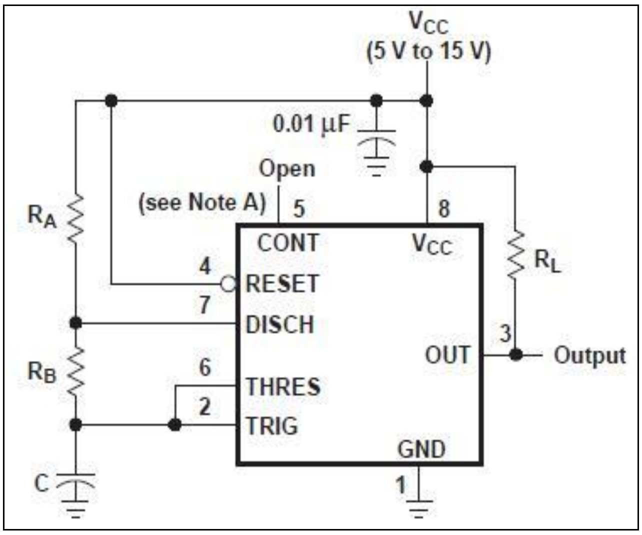


Figure 3.5: The first 555 timer circuit diagram

For the second 555 timer circuit, the pulse will be width-modulated, proportional to the modulation input voltage. The amplitude for the fixed frequency pulse and the PWM waveform from the second timer equals the supply voltage, V_{cc}. Hence, a V_{cc} of 5V will be sufficient to turn on the Power MOSFET.

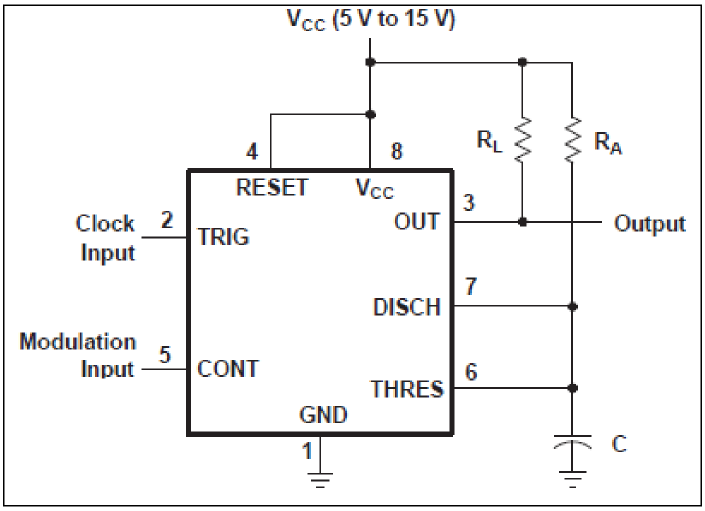


Figure 3.6: The second 555 timer circuit diagram

3.7 Integrator as Feedback

Modulation input would be required by the second 555 timer to vary the duty ratio of the PWM, shown in Figure 3.6. In order to obtain the appropriate modulation input voltage, an integrator circuit will be implemented to tap the output voltage of the converter.

The integrator will operate in such a way that when the boost converter output voltage is below 12V, it will produce higher voltage from the output of the integrator. The output of the integrator will be the modulation input to the 555 timer, causing the duty ratio of the PWM to increase. This will then increase the output voltage of the boost converter. The opposite happens when the boost converter output voltage is above 12V.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Background

This chapter will discuss on the experimental results from various tests.

4.2 Supercapacitors

The supercapacitors that have been purchased are two 100F Supercapacitors from Illinois Capacitor with a maximum current rating of 61.4A. Note that the capacitor must not be charged with current higher than 61.4A or discharging in such a magnitude, to avoid permanent breakdown or failure of these capacitors. These two supercapacitors will be connected in series to be the input of a boost converter, similar to being a battery source. Since the maximum DC rating of the supercapacitor is 2.7V, the intention is to operate the boost converter and produce a regulated output of 12V while the voltage across the series-connected supercapacitors is within the range of 3 to 5.4V.

Initially, there was a plan to design the charging circuit for the supercapacitors. By referring to circuit theory, the simplest charging circuit was to use a first order RC circuit. The time constant, τ is denoted by RC, which is the product of resistance, R and capacitance, C. Charging time is approximately 5RC, where the capacitor will be charged up to 99.3% of its steady-state value. However, this is only applicable when the capacitance is small, especially in milifarad range and smaller, hence making charging time to be fast.

$$V_C(t) = V_\infty (1 - e^{-(t/RC)}) \tag{4.1}$$

where

V_C = Voltage of capacitor, V

V_∞= Charging voltage, V (steady-state value)

R = Resistance, ohm

C = Capacitance, Farad

The main problem is that supercapacitor has capacitance of 1F and higher, up to 5000F. Hence, a power resistor of very low resistance is needed. Consequently, maximum power dissipation of a power resistor will limit the amount of current that will be pumped into the capacitor during charging. With this, there will be no need for over-current protection circuit, but the charging time might increase.

The DC power supply with digital display available in the electronics lab in UTAR FES is capable of supplying a maximum current of 3A regardless of the supply voltage (up to 30V), implying no over-current will happen. Hence, the DC power supply is sufficient to be a charging circuit, by connecting the supercapitors directly, since the DC power supply has its own internal series resistance.

As for discharging, connecting the charged supercapacitor in series with a 1Ω 5W power resistor would do. This will limit the discharge current to a maximum of 2.7A. The voltage of the capacitor, at any time, t is related to the formula below.

$$V(t) = V_C e^{-(t/RC)} \tag{4.2}$$

where

V_C = Voltage of charged capacitor, V

R = Resistance, ohm

C = Capacitance, Farad

4.2.1 Supercapacitor Dielectric Leakage

Leakage is the gradual loss of energy from a charged capacitor. A capacitor will conduct a small amount of current to the electronic devices it is connected to, such as diode, even when the whole circuit is turned off. Another reason for leakage is due to the imperfection of the dielectric materials of the capacitor, causing the capacitor to slowly discharge. This process is called dielectric leakage and even happens when the capacitor is not connected to any device, where it would discharge onto the surrounding (air).

The measurements of the supercapacitor dielectric leakage when open-circuited will help in preventing the loss of energy from the capacitor when the boost converter is not turned on. Small dielectric leakage is one of the important characteristics of a good capacitor.

The Figure 4.1 below shows the voltage retention ability of capacitors having the values of 22, 50, and 100F respectively. In total, there are 5 supercapacitors. The 22 and 50F capacitors are older types of supercapacitors, thus having a voltage rating of 2.3V, while the 100F has a voltage rating of 2.7V. The 100F capacitors are initially charged up to 2.45V while the others at 2.07V. Full data tabulation can be found in Appendix A.

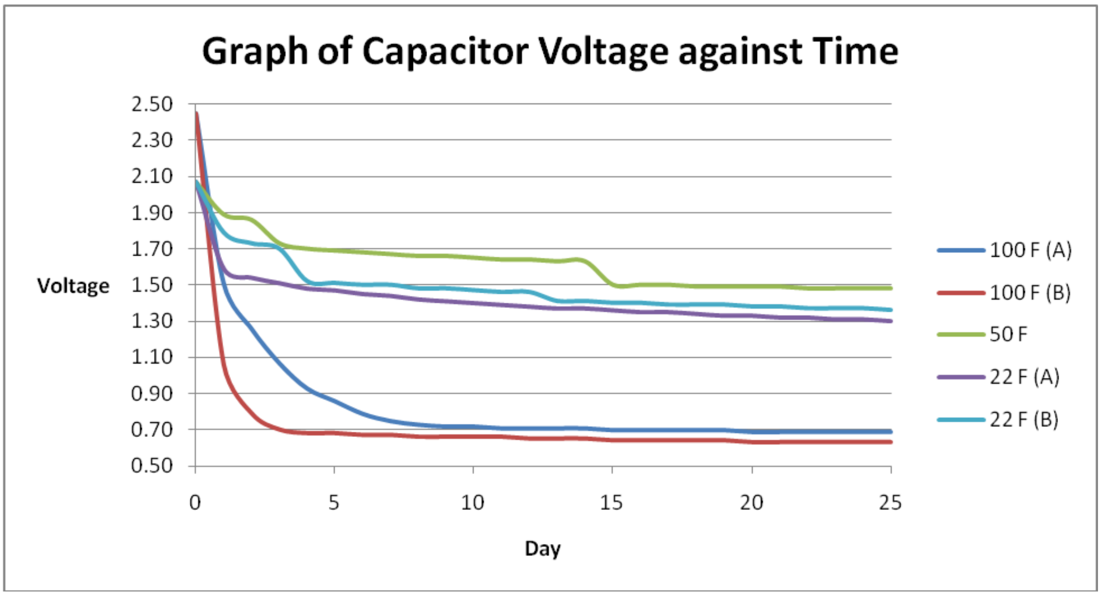


Figure 4.1: Capacitor Self Discharge Graph

Table 4.1: Voltage Retention Ability

Type	Retention (%)
100 F (A)	28.16327
100 F (B)	25.71429
50 F	71.49758
22 F (A)	62.80193
22 F (B)	65.70048

The Table 4.1 above showed that the 100F capacitors have the lowest voltage retention compared to the others. However, do note that the 100F supercapacitors are still new, and have not been regularly charged and discharged. A follow-up similar experiment is performed only on the 100F supercapacitors, after being charged and discharged rapidly for at least 50 times, as shown in Figure 4.2.

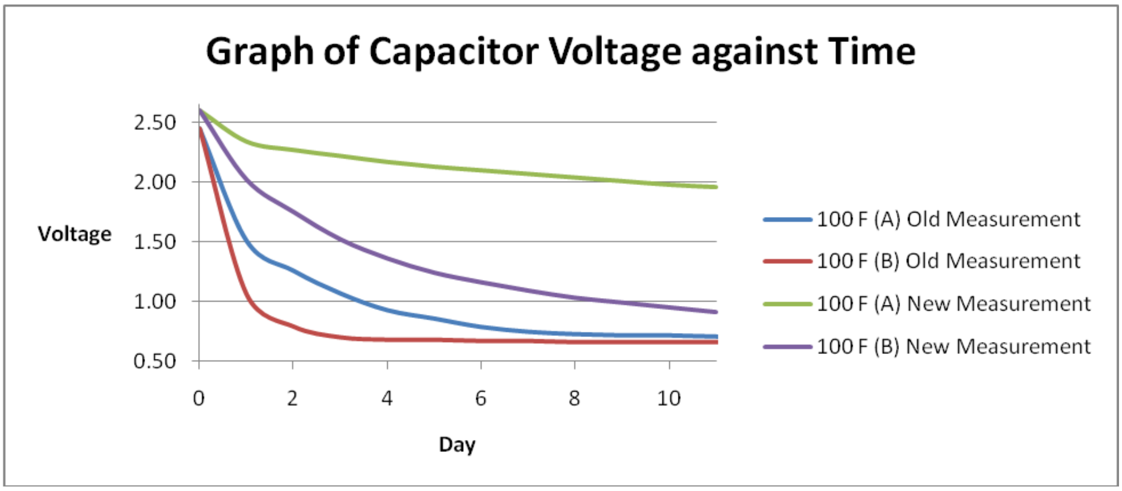


Figure 4.2: 100F Capacitors Self Discharge Graph

Table 4.2: Improvements on Voltage Retention Ability

Type	Initial Voltage (V)		Voltage at Day 10 (V)		Retention (%)	
	Old	New	Old	New	Old	New
100 F (A)	2.45	2.60	0.72	1.98	29.39	76.15
100 F (B)	2.45	2.60	0.66	0.95	27.5	36.54

As observed in both Figure 4.2 and Table 4.2, there is improvement in the voltage retention capability on both 100F supercapacitors. The 100F (A) supercapacitor will obviously meet the characteristics of a good capacitor, since it was able to retain 76.15% of its initial voltage after 10 days being kept open-circuited. As for the 100F (B) supercapacitor, the graph has proved that quality control is important when considering the use of supercapacitors as the input energy for boost converter.

In brief, it is important to determine the dielectric leakage of the supercapacitor, though it has been stated in its respective datasheet. This is because the value stated is only the average value of thousands or millions under the manufacturing test control, and this might not reflect the dielectric leakage of each supercapacitor.

4.3 Boost Converter Module

This subchapter will focus on the development of the boost converter circuit. It will provide details of converter efficiency, factors affecting converter efficiency and improvements that have been made onto it.

4.3.1 Parameter Measurements of Boost Converter Components

To have a high efficiency boost converter, the parameters of the each devices within the converter plays an important role. In brief, the explanations are:

a) The inductor should have low ESR and be able to withstand high input current, I_I. The input current is always higher than the output current because of voltage step up.
b) The diode should have low diode forward resistance, R_F and low threshold voltage, V_F.

c) The power MOSFET should be able to withstand high current across and has low MOSFET on-resistance, r_{DS}.
d) The filter capacitor should have reasonably high capacitance to provide good voltage regulation and low ESR.

All of the above will contribute to higher efficiency, if the requirements are met. Below are the measurements of the selected devices for the boost converter, using the Topward LCR Meter 5040.

Table 4.3: Parameters Measurement

Capacitor Rating (µF)	Voltage Rating (V)	At 1 kHz		At 10 kHz	
		Capacitance (µF)	ESR (Ω)	Capacitance (µF)	ESR (Ω)
47	50	43.86	1.132	42.27	1.573
68	50	62.8	0.331	59.8	0.263
330	25	346.2	0.108	410.6	0.102
680	25	686.5	0.066	1193	0.059
1000	25	902.5	0.041	2115	0.035
2200	25	1968	0.040	Unmeasureable	0.036

Inductor Rating (µH)	Maximum Current Rating (A)	At 1 kHz		At 10 kHz	
		Measured Inductance (µH)	ESR (Ω)	Measured Inductance (µH)	ESR (Ω)
100	4	97.49	0.155	94.15	0.254
100	4	102.1	0.155	98.53	0.232
100	4	103.5	0.150	91.87	0.264
100	4	94.38	0.268	91.62	0.381

From the measurements result above, it is observed that with increasing frequency, capacitance and ESR reduce for filter capacitors with ratings of 330µF and above. Higher capacitance is desirable to reduce ripple voltage. Lower ESR ensures lower power losses across the capacitor. This can be proven through both calculations and simulation.

As for the power inductors, with higher frequency, it is shown that ESR will increase and measured inductance is reduced. In comparison to capacitors, the ESR of the power inductors is a primary concern, since its magnitude is reasonably high to play a major effect to the efficiency of the converter.

Therefore, it is deduced that the switching frequency of the PWM waveform will affect the ESR experienced by the devices. As for the forward resistance, R_F of the Schottky diode is not measureable through lab equipments; we assume the value is small that the diode power loss can be neglected. An IRF530N n-channel power MOSFET will be used because it has a nominal ultra low on-resistance ($r_{DS(ON)}$ = 0.064Ω when V_{GS} = 10V) and current carrying capability of up to 22A. The full parameters of the Power MOSFET will be referred from the manufacturer's datasheet, which can be found in Appendix C.

4.3.2 Initial Boost Converter Design

The initial boost converter design started with:

a) Switching frequency, f_s = 100 kHz (from function generator)
b) Inductor, L = 200µH (nominal)
c) Capacitor, C = 380µF (measured 346.2µF and 0.108Ω at 1 kHz)
d) Fixed 12V output voltage by controlling switching frequency duty ratio, *D*.
e) Fixed input voltage using power supply (3V to 5.4V)

Three resistive loads are tested, which are 981Ω, 326Ω and 100Ω to obtain output currents of 0.012A, 0.036A and 0.12A respectively. The output voltage is regulated at 12V. From the Figure 4.3 shown below, it shows that the boost converter can maintain an efficiency of more than 80%, regardless of whether the input voltage is 3V or 5V, when the output current is less than 55mA or when the output power is less than 0.66W. Full result is attached in Appendix A.

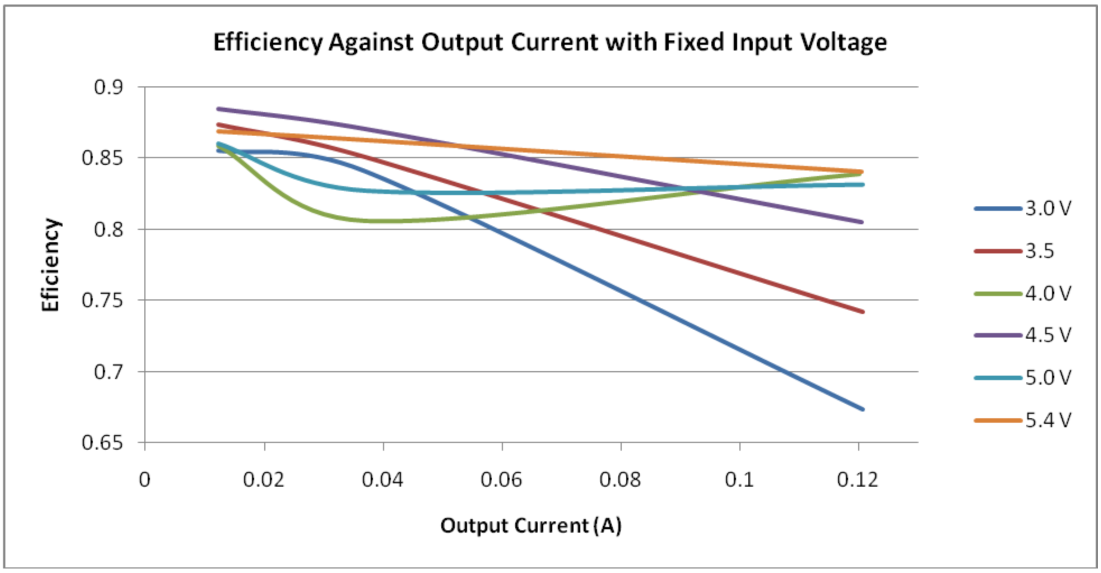


Figure 4.3: Converter Efficiency against Output Current

The next dramatic approach is to produce an output current of about 1A using the same circuit configuration. A high input current is required, up to 2.46A, resulting in a very low efficiency. Furthermore, though controlling the duty ratio, D the regulated output voltage, V_O of 12V could not be achieved (maximum output voltage of 8.5V and output voltage of 0.71A).

The problem of efficiency drop when the output current is more than 55mA and failure to obtain output of 12V, 1A prompted for the following future improvements:

- To increase efficiency – At large output current, efficiency is drastically reduced.
- To improve output voltage stability - With increasing output current, noticeably from 100mA and greater, the output voltage ripples become worse. Oscilloscope shows that the ripple is a decaying sinusoidal wave of high frequency.

Next, would be testing a DC PM Motor with ratings of 12V, 1A as the load of the prototype circuit. The motor rotates under no load condition; therefore the current consumption is small, at 80mA. Results are shown below.

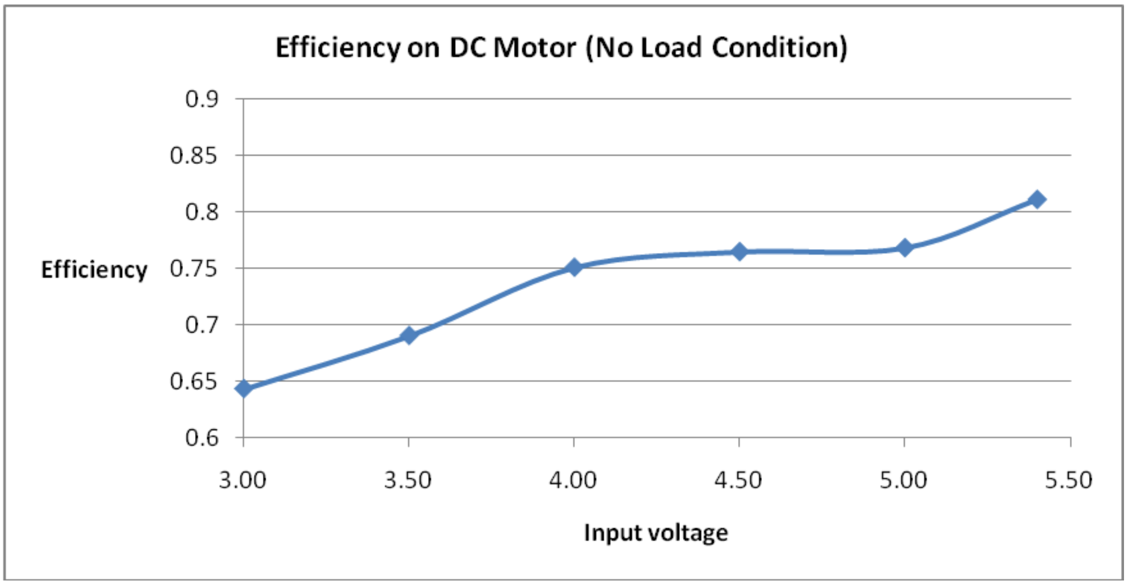


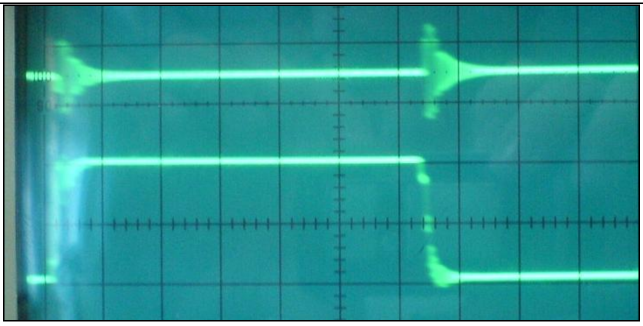
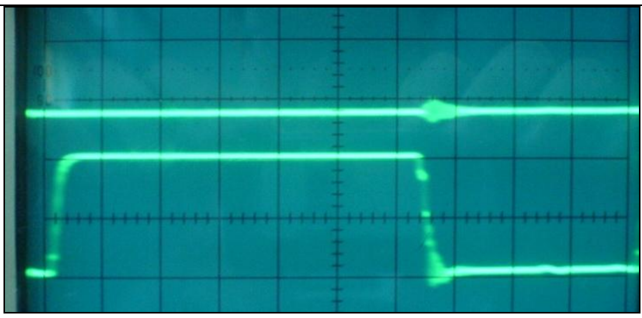
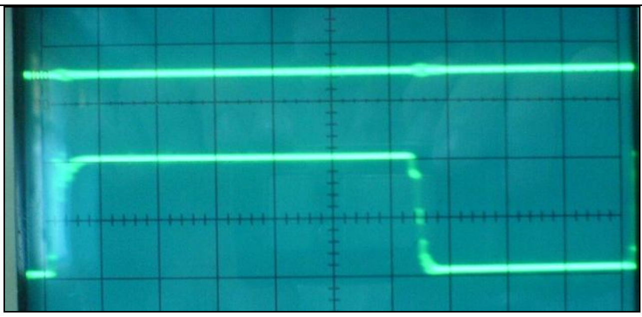
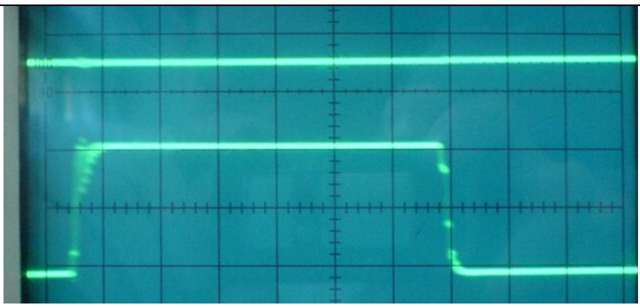
Figure 4.4: Efficiency on DC Motor under No-Load Condition

Apparently, with lower input voltage, the efficiency becomes lower. Under the same output current condition, the efficiency is lower when compared to using a pure resistor as load. This may due to the fact that the DC PM motor can be regarded as an inductive load. Therefore, there is a need to improve the initial boost converter design, in terms of efficiency, voltage quality (ripples) and higher output current. This will be discussed in the next few subchapters.

4.3.3 Improvements on Initial Boost Converter Design

As discussed earlier, the problems with the initial design is low efficiency and high output voltage ripples at high output current. For the voltage ripples, a low pass filter must be incorporated into the basic boost converter circuit, as shown in Table 4.3.

Table 4.4: Improvement for Output Voltage

Conditions	Oscilloscope Output	Observation
No filter		High voltage ripples are observed at the output voltage, V_O during switching time of the PWM signal. The pulse in the oscilloscope is the PWM signal.
Filter 1		Smaller voltage ripples are observed at the output voltage, V_O during switching time of the PWM signal. However, it results in a lower output voltage. Output voltage, V_O = 8.6V.
Filter 2		A small ripple voltage is observed. Output voltage, V_O = 12V.
Filter 3		A minimum ripple voltage is observed. Output voltage, V_O = 12V.

Voltage ripple is proportional to the output current, I_O. Hence, the low pass filter is tested under the conditions of V_O = 12V, I_O = 0.12A, V_I = 5.4V where the efficiency of the converter is relatively high, about 84%.

To achieve the smallest output ripple voltage, it has been shown experimentally that Filter 3 has produced the best outcome. Filter 3 would only require an additional inductor that is placed between the Schottky diode and the load. The source of ripple voltage is found to come from the filter capacitor that stabilizes the output voltage. Now that the voltage quality (ripples) has been improvised, the next subchapter will focus on improving the efficiency and analysing the present boost converter's parameters.

4.3.4 MATLAB Simulation Results

It was first thought that the low efficiency of the initial boost converter design is due to the low inductance value of the power inductor. In the chase for improving efficiency, there were ideas of:

a) using cascaded switching,
b) using bipolar switching with or without transformers,
c) using synchronous rectifiers,
d) to parallel up the power supply to increase input current as power supply is only capable of delivering 3A at any given voltage, and
e) to use buck-boost converter instead, if the efficiency is higher.

However, the ideas above will add complexities to the present boost converter circuit, and there might be more power losses associated with the introduction of new components into the boost converter circuit. With the availability of MATLAB software to simulate the working characteristics of the boost converter circuit under different parameter values, the findings as shown by the simulations result are:

a) Merely increasing inductance value does not help in increasing efficiency. The inductor's inductance value will determine whether the circuit will operate in either continuous conduction Mode (CCM) or discontinuous conduction mode (DCM)
b) Simulation results show that frequency of the PWM waveform, whether it is 10 kHz or 100 kHz, it does not affect the efficiency. It only affects the frequency of the output ripple voltage of the boost converter. However, experimental results has shown that using 10 kHz frequency for the PWM waveform will result in higher efficiency, up to 10% more, compared to using 100 kHz frequency.
c) Simulating an almost ideal boost converter, with low ESR on both the filter capacitor and power inductor, will yield high efficiency (when V_I = 5V, efficiency is about 84.6% for I_O = 1A with D = 0.642, f_s = 100 kHz). In contrast, substituting the low ESR with measured ESR of both the filter capacitor and power inductor, output current of 1A could never be reached. Therefore, ESR, especially from the power inductor, will tremendously affect the efficiency of the boost converter. (Note that for both simulation models, all other parameters values are the same, following respective measured value or from the datasheet)
d) A particular duty ratio, D of the PWM waveform at any frequency will not result in the same output voltage of the boost converter, even when the input voltage is the same.

With the findings above, the limitations of the initial circuit design have been discovered. To get the best components for the boost converter, such as obtaining a power inductor with a very low ESR is possible, but might be difficult. It may need to custom-made or purchased online from the Internet. Therefore, it is of best interest to improve the initial circuit design by doing appropriate simulations. The best inductance value is found to be 100μH.

A simulation example is shown in Figure 4.5 and Figure 4.6. With V_I = 5V, efficiency is about 82.7% for I_O = 0.5A, D = 0.645, L= 100μH and f_s = 10 kHz. The circuit can be observed operating in DCM, where the inductor current (Iout in Pin in

Figure 4.6) will fall to zero at particular time interval. Since the simulation result has shown that an inductance of 100µH will yield the highest efficiency with output current of up to 0.5A, it is essential to determine whether the simulation result agrees with the experimental result. This will be covered in the next subchapter.

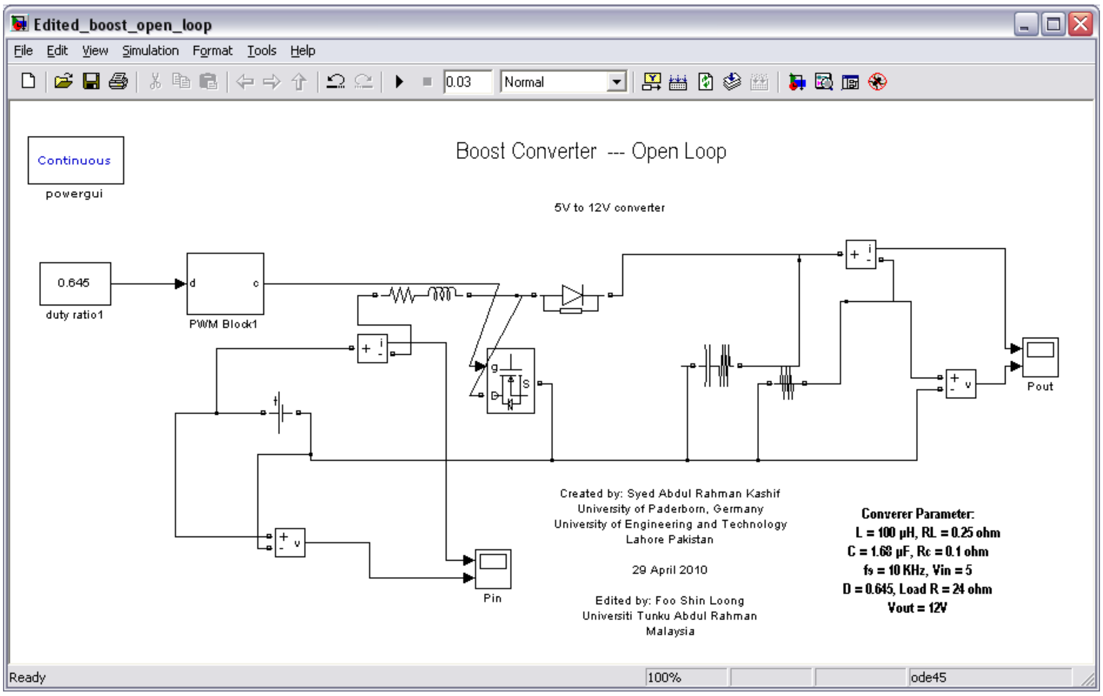


Figure 4.5: MATLAB Simulink Model

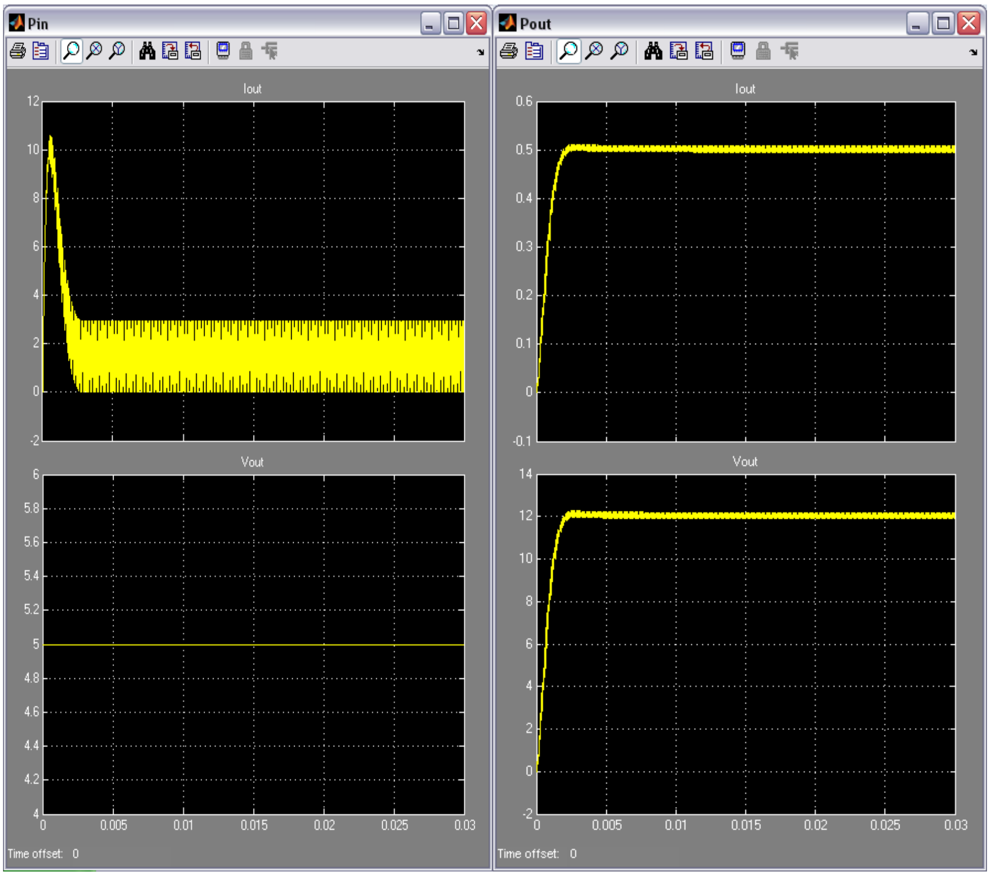


Figure 4.6: Efficiency Meter in Simulink Model

4.3.5 Efficiency Analysis

The MATLAB simulation results has pointed out that inductance value of 100µH would provide high efficiency at higher output current, I_O. Meanwhile, it is also discovered experimentally that switching frequency, f_s of the PWM waveform will affect the efficiency of the boost converter at higher output current, I_O.

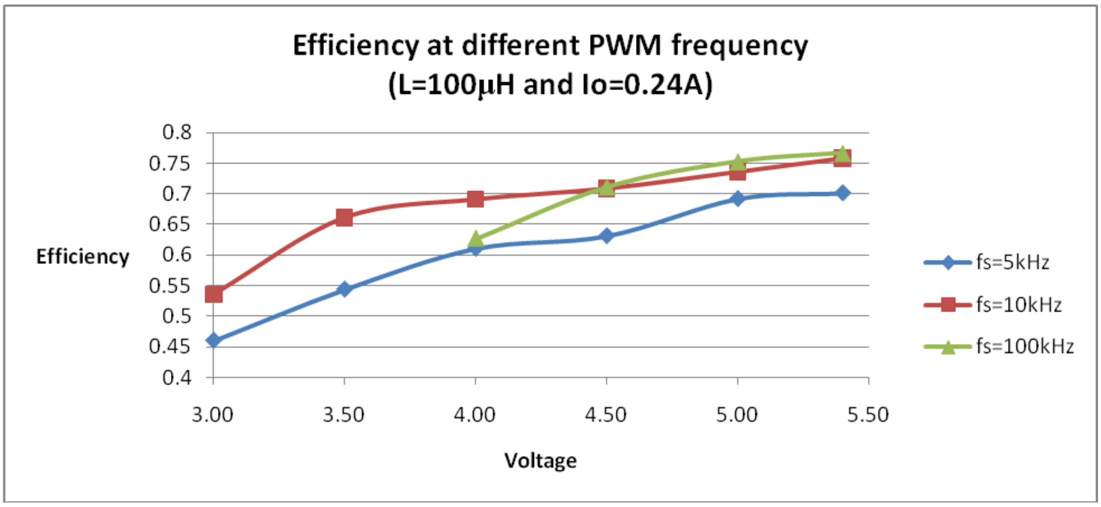
It is then necessary to verify the simulations result with the experimental results. Below is the configuration of the circuit.

a) Switching frequency, f_s = 5, 10 or 100 kHz (from function generator)
b) Inductor, L = 100 or 200µH (nominal)
c) Capacitor, C = 380µF (measured 346.2µF and 0.108Ω at 1 kHz)

d) Fixed 12V output voltage by controlling switching frequency duty ratio, *D*.

e) Fixed input voltage using power supply (3 to 5.4V)

The full data from the experiment can be referred in Appendix A. For ease of understanding, the graphs below are plotted.



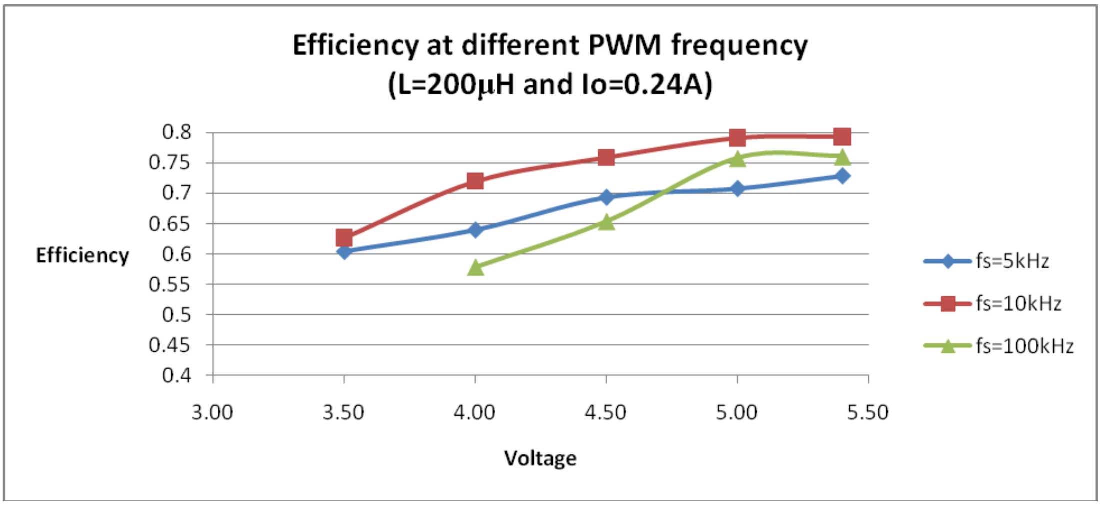
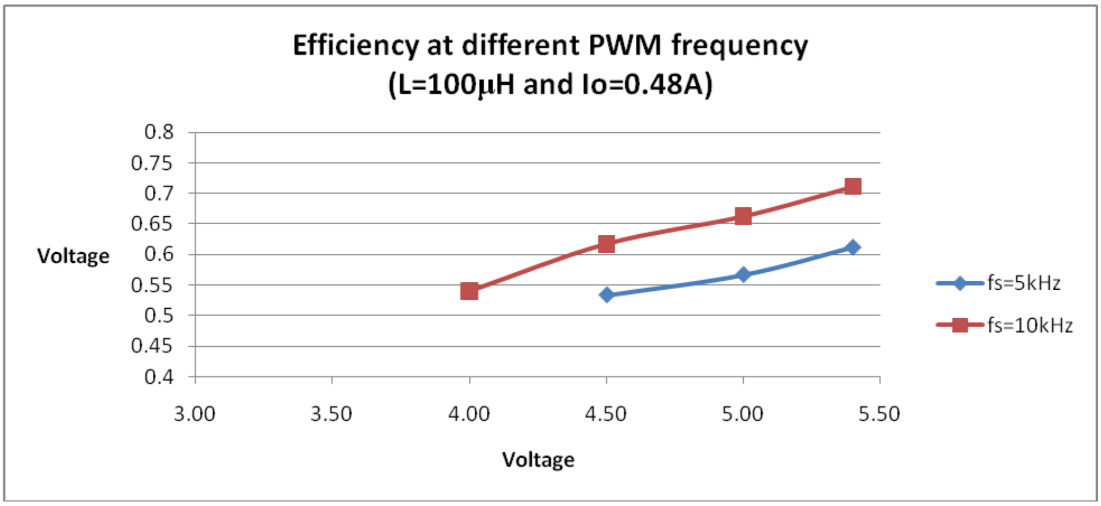


Figure 4.7: Efficiency Graph when L=100µH or 200µH and $I_O = 0.24$A

As shown from both Figure 4.7, at output current of $I_O = 0.24$A, using an inductor of L = 200µH will yield slightly higher efficiency, regardless of the switching frequency, f_s. However, do note that when L = 200µH, the output of 12V and 0.24A will not be reached, when the input voltage is 3V. This is due to the reason that higher duty ratio of the PWM waveform is needed to boost (step up) the low input voltage, but high duty ratio (D>0.85) leads to more power losses in resistive elements of the individual devices within the boost converter, particularly the power inductor. Thus, voltage boosting to 12V is not possible. When the concern of meeting the requirement for the boost converter to be operational when the input voltage is between 3 to 5.4V, using L = 100µH will be a better choice, while compromising a little on efficiency.

Simulations results have also revealed that output current of 0.5A can be achieved with the present circuit (With V_I = 5V, efficiency is about 82.7% for I_O = 0.5A, D = 0.645, L= 100µH and f_s = 10 kHz). Below are the two graphs that reflect the experimental results.



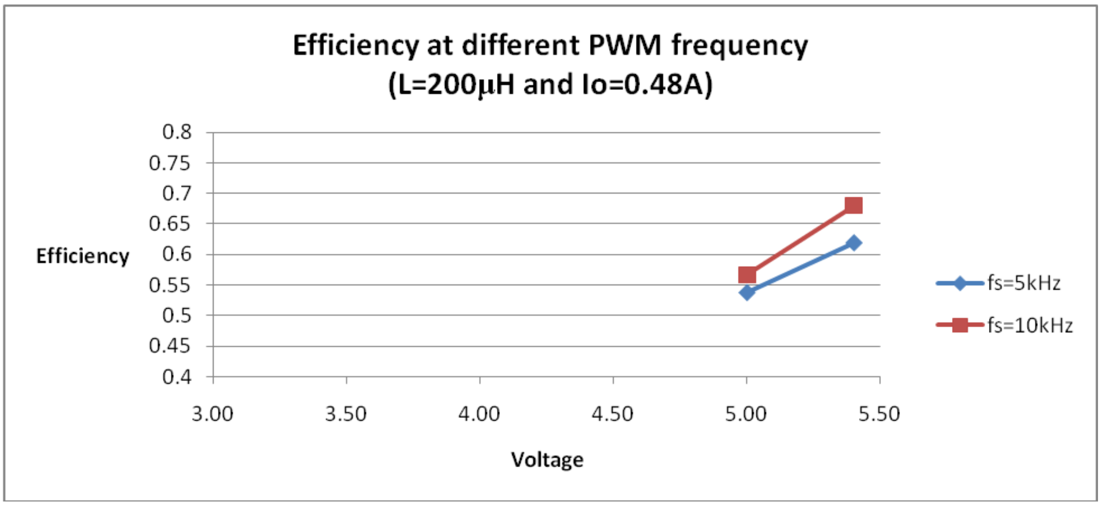


Figure 4.8: Efficiency Graph when L=100µH or 200µH and I_O = 0.48A

The actual result of about 66% compared to the simulated result of 82.7% clearly does not tally. However, the finding has shown that an output of 0.5A is achievable, though the efficiency is mostly reduced by the ESR of the inductor. The results when switching frequency, f_s is 100 kHz is not shown because boosting is totally impossible (ESR of the inductor is higher at higher frequency, leading to greater power losses). Hence, it can be concluded that inductance of L = 100μH and f_s = 10 kHz will be chosen, as supported by the graphs above.

4.3.6 Finalised Boost Converter Design

The few earlier subchapters have has pointed out few improvements that can be implemented on the present boost converter. Therefore, the finalised boost converter will incorporate an inductor that is placed between the Schottky diode and the load as a low pass filter. Apart from the change of PWM frequency from 100 kHz to 10 kHz and inductance value to 100μH for efficiency improvements, the other parameters remain the same as the initial design value.

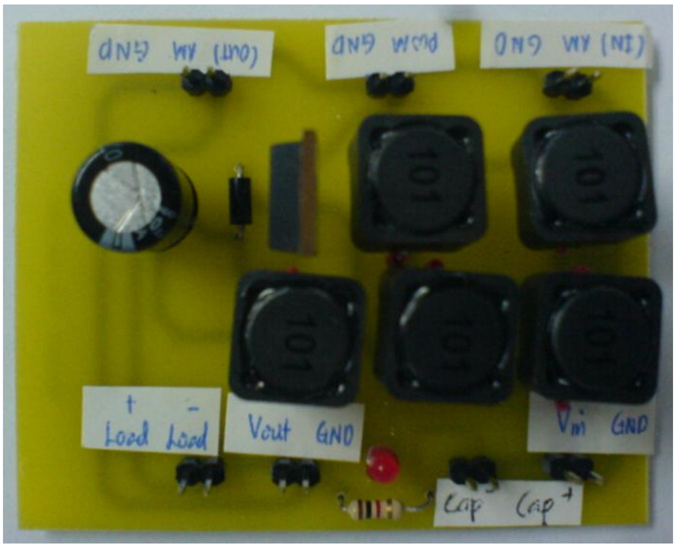


Figure 4.9: Finalised Boost Converter Design

4.4 PWM Module

With reference to subchapter 3.6, a PWM Module is designed. The values of components being used are:

a) R_A = 46.7Ω (Nominal value 47Ω)
b) R_B = 3.83k Ω (Nominal value 3.9kΩ)
c) C = 0.069µF (Nominal value 0.1µF)

This yields a PWM frequency of about 5.69 kHz, as shown in Figure 4.11. Unfortunately, the desired frequency of 10 kHz can't be reached due to the hardware limitation of the 555 timer itself. The PWM can be modulated to have a duty ratio ranging from 0.1 to 0.95, proportional to modulation input from 0.3V to 4.6V (V_{CC} = 5V). This can be seen from Figure 4.11. For any higher duty ratio higher than 0.95, the PWM module will reduce its PWM frequency by half (frequency divider). However, this will not become a problem since boosting is not possible at duty ratio more than 0.95, since power losses are high.

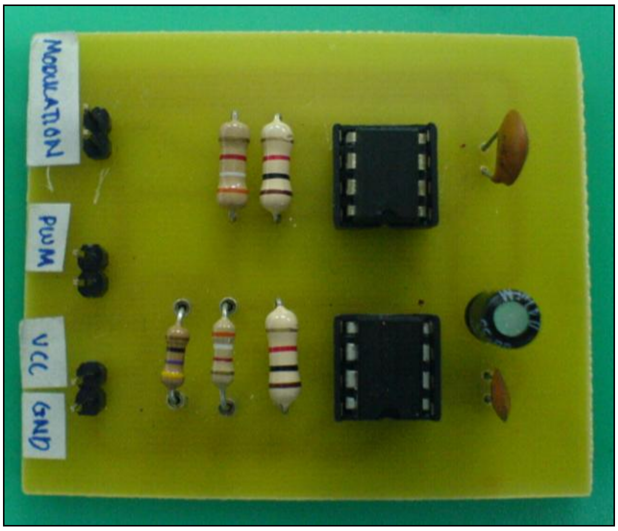


Figure 4.10: PWM Module

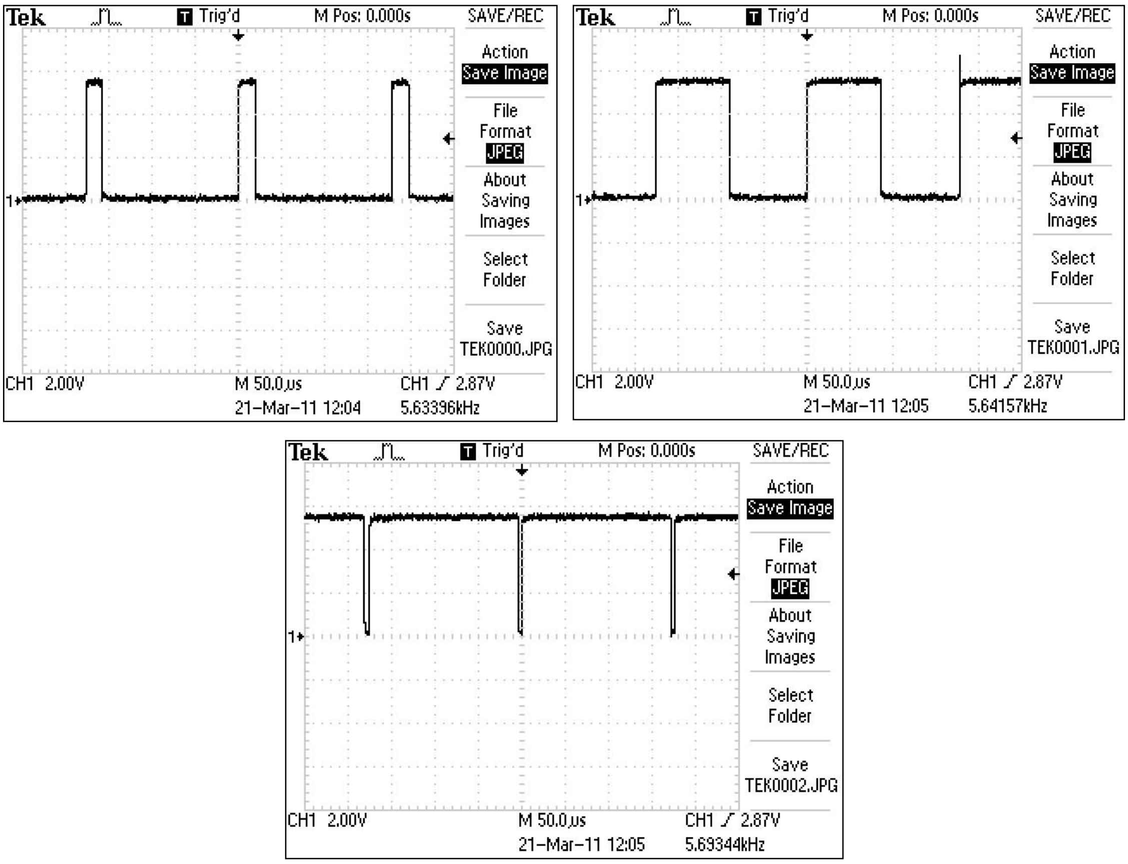


Figure 4.11: Variable Duty Ratio Waveform from PWM Module

The next question is then to justify the performance of this PWM module shown in Figure 4.12 compared to the PWM waveform from the function generator. The input voltage of the boost converter is supplied by the DC power supply in this experiment. As compared to Figure 4.3, where the PWM is supplied by the function generator, there is a decrease of about 10% of efficiency when using the PWM module. But, do note that when switching frequency, f_s is 100 kHz (For Figure 4.3), efficiency is definitely higher at low output current (I_O < 0.12A). With higher output current, efficiency will be at its optimum value when switching frequency, f_s is 10 kHz. Meanwhile, the PWM module can only generate PWM frequency of 5.69 kHz compared to the desired frequency of 10 kHz. This will definitely reduce the efficiency by a little amount.

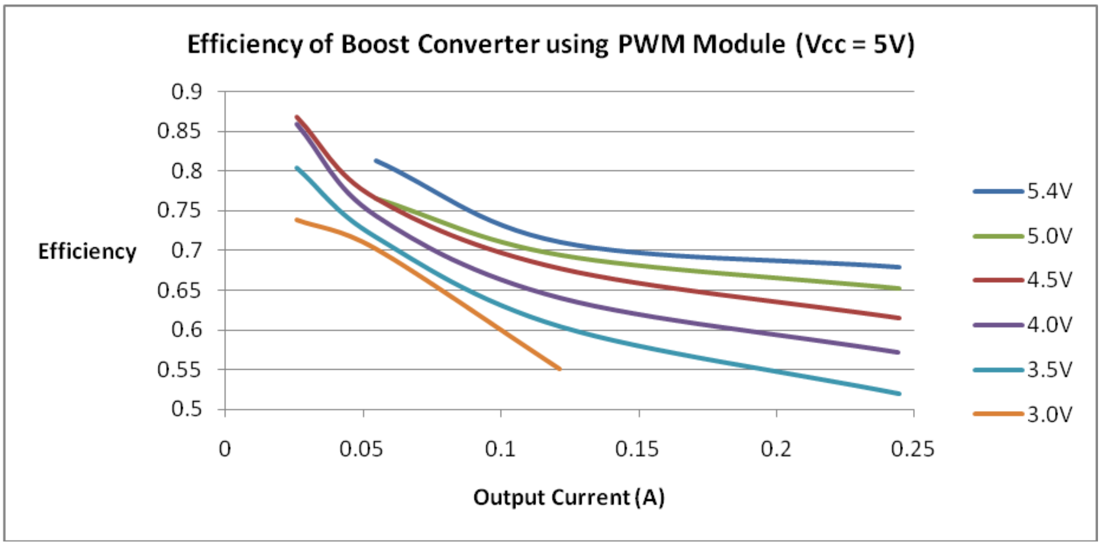


Figure 4.12: Efficiency of Boost Converter using PWM Module (V_{CC} = 5V)

When the PWM module is used to drive the MOSFET to achieve higher output current, I_O at the boost converter side, particularly in the range of 0.48A, the PWM module was unable to produce a perfect PWM waveform. This scenario happened when the PWM Module increased its PWM waveform duty ratio to maintain a regulated output voltage at the boost converter side. Hence, this increased the amount of current flowing across the power inductor and MOSFET. The inability of the PWM module to sustain it PWM waveform led to the results observed in Figure 4.13.

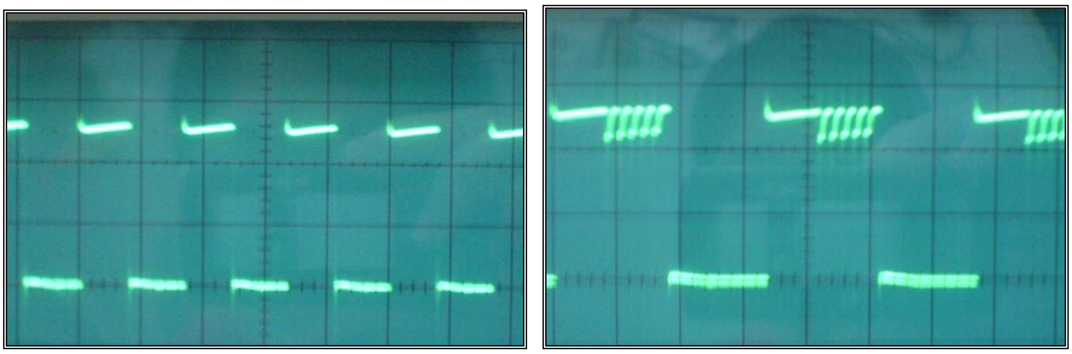


Figure 4.13: PWM waveform Distortion as the duty ratio increases, leading to distortion and frequency division.

Such ripple on the PWM waveform could only be observed on the analogue oscilloscope, while through digital oscilloscope, it will be fairly displayed out as small noises. Note that the amplitude of the PWM is 5V (2V/division). Further troubleshooting has shown that the minimum amplitude for the PWM, to avoid distortion is 5.4V. This implies that the required minimum voltage supply to the timer, V_{CC} would be 5.4V as well. For this reason, the V_{CC} supply will be of a value higher than the minimum to avoid distortion (V_{CC} = 5V was used in previous tests) and ensuring high output current of 0.48A. This improvement, of using V_{CC} = 6V instead of 5V, will be implemented and discussed in the next subchapter. In the next subchapter, the system will comprise of the boost converter, the PWM Module and the Integrator Module.

4.5 Integrator Module

The boost converter and the PWM module has been an open loop circuit throughout the previous experiments. Modulation input was given manually to the PWM Module to regulate the output voltage, regardless of the input voltage and output current. Through the introduction of an integrator module into the present circuit, a closed loop circuit is formed.

With the inclusion of the integrator module, the PWM is dynamically changing. Below, as shown in Figure 4.14, is the graph of the efficiency of the boost converter incorporating the PWM module and Integrator Module to form a closed-loop circuit. Note that the V_{CC} of the PWM module is now 6V, and consequently there will be no PWM waveform distortion anymore. In addition, the losses associated with the distortion is no longer existing, leading to higher efficiency throughout the range of output current compared to Figure 4.12. Output current of 0.48A is also achievable at certain range of input voltage, which is between at 5 to 5.4V.

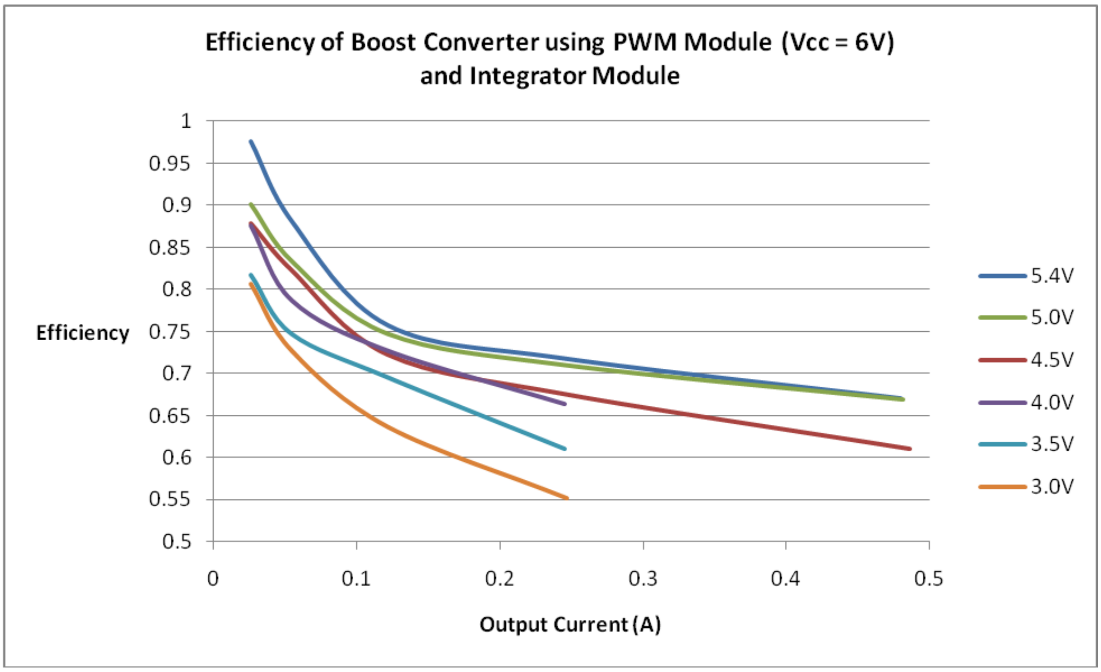


Figure 4.14: Efficiency of Boost Converter using PWM Module (V_{CC} = 6V) and Integrator Module

4.6 Using Supercapacitor as an input source to the Boost Converter

Generally, a supercapacitor, when fully charged, will be storing an amount of energy. The energy stored is dependent on its capacitance and also voltage rating. With the completion of the closed loop boost converter, the next step is to proceed with using the supercapacitor as the input source to the boost converter. Unlike the DC Power Supply, the voltage of the supercapacitor will not be constant. In fact, it decreases as energy is being discharged out from the supercapacitor.

The result of this experiment is measured and recorded through Universal asynchronous receiver and transmitter (UART) using the PICKIT 2 that is connected to the power meter developed by my project partner, Mr. Choong Pak Wai. Through this, real-time monitoring is accomplished where at every small interval of time, the measurements of voltages and currents are made.

The data recorded in this experiment will be used by Choong Pak Wai for his tabulation of efficiency and further analysis. Hence, this subchapter will not be touching much on the data of the experiment. However, there are two new findings that was made while the experiment was conducted, that will be briefly discussed here. They are as follow:

a) When higher amount of current is being drawn out from the supercapacitor, there is drastic drop of voltage across the supercapacitor. Amazingly, the voltage will increase when the supercapacitor is taken out from the system.
b) The integration of the power meter into the boost converter system (with PWM and Integrator Modules) will incur a small loading effect through its current measurements. Hence, do anticipate that the efficiency tabulations from the UART will be marginally lower that what that has been discussed in this whole chapter.

4.6.1 Voltage Regulation and Duration of Use

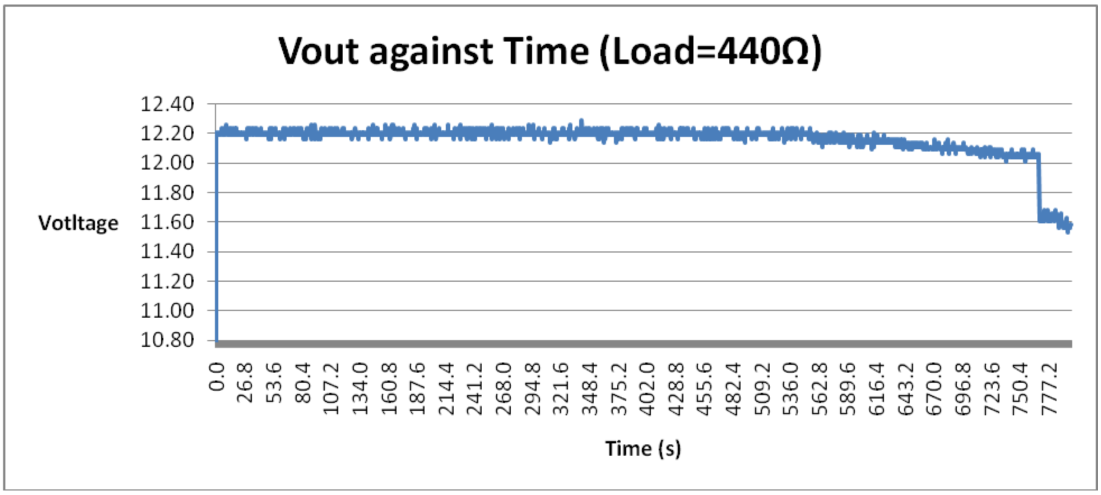
With reference to Figure 4.15, the closed loop energy storage system comprising of the boost converter, PWM Module, Integrator Module and supercapacitor as the energy input is tested on there resistive loads, which are 440Ω, 50Ω and 25Ω.

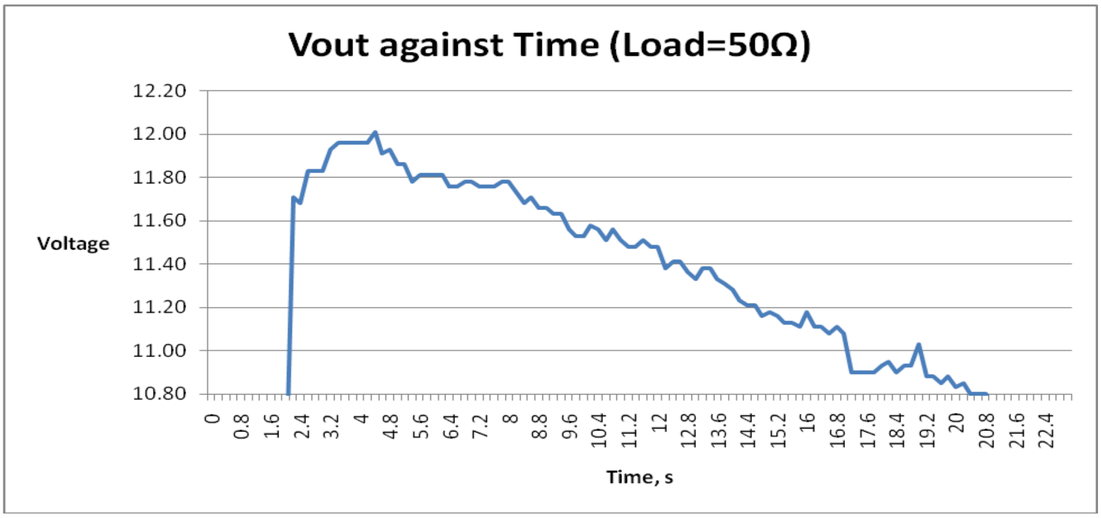
In this test, two 100F supercapacitors are connected in series and charged up to 5V (nominal energy amount of 625J). Note that when the load is 440Ω, the regulation time, t_r is about 768 seconds (12.8 minutes). The regulation time, t_r is the duration where the system is capable to maintain a voltage at around a constant value of 12V.

However, when a load of smaller resistance such as 50Ω is used, implying a higher output current of 0.24A, regulation time is actually smaller. As shown from the graph, the regulation time, t_r is about 16.4 seconds (from 12V until it dropped to 10.8V). Meanwhile, when load of 25Ω is used, boosting to 12V is not achievable (maximum voltage was about 7.5V).

The explanations for these two load conditions (50Ω and 25Ω) are actually quite simple. For the case of 50Ω, with higher output current at the boost converter side, more energy is drawn from the supercapacitors in a shorter period. The lesser the energy that still remains in the supercapacitors, the lesser the voltage across it. Since boosting to 12V is normally achievable when the input voltage to the boost converter is equal or higher than 3V, this means that the output voltage regulation of 12V is no longer possible after 16.4 seconds because the input voltage (supercapacitors voltage) is already below 3V (Input voltage graph is not shown here).

As for the case of 25Ω, when high current in ampere range is drawn from the supercapacitor, the supercapacitor voltage drops instantly from its intial voltage of 5V. This phenomena actually happened for case of 50Ω as well, but the supercapacitors' voltage was still higher than 3V at the very beginning, thus boosting to 12V was still possible. In this case of 25Ω, the current drawn from the supercapacitor was 2A and voltage across the supercapacitors after the instantaneous drastic drop was measured to be less than 3V. This instantenous voltage drop happened in less than 1 second, with an initial supercapacitors' voltage of 5V. Hence, output voltage of 12V on the boost converter is not possible. Do note that if the supercapacitor is taken out from the system directly, the supercapacitors' voltage will increase back, up to 1 to 1.5V.





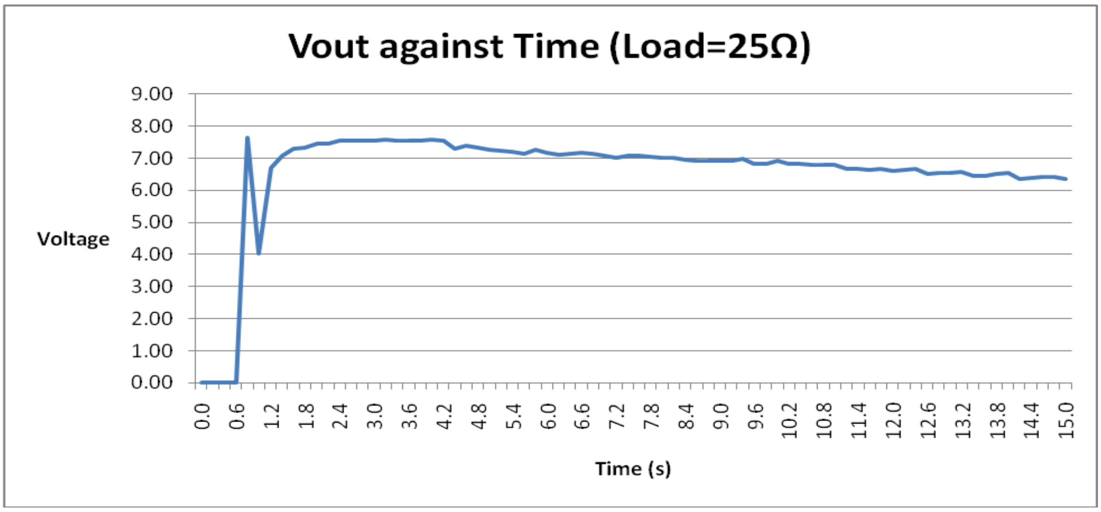


Figure 4.15: Voltage Regulation when the load resistance is 464Ω, 50Ω and 25Ω

The resistive load is then replaced with a DC motor, as shown in Figure 4.16. The DC motor consumes about 80mW in this experiment. The outcome of this experiment is actually quite promising, since with just 2 supercapacitors of 100F each, the DC motor can be operated for about 117 seconds (1.95 minutes). Scaling up of this system can be done in the future so that it can be used on the DC motor of an electric vehicle (EV).

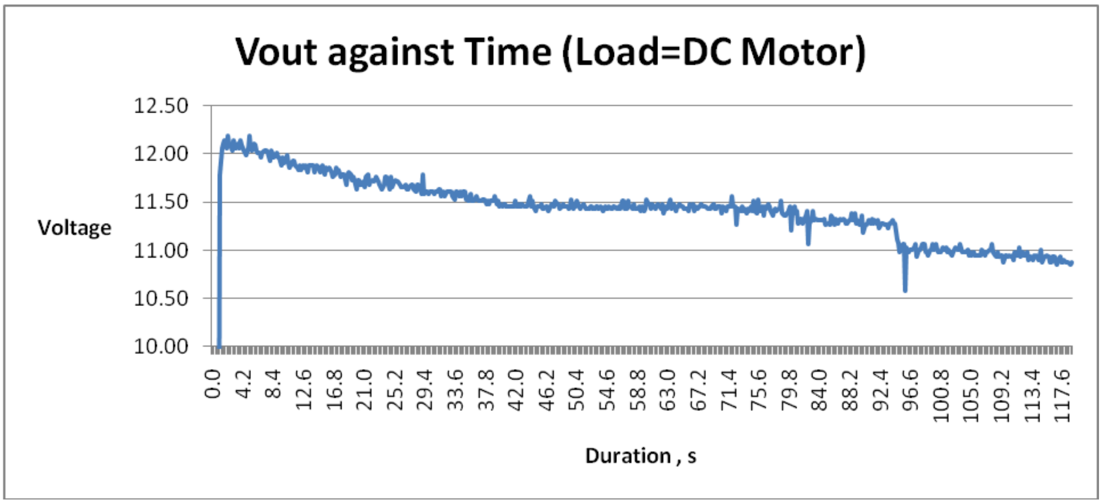


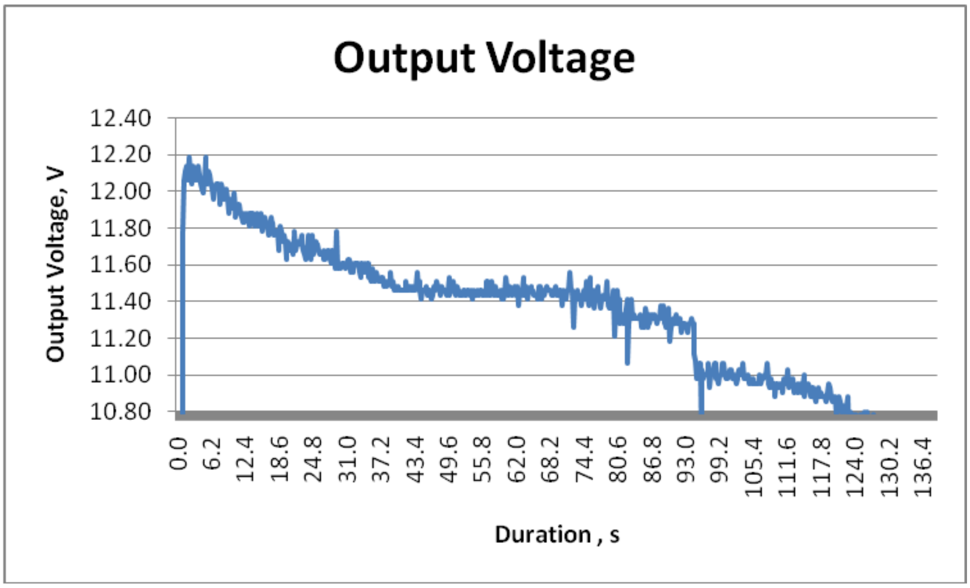
Figure 4.16: Voltage Regulation when the load is a DC Motor

4.6.2 Loading Effect from the Current Sensing

The graphs shown in subchapter 4.6.1 incorporate the use of the ammeter module, which causes the reduction of efficiency. Efficiency is reduced because there is power dissipation across the sensing resistors, which function to measure the current at the input and output side of the boost converter.

The loading effect is illustrated in Figure 4.17, with DC Motor as the load of the boost converter. When sensing resistors are included for the purpose of current measurement, the regulation time is found to be 93 seconds. Meanwhile, when sensing resistors are excluded from the system, the observed regulation time is 134.6 seconds. The output voltage of 11.2V is made as the threshold point for voltage regulation in this test.

Here, there is an increment of about 31% of regulation time when sensing resistors are removed. Obviously, the loading effect, which refers to the power dissipation acros the sensing resistor, will have an effect to the boost converter's operational time. Therefore, the ammeter module has to be improvised in order to reduce or eliminate the loading effect.



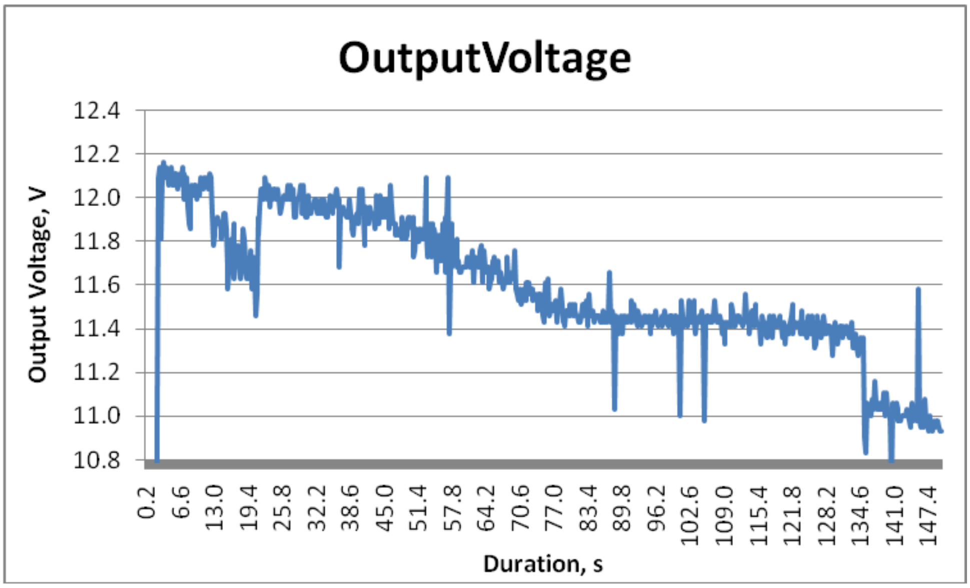


Figure 4.17: Regulation time with and without sensing resistors

4.7 Comparison of Finalised Boost Converter Design with Integrated Circuit Voltage Regulators and Theoretical Calculations

The few previous chapters have been analysing the operations of the self-designed boost converter. To make this product marketable, it is essential to make a comparison with the switching-mode IC voltage regulators that are available in the markets. The comparison is shown in Figure 4.18 with MAX1674 by Maxim Integrated Products.

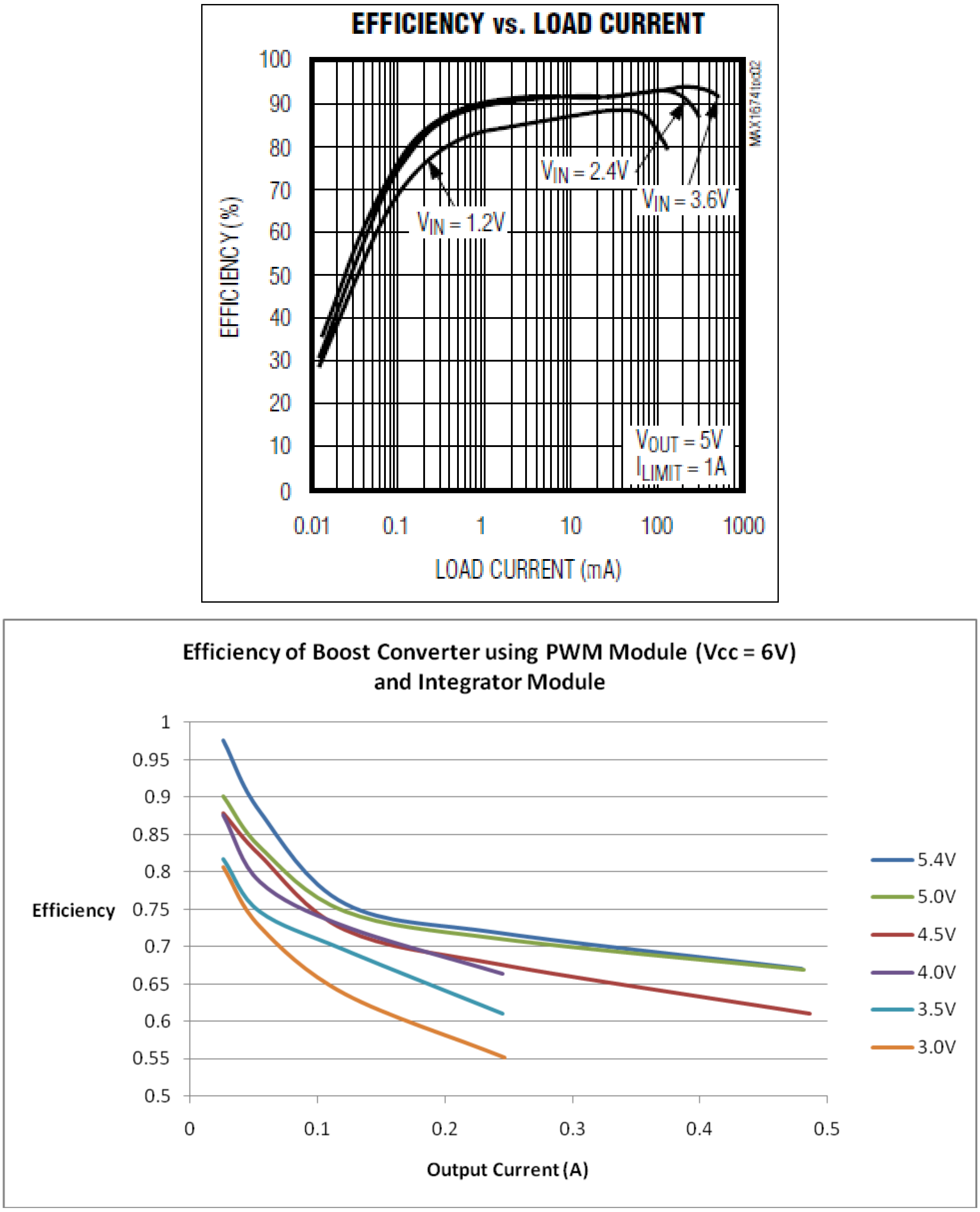


Figure 4.18: Efficiency graph for IC Voltage Regulator MAX1674 (V_O = 5V) and Self-designed Boost Converter (V_O = 12V)

Ultimately, in terms of efficiency, the self-designed hardware is lagging behind when it comes to higher output current. However, the versatility of this self designed hardware is that the parameters of the boost converter can be changed, so that the efficiency can be increased. An as example, the aspect of improvement can be from reducing the ESR of circuit, especially at the power inductor side. Thus, the self-designed boost converter can still be considered in development stage, where many enhancements are possible, if more time is given. Furthermore, the power output of the IC voltage regulator is limited to 5W, while for the self-designed hardware, power output can be more than what it is capable now (6W), provided that necessary adjustments in parameters are made.

In the subchapter 3.5, it was mentioned that the calculations on the boost converter circuit will be based on the book *Pulse-width Modulated DC-DC Power Converter* by Kazimierczuk, M. K. As there were many formulas that would be used, the calculations were made easier by putting them in Microsoft Excel Spreadsheet. Calculations were done on both CCM and DCM formulas. The DCM formula, which was not included in Chapter 2, is shown below (4.3). However, the result of the theoretical calculations didn't bring positive outcome, as the calculated efficiency is very high, compared to the experimental results. Even output of 12V, 0.5A is possible when the input voltage is 3V, through calculations. This on the other hand, is not possible with the actual circuit.

$$\eta(DCM) = \left[1 + \frac{4 r_{DS} R_L D^3}{3 f_s^2 L^2} \frac{1}{\left(1 + \sqrt{1 + \frac{2D^2 R_L}{f_s L}}\right)^2} + \frac{4DR_F}{3 f_s L} \frac{1}{\left(1 + \sqrt{1 + \frac{2D^2 R_L}{f_s L}}\right)} + \frac{2Dr_L}{3 f_s L} + \frac{V_F}{V_O} + f_s C_O R_L \right]^{-1} \tag{4.3}$$

where

η = efficiency of converter

r_{DS} = MOSFET on-resistance, ohm

f_s = switching frequency, hertz

D = duty cycle ratio

L = inductance, Henry

R_F = diode forward resistance, ohm

R_L = load resistance, ohm

r_L = ESR of inductor L, ohm

V_F = threshold voltage of diode, V

V_I = input voltage, V

V_O = output voltage, V

C_O = transistor output capacitance, assuming linear, Farad

The theoretical calculations could not be accepted in our comparison because many parameters are obtained from the datasheets and not through actual measurements. Besides that, many assumptions are made, such the paramaters are constant all the time (practically, r_{DS} changes with V_{DS}). As for this moment, MATLAB Simulation provides the best results that can tally with the experimental results, though they are some differences.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Summary

In the practical design of a boost converter, it is necessary to obtain the parameters of the components that will be used. This includes the power inductor, the Power MOSFET, the diode and the filter capacitor. The parameters are important, since it will affect the efficiency of the boost converter. Analysis of the circuit is also important, so that minimum requirements for the circuit to function normally are met. Below are the summarised findings.

1. **Equivalent Series Resistance (ESR)**

   In practise, capacitor and inductor will have non-zero resistance. The resistance can be modelled in series with the capacitance or inductance, which is called the equivalent series resistance (ESR). It is normally measured at direct current (DC) condition; hence it is also common to be referred as DC resistance (DCR).

ELECTRICAL SPECIFICATIONS

Capacitance: 100 F
Temperature range: -40°C to +65°C
ESR (AC):9 milliOhms at 120 Hz and 20°C
ESR (DC): 12 milliOhms at DC and 20°C
Weight: 21 grams

Figure 5.1: Specifications showing that ESR is dependent on frequency

Through measurements, it has been found that the ESR of the devices, particularly the power inductor and filter capacitor is not constant. With increasing frequency, the ESR of the power inductor increases while the ESR of the filter capacitor decreases. Figure 5.1 above refers to the specifications of the supercapacitors from Illinois Capacitor, which has proven the earlier statement of ESR change with frequency. The increment of the ESR in the power inductor will contribute to more power losses, hence lower efficiency.

The power inductor used in this boost converter is a Surface Mounted Power Inductor, with a rated ESR value of 0.15Ω at DC and maximum current of 4A. The increase of ESR is mainly due to the ferrite core of the inductor in addition of skin effect with higher frequency. Hence, when the design of the boost converter is concerned, there might be a need for custom design, or through proper selection so that the ESR is as low as possible.

2. PWM switching frequency, f_s

It has been shown experimentally that at high PWM switching frequency, f_s namely 100 kHz, high output current of 0.48A could not be reached. In addition, at fixed output voltage and high output current, it was found that efficiency is different, depending on the switching frequency, f_s. This experimental finding is actually supported by the datasheet of LTC3422, a switching-mode IC voltage regulator by Linear Technology, shown in

Figure 5.2 (Efficiency is highest when PWM oscillation frequency is 300 kHz). For the self-designed boost converter, 10 kHz frequency is proven to yield the highest efficiency. However, such range of frequency will incur noise that is audible with human ears, when the power MOSFET is driven by the PWM waveform. It is recommended that the power MOSFET to be encased properly to prevent electromagnetic interference (EMI) or noise disturbance to human ears, in addition to ensuring that heat dissipation is optimised.

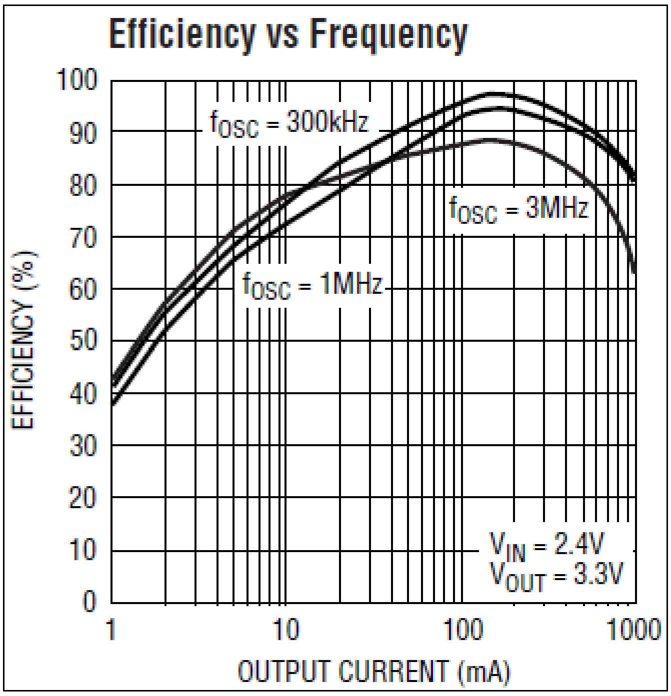


Figure 5.2: Specifications showing that efficiency is dependent on frequency

3. PWM waveform amplitude

It was first thought that amplitude of 5V for the PWM waveform, implying that V_{CC} = 5V, would be sufficient to drive the Power MOSFET. However, to produce a high output current from the boost converter, it will be unachievable since the PWM waveform will be distorted and frequency divided. For the application of this boost converter, 5.4V is found to be minimum threshold point to avoid waveform distortion.

4. Range of operation

The prototype circuit has met the objective of providing a regulated voltage over a range of output current. It is a scaled-down circuit to determine the possibility of using supercapacitors as the input source for the boost converter circuit to power up the target application, mainly the DC motor of an electric vehicle (EV), at a scaled-down rating of 12V and up to 0.5A. However, high efficiency is only achieved when the output current is relatively small, that is when it is less than 0.1A.

The input source of the boost converter, which are the 2 supercapacitors connected in series, will be turning on the boost converter while the voltage across it is between 3 to 5.4V. Output voltage will be regulated at about 12V through the dynamic feedback to the PWM module using the Integrator Module.

5. Power Consumption

The whole prototype circuit, excluding the boost converter module, will be powered by a DC power supply of ±9V, which will go through few linear voltage regulators to provide voltage supplies of +3.3V, ±5V and +6V. This includes the PWM module, Integrator module and the modules designed by my project, Mr. Choong Pak Wai (LED display, power mMeter). The Table 5.1 below provides the list of linear voltage regulators that are used in the prototype circuit.

Table 5.1: List of Linear Voltage Regulators Used

Voltage Regulator	Nominal Voltage (V)	Manufacturer
LM1117T-3.3	+3.3	National Semiconductor
L7805CV	+5.0	STMicroelectronics
L7806CV	+6.0	STMicroelectronics
7905ACT	-5.0	Motorola

The only current consumption is 30mA at the +9V side of the DC Power Supply. Hence the total power consumption for PWM generation, feedback and efficiency monitoring would be about 270mW during normal operation. As shown from Table 5.2, the calculated power consumption by all of the devices only sums up to 160mW. Note that total power consumption by the whole system excluding the boost converter is 270mW as mentioned earlier. The difference of 110mW can be related to the low efficiency of the linear voltage regulator, which can be estimated as 59%.

Table 5.2: Calculated power consumption for each device

Device	**Power Consumption (mW)**	**Voltage Supply (V)**
NE555P	90	+6.0
UA741CN	22	±5.0
LM324	15	+5.0
PIC24FJ64GA002	18	+3.3
JHD162A	15	+5.0
Total	160	

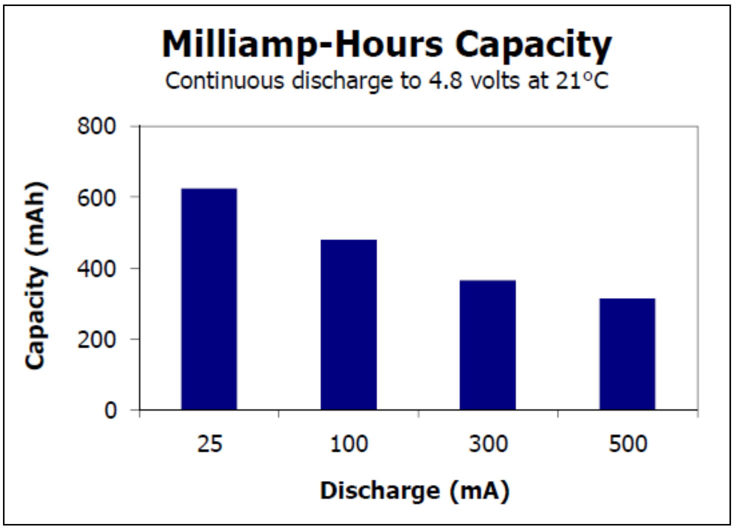


Figure 5.3: Miliamp-Hours Capacity of Energizer 9V Battery

Above, in Figure 5.3 is the graph of current discharge capacity of Energizer 9V battery at difference current discharge. A current discharge of

25mA implies to capacity of 600mAh, resulting in 24 hours of usage from the battery itself. Since this graph profile refers to continuous discharge to 4.8V and the 6V linear regulator would require at least input voltage of 7V or higher, it is predicted that the usage time of the Energizer 9V battery at 30mA current discharge would last about 16 hours if it is to be used to replace the DC power Supply.

6. Application of the prototype circuit

Though this prototype circuit is primarily targeted for EV DC Motor, it should be restricted to that particular application only. As suggested in Chapter 2, supercapacitors can be an alternative solution for batteries, as emergency power reserve during outages and to power up electronic devices. Furthermore, the use of supercapacitors an energy storage or source, will promote green energy, at this present time, when natural non-renewable resources are fast depleting.

5.2 Recommendations

There are certainly plenty of improvements that can be made on the final system design. In this project, 555 timers were used to generate the PWM waveform. If hardware reduction is necessary, it is possible to use the PIC that was responsible for efficiency calculation to generate PWM waveform instead. Feedback can also be channelled to the PIC directly using a buffer, where the PIC will then adjust the PWM duty ratio appropriately.

The boost converter is still boosting (stepping up) the input voltage even when output voltage regulation at 12V is no longer possible (Figure 4.15). This scenario happens because the maximum PWM duty ratio, D = 0.95 of the PWM Module has been reached (with V_{CC} = 6V, there are no more PWM distortion and frequency division, hence the PWM duty ratio remains at 0.95). Hence, one further improvement is to use comparator to turn off the Integrator Module when output voltage of 12V is no longer possible, which in turn off the PWM waveform generation from the PWM Module.

As shown in Table 5.2 earlier, the calculated power consumption shows that the 555 timers that are responsible for the PWM waveform generation consume the highest power among all of the devices. Hence it is reasonable to use low power consumption 555 Timer such as TLC555 by Texas Instrument (Typical: 1mW at V_{DD} = 5V).

Efficiency of the linear voltage regulators that provide constant voltage supply to the whole system except for the boost converter is relatively low, that is 59% by estimation. Hence, the suggestion is to use switching-mode IC voltage regulators, such as the ones that were mentioned in Chapter 3, as they possess higher efficiency (80% to 90%).

Lastly, as the boost converter is concerned, there is need to reduce the ESR of components, especially the power inductor. The best efficiency of the boost converter will be brought out if PWM waveform of 10 kHz is used as the switching frequency (the PWM Module’s frequency is 5.7 kHz).

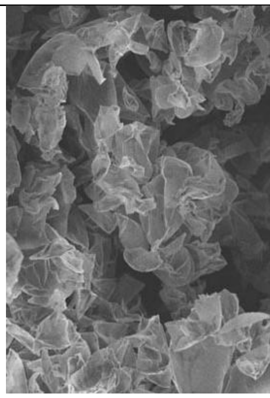
5.3 Future Directions

With a scaled-down prototype circuit of an energy storage system capable of delivering 12V and up to 0.5A, the future directions will be to scale up this prototype circuit.

Let’s start with the supercapacitor as the energy input source to the DC Motor of an electric vehicle. A good reference point would be the 3-module liquid-cooled 400V lithium-ion battery with a capacity of 40Ah for each module, bringing the total energy content to be 48kWh for the Mercedes-Benz SLS AMG E-Cell, a full EV.

By taking the average value of 170Wh/kg from Table 2.6 for lithium-ion, the total weight of the 3-module battery would be about 282.4kg. In comparison with the 100F supercapacitor that is used in this project, the energy density is only 4.82 Wh/kg. Obviously, to use this particular supercapacitor is not feasible as the weight of these supercapacitors with the same energy content would be 9.9585 tonnes! However, do note that at the present moment, the highest density of supercapacitor is 30Wh/kg, which belongs to Premlis® supercapacitor. This would make the expected supercapacitor weight to be 1.6 tonnes, a reduction of weight by 84% compared to the earlier estimation.

Table 5.3: Comparison of Energy Density

Lithium-ion Polymer	**Supercapacitor**	**Premlis®**	**Graphene Supercapacitor**
			
170 Wh/kg (Average)	4.82 Wh/kg	30 Wh/kg	85.6 Wh/kg (Room Temperature)
3.7 V	2.7 V	2 – 4 V	Under Research

The recent research by Bor Jang of US-based Nanotek Instruments and colleagues on graphene-based supercapacitor has achieved a specific energy density of 85.6 Wh/kg at room temperature and 136 Wh/kg at 80 °C. If the production of such supercapacitor with the same energy density is possible within the few years to come, this means the required weight of the supercapacitors to replace the 3-module lithium-ion battery is only about 560.7 kg, which is almost twice the weight of the lithium-ion battery.

Next, is to scale up the boost converter circuit. At specifications of 12V and maximum of 0.5A, scaling it up to 400V would result with current rating of 16.67A. From this forecast, the current rating is considerably good enough for a conventional EV, since the reference EV model is Mercedes-Benz SLS AMG E-Cell, a luxury high performance vehicle.

While the development of the grapheme-supercapacitor is ongoing, the best suggestion would be to implement the usage of supercapacitor as energy input on electric motorcycle, single-seat electric car or dual-seat electric car instead of conventional 5-seat electric car. This is because, with smaller vehicle size and weight, in addition to lower DC motor power rating, the feasibility of the supercapacitor as energy input can be tested in the long run.

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APPENDICES

APPENDIX A: Data

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APPENDIX B: Schematic and PCB Design

APPENDIX C: Datasheet