BUCK CONVERTER SWITCHING DESIGN USING MICROCONTROLLER

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ABSTRACT

This paper presents an implementation of a PIC18F4550 microcontroller to control the operation of a buck converter. Buck converter is a DC-DC converter which will step down a higher voltage to a lower voltage level. This microcontroller is used to produce Pulse Width Modulation (PWM) signal with constant duty cycle to drive the switch of the converter. The switch then will alternate turn the converter on and off to produce regulated voltage. The buck converter was modeled and evaluated by computer simulations. The author also present the simulation results related to the theoretical aspects mentioned in the paper. The result shows that the proposed PIC18F4550 microcontroller operation is capable to control the operation of the buck converter.

ABSTRAK

Penulisan ini membentangkan pelaksanaan pengawal mikro PIC18F4550 untuk mengawal operasi penukar *buck*. Penukar *buck* penukar adalah penukar *DC-DC* yang akan menukar voltan yang lebih tinggi ke tahap voltan yang lebih rendah. Pengawal mikro ini digunakan untuk menghasilkan isyarat *Pulse Width Modulation (PWM)* dengan kitar tugas yang tetap untuk memacu suis penukar. Suis akan bertukar ganti menghidup dan mematikan penukar untuk menghasilkan voltan yang terkawal. Penukar *buck* telah dimodelkan dan dinilai oleh simulasi komputer. Penulis juga membentangkan hasil simulasi yang berkaitan dengan aspek-aspek teori yang disebut di penulisan ini. Keputusan menunjukkan bahawa cadangan operasi pengawal mikro PIC18F4550 mampu untuk mengawal operasi penukar *buck*.

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LIST OF SYMBOLS AND ABBREVIATIONS

DC	-	Direct current
PWM	-	Pulse Width Modulation
V	-	Voltage
A	-	Ampere
m	-	mili
CCM	-	Continuous Conduction Mode
DCM	-	Discontinuous Conduction Mode
KVL	-	Kirchhoff's Voltage Law
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
IGBT	-	Insulated Gate Bipolar Transistor
PIC	-	Peripheral Interface Controller
Hz	-	Hertz
I/O	-	Input/Output
CCP	-	Capture/Compare/PWM
USB	-	Universal Serial Bus
ADC	-	Analog-to-Digital (A/D) converter
SPI	-	Serial Peripheral Interface
I^2C	-	Inter-Integrated Circuit

CHAPTER 1

INTRODUCTION

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

1.1 Research background

Step-down switching or buck converters are vital to modern electronics. They can convert a voltage source (typically 8 V to 25 V) into a lower regulated voltage (typically 0.5 V to 5 V). Step down converters transfer small packets of energy using a switch, a diode, an inductor and several capacitors. Though considerably larger and noisier than their linear-regulator counterparts, buck converters offer higher efficiency in most cases.

As usually known, the conventional buck converter [5] [6] is widely used in the industry. DC–DC converters have been effectively controlled for many years using analog integrated circuit technology and linear system design techniques [4].

The analog control circuits present some drawbacks as follows: monitor a reduced number of signals to save costs, solve only specific task, requires auxiliary active and passive electronic devices [8], use pulse amplifier as interface for the electronic power switches, shown reduced noise immunity and difficulty to assure further developments or new more complex control functions.

Digital control in power electronics has been intensively used during the last decade [1]. The improved performances and price reduction of digital controller has enable their application in power electronic control.

The primary advantages of digital control over analog control are higher increased flexibility by changing the software, more advanced control techniques and reduced number of components [2]. The implementation of complex control function with analog circuits is difficult but using a digital programmable device the implementation becomes easier [3]. Digital controllers offer several benefits as summarized below [9]:

- Provision of new capabilities such as implementation of advanced algorithms enabling higher performance, and lower energy consumption, among other things.
- Immunity to drifts since digital controller’s functioning is substantially unaffected by either time or temperature drifts. Equations in software do not drift, unlike analog controllers.
- Software implemented on programmable controllers can calibrate out the inaccuracies and can automate this calibration process, hence lowering the cost of manufacturing by eliminating a manual calibration step.
- Ease of implementation since functions are easily implemented in software.
- Faster time to market since digital controllers make it possible to leverage existing off-the-shelf controllers, which allow the fastest realization of a design. In addition, the design of controllers is often an iterative process, with repeated design and test steps, until the specifications are met. Such an iterative process can be executed rapidly by means of a software-configurable controller.
- Control law changes are done by software updates, hence a much faster process than incorporating these changes with hardware.
- Far less sensitive to component tolerances since software in digital controllers are far less susceptible to component tolerances.

A significant difficulty in power electronics is to control or to design main controllers for different kind of switched mode converters. The regulation is normally achieved by the pulse width modulation (PWM) at a fixed frequency [1]. The efficiency characteristics of a buck converter, however, change dramatically as the switching frequency is increased [10]. The switching device is a power MOSFET [7].

1.2 Problems Statement

Analog control technology has been successfully employed in controlling the operation of DC-DC converter. But analog technology has many disadvantages that limit the buck converter operation. Digital technology has been considered to replace the analog technology. This project will investigate the ability of digital control of the buck converter using microcontroller to control the operation of the DC-DC converter.

1.2.1 Research Objective

- To implement digital technology using microcontroller for controlling buck converter operation.
- To produce a reliable design circuit for buck converter operation.

CHAPTER 2

LITERATURE REVIEW

This chapter will cover topic on buck converter issues.

2.1 DC to DC conversion method

There are three techniques to convert DC voltage from higher value to lower value. These techniques are:

- Voltage divider
- Linear voltage regulator
- DC-DC converter (buck)

A comparison will be made on the efficiency of each method to do the DC conversion. Consider an application that requires 100mA at 5V. The supply is +15V. With a voltage divider circuit such as in Figure 1, the maximum load is 5V /100mA = 50Ω resistor. For smaller load currents, the equivalent resistor will be larger. The design reaches 5V across the load for the maximum load current requirement.

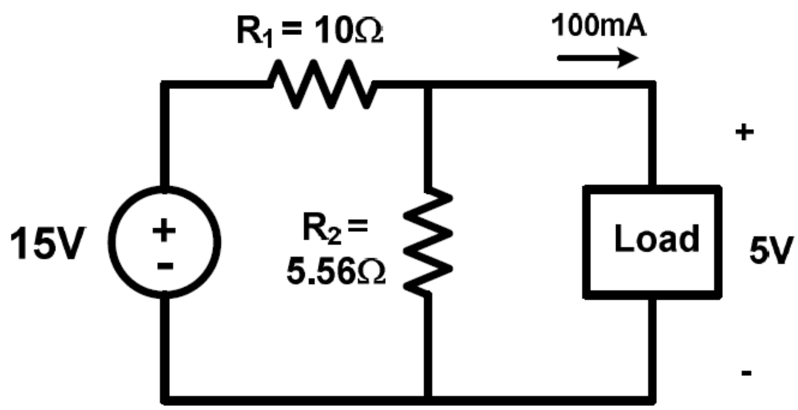

Figure 1: Voltage divider

Kirchhoff's voltage law (KVL) tell that there should be 15V – 5V = 10V across the 10Ω resistor and, therefore, we are drawing 1A from the 15V supply. Thus the voltage divider efficiency, η is:

$$\eta = \frac{P_{OUT}}{P_{IN}} \times 100 = \frac{5V(100mA)}{15V(1A)} \times 100 = \frac{0.5W}{15W} \times 100 = 3.33\%$$

Clearly the voltage divider is not effectively using input voltage energy. In fact the circuit is wasting $(1A)^2$ 10Ω =10W in the one resistor and $(5V)^2$ / 5.56Ω = 4.5W in the other.

Figure 2 shows linear voltage regulator using LM317 chip. The LM317 works by creating 1.25V across the 120 Ω resistor. So the current in 120 Ω resistor, $I_{120\,\Omega}$ = 1.25V /120 Ω =10.4mA. With zero current leaving the bottom of the chip, this means that there is 10.4mA x 360 Ω = 3.75V across the bottom resistor, so that there is always 1.25V + 3.75V = 5V across the load.

Using KCL, output current from LM317, $I_{317(out)}$ = 100 mA + 10.4 mA. Then applying KCL to the entire LM317 chip, the input current must be the same as the output current or $I_{317(in)}$ = $I_{317(out)}$ = 110.4 mA. We can then calculate the efficiency as

$$\eta = \frac{P_{OUT}}{P_{IN}} \times 100 = \frac{5V(100mA)}{15V(110.4mA)} \times 100 = \frac{0.5W}{1.656W} \times 100 = 30.2\%$$

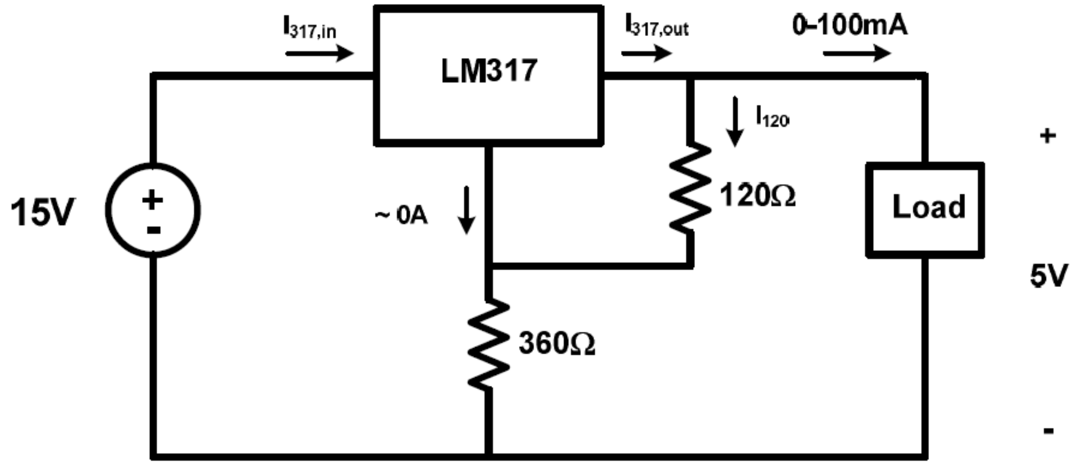

Figure 2: Linear voltage regulator

Even though the efficiency is better than voltage divider, linear voltage regulator are still inefficiently using the power supply energy and wasting 1.656W - 0.5W = 1.156W in the chip and resistors.

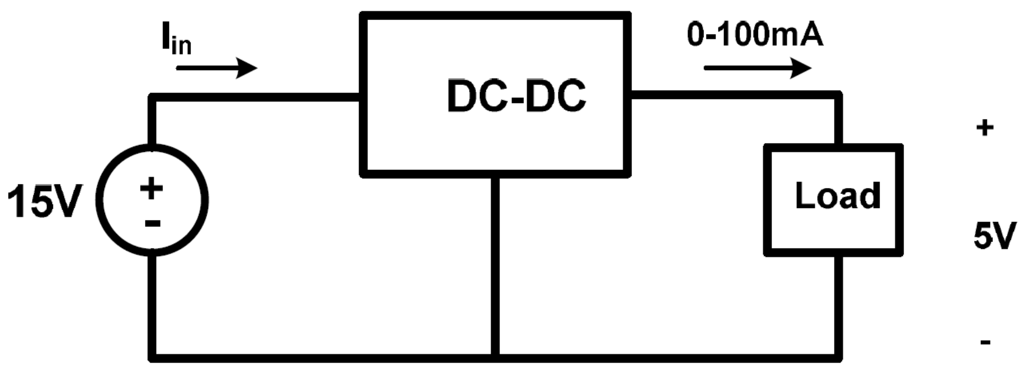

Figure 3: DC-DC converter

With a buck converter with assuming efficiency of 92%, the required input power from the supply is

$$P_{in} = \frac{P_{OUT}}{\eta} = \frac{0.5W}{.92} = 0.543W$$

Thus we are only “wasting” 0.543W - 0.5W = 0.043W and the required input current has dropped to $I_{in} = P_{in} / V_{in}$ = 0.543W /15V = 36.2 mA. The converter is drawing far less current from the supply voltage with improved efficiency.

2.2 Buck converter

A buck converter is a step-down DC to DC converter. For a DC–DC converter, input and output voltages are both DC. It uses a power semiconductor device as a switch to turn on and off the DC supply to the load.

The switching action can be implemented by a BJT, a MOSFET, or an IGBT. Figure 4 shows a simplified block diagram of a buck converter that accepts a DC input and uses pulse-width modulation (PWM) of switching frequency to control the switch. An external diode, together with external inductor and output capacitor, produces the regulated dc output. Buck, or step down converters produce an average output voltage lower than the input source voltage.

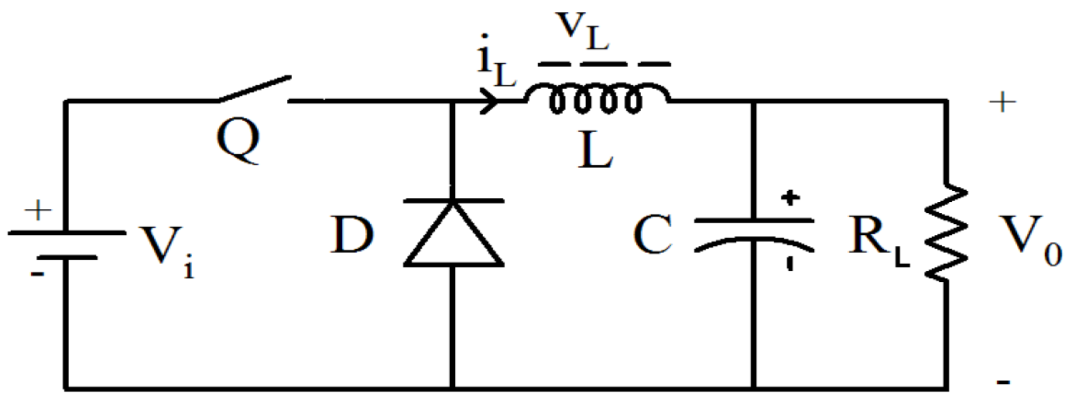

Figure 4: Buck converter

2.3 Buck converter operation

The operation of a buck converter happens in two modes. The first mode is when switch Q close, and the second one is when switch Q open.

When switch Q closes, current flows from the supply voltage V_i through the inductor and into the load, charging the inductor by increasing its magnetic field and increasing V_o. Diode D will be on reverse bias, thus blocking the path for current. An inductor reduces ripple in current passing through it and the output voltage would contain less ripple content since the current through the load resistor is the same as that of the inductor. At the same time, the current through the inductor increases and the energy stored in the inductor increases. When V_o reaches the desired value, switch Q is open and diode D is turned on. Figure 5 shows this mode.

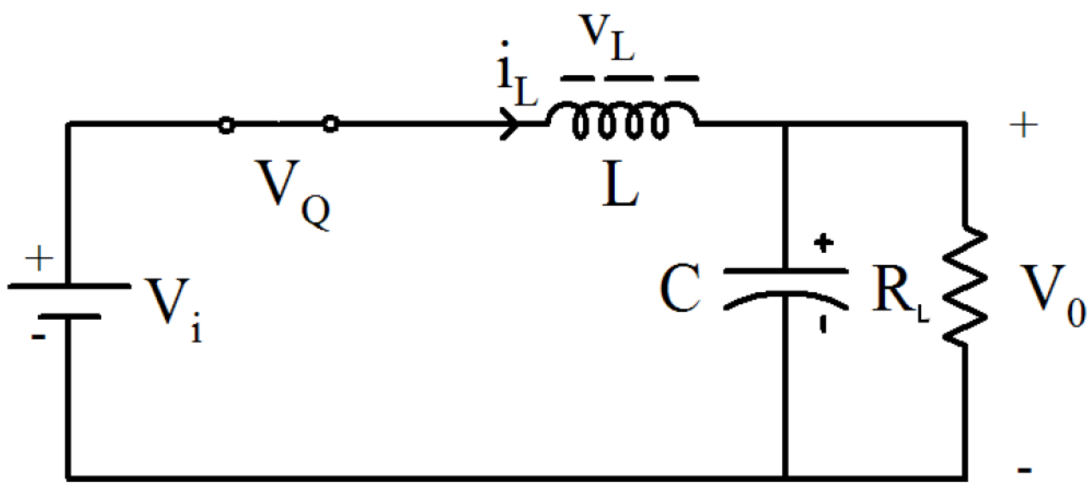

Figure 5: Switch Q closed

When the switch Q opens, the inductor acts as a source and maintains the current through the load resistor. During this period, the energy stored in the inductor decreases and its current falls. Current continues to flow in the inductor through the diode D as the magnetic field collapses and the inductor discharges. Before the inductor completely discharges, diode D is open and Q is closed and the cycle repeats. It is important that there is continuous conduction through the load for this circuit. Figure 6 shows this mode.

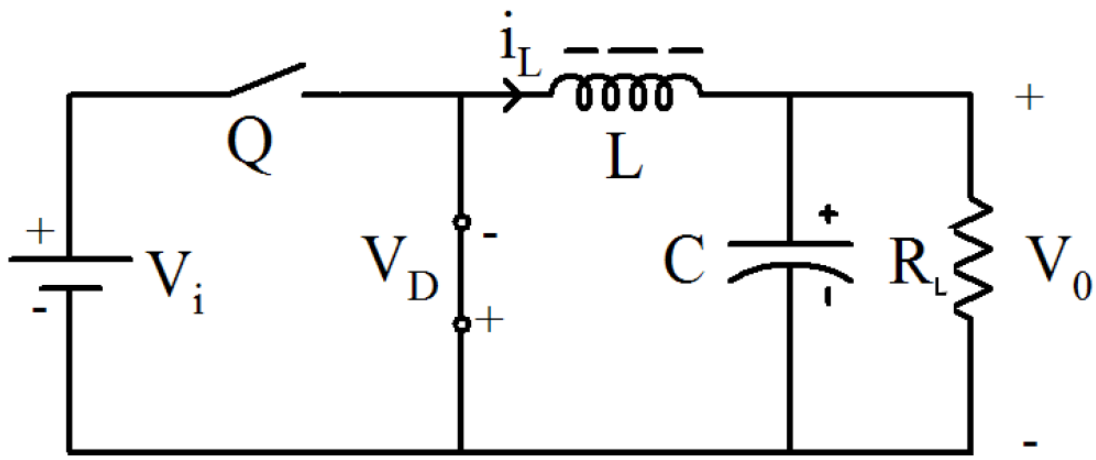

Figure 6: Switch Q open

2.4 Buck converter duty cycle

The ratio of output voltage, V_{out} to input voltage, V_{in} can be adjusted by varying the duty cycle of switch Q. The longer Q is turned on, the greater V_{out} will be. The duty cycle of Q is usually called the converter's duty cycle. If the switches and the inductor are lossless, V_{in} is converted to V_{out} with no loss of power and the conversion is 100% efficient. Figure 7 shows variation of duty cycle.

Duty cycle is always being presented in percentage value. A 60% duty cycle means the power is on 60% of the time and off 40% of the time. While a 50% duty cycle means the power is on 50% of the time and off 50% of the time.

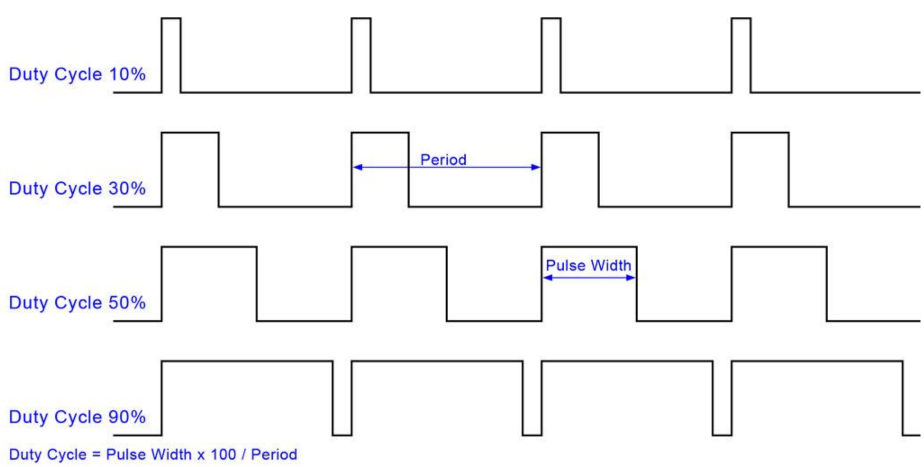

Figure 7: Duty cycle

2.5 CCM and DCM

The buck converter can operate in two different modes; continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The difference between the two is that in CCM the current in the inductor does not fall to zero.

A buck converter operates in continuous mode if the current through the inductor never falls to zero during the commutation cycle. In DCM, the current through the inductor falls to zero during part of the period. Practically, converter can operated in either operation modes. Figure 8 shows CCM and DCM mode.

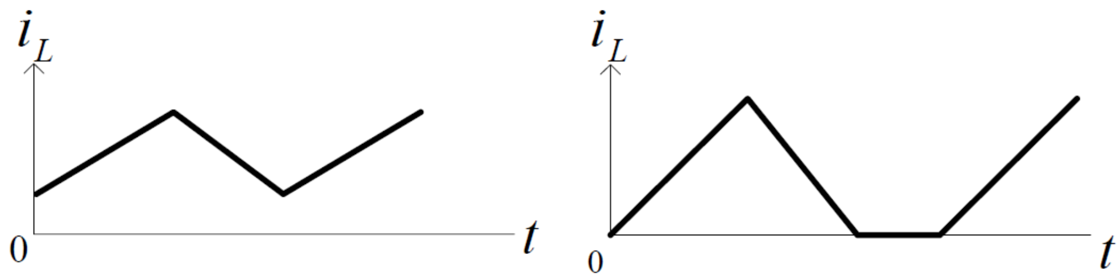

Figure 8: (a) CCM (b) DCM

2.6 Buck converter analysis

The initial study of this circuit utilizes the following assumptions. Capacitor is large enough that the output voltage ripple is small relative to its average value. Inductor is large enough to ensure that the inductor current stays positive for the switching period. This is referred to as continuous conduction mode or CCM.

This ensures that when the switch is off, the diode must be on. All components are initially assumed ideal. The circuit is in the steady state, implying that all waveforms are in fact periodic, ensuring that they have the same value at the beginning and end of a switching period.

Two state of operation is considered. First, switch Q turn on and D turn off. After steady state condition has been reached, switch Q will turn off and D turn on. Figure 9 shows these two operations.

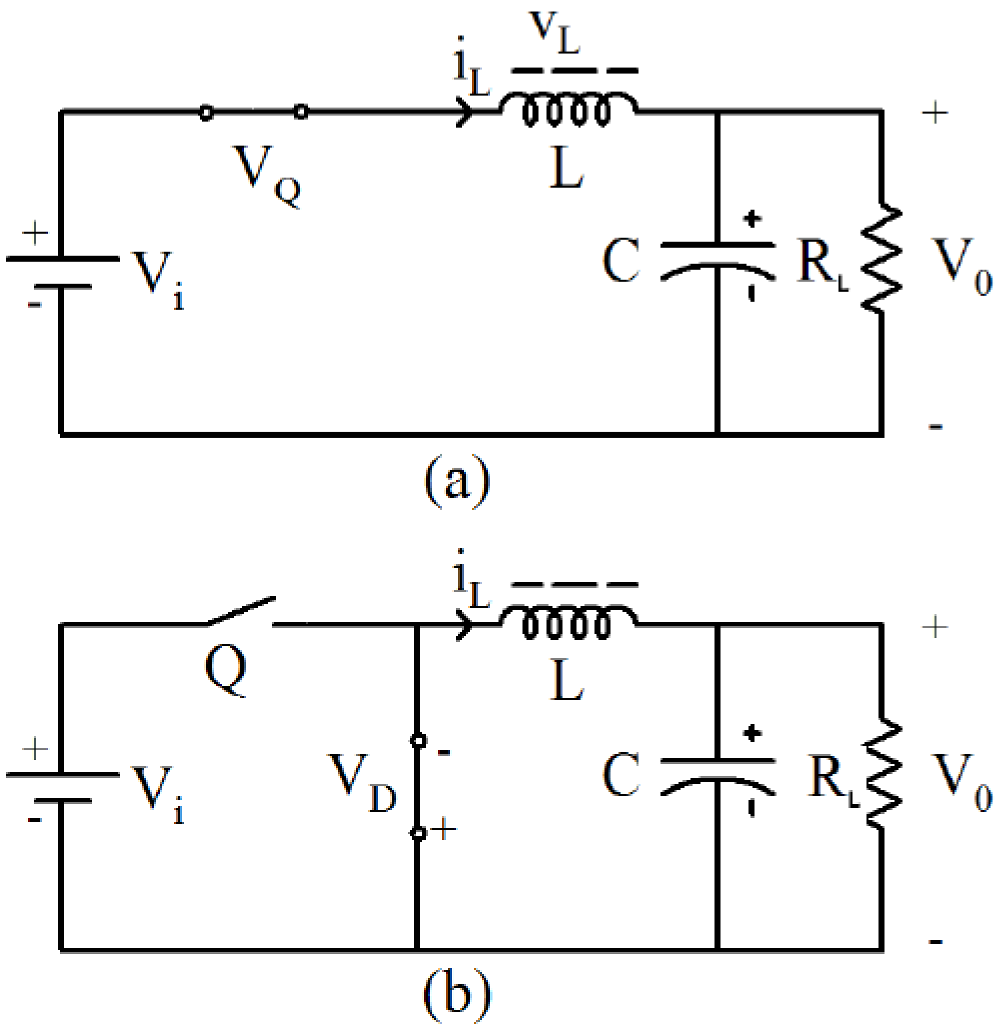

Figure 9: Buck converter operation (a) Q turn on (b) Q turn off

By using Kirchhoff's Voltage Law (KVL), the voltage across the inductor when switch Q is closed is:

$$V_L = V_i - V_Q - V_o \tag{2.0}$$

At the same time, the voltage V_L across the inductor is related to the change in current flowing through it which is:

$$V_L = L\frac{di_L}{dt} \tag{2.1}$$

Rearranging equation (2.0) will result in:

$$L\frac{di_L}{dt} = V_i - V_Q - V_o$$

So the amount of inductor current is:

$$\frac{di_L}{dt} = \frac{V_i - V_Q - V_o}{L} \tag{2.2}$$

The duty cycle of the buck converter is defined as:

$$D = \frac{T_{ON}}{T_{ON} + T_{OFF}} = \frac{T_{ON}}{T} \tag{2.3}$$

From Figure 10, $dt = \Delta t_1 = T_{ON}$

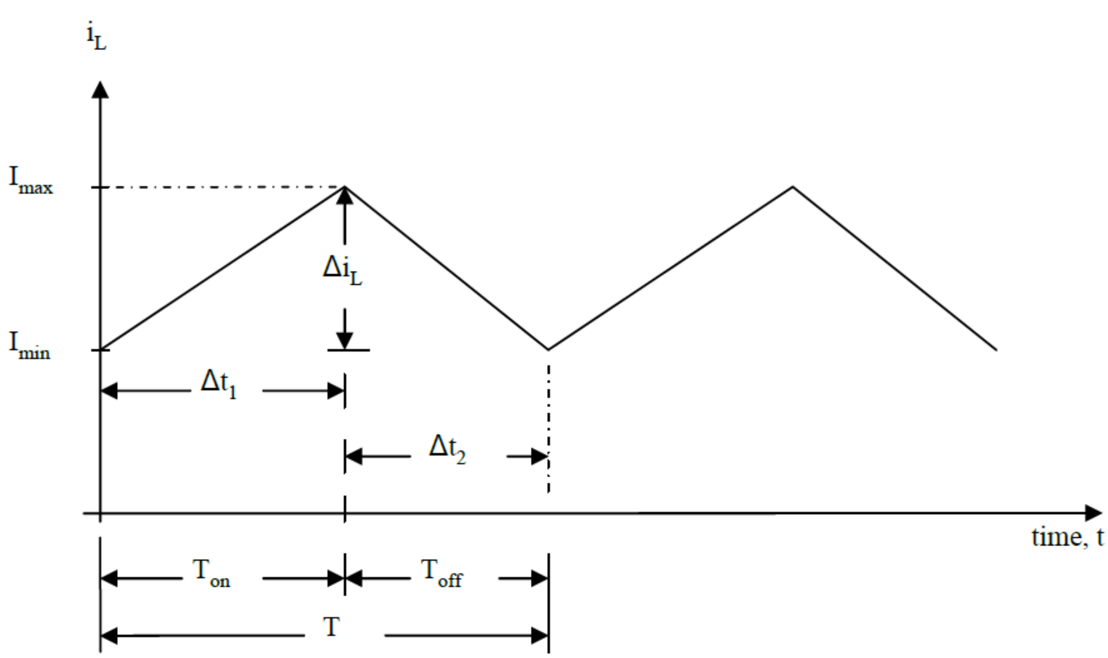

Figure 10: Inductor current

So the inductor current increase during the on state is given by:

$$\Delta I_L(on) = \frac{V_i - V_Q - V_o}{L} T_{ON} \tag{2.4}$$

When switch Q open, the voltage across inductor is:

$$V_L = V_o + V_D \tag{2.5}$$

$$L\frac{di_L}{dt} = V_o + V_D$$

$$\frac{di_L}{dt} = \frac{V_o + V_D}{L} \tag{2.6}$$

Again from Figure 7, $dt = \Delta t_2 = T_{OFF}$

So the inductor current increase during the on state is given by:

$$\Delta I_L(off) = \frac{V_O + V_D}{L} T_{OFF} \tag{2.7}$$

For steady-state operation, ΔI_L (on) and ΔI_L (off) must be equal. Or else, the inductor current would have a net increase or decrease from cycle to cycle which would not be a steady state condition. Thus, these two equations can be equated and solved for V_O to obtain the continuous conduction mode buck voltage conversion relationship.

$$\Delta I_L(on) = \Delta I_L(off) \tag{2.8}$$

$$\frac{V_i - V_Q - V_o}{L} T_{ON} = \frac{V_O + V_D}{L} T_{OFF}$$

$$V_i T_{ON} - V_Q T_{ON} - V_o T_{ON} = V_o T_{OFF} + V_D T_{OFF}$$

$$V_O T_{ON} + V_O T_{OFF} = V_i T_{ON} - V_Q T_{ON} - V_D T_{OFF}$$

$$V_O (T_{ON} + T_{OFF}) = V_i T_{ON} - V_Q T_{ON} - V_D T_{OFF}$$

$$V_O T = T_{ON} (V_i - V_Q) - V_D T_{OFF}$$

$$V_O = \frac{T_{ON} (V_i - V_Q) - V_D T_{OFF}}{T}$$

$$V_O = (V_i - V_Q) D - V_D \frac{T_{OFF}}{T} \tag{2.9}$$

And using

$$\left(1 - D\right) = \frac{T_{OFF}}{T} \tag{2.10}$$

$$V_O = (V_i - V_Q) D - V_D (1 - D) \tag{2.11}$$

The steady-state equation for V_O is:

$$V_O = \left(V_i - V_Q\right) D - V_D \left(1 - D\right)$$

This equation demonstrates the fact that, output voltage V_O is defined with the duty cycle, D for the converter. For this explanation, the buck converter output voltage is lower than input voltage because D is a number between 0 and 1. To generalize (2.11), V_Q and V_D are neglected because they are small enough to ignore. Simplified output voltage can be calculated by:

$$V_O = V_i D \tag{2.12}$$

In a steady state, inductor current is given by:

$$I_L = I_C + I_O \tag{2.13}$$

Since $I_C = 0$ in steady state condition, we have:

$$I_L = I_O \tag{2.14}$$

Ohm's law requires that

$$I_O = \frac{V_O}{R_L} \tag{2.13}$$

So the average value of I_L is:

$$I_L = I_O = \frac{V_O}{R_L}$$

From Figure 7 we can write:

$$I_{L(\max)} = I_L + \frac{|\Delta I_L|}{2} \tag{2.14}$$

From equation 2.7 and 2.13, we can write:

$$I_{L(\max)} = \frac{V_O}{R_L} + \frac{V_O}{2L}(1 - D)T \tag{2.15}$$

Similarly from Figure 7 we can write

$$I_{L(\min)} = I_L - \frac{|\Delta I_L|}{2} \tag{2.16}$$

or

$$I_{L(\min)} = \frac{V_O}{R_L} - \frac{V_O}{2L}(1-D)T \tag{2.17}$$

To guarantee an uninterrupted flow of I_L through the inductor, we need I_L (min) > 0. So we need

$$I_{L(\min)} = \frac{V_O}{R_L} - \frac{V_O}{2L}(1-D)T > 0$$

$$\frac{V_O}{R_L} > \frac{V_O}{2L}(1-D)T$$

$$L > \frac{(1-D)}{2}TR_L$$

$$L > \frac{(1-D)}{2f}R_L \tag{2.18}$$

Where $f = \frac{1}{T}$

CHAPTER 3

METHODOLOGY

This chapter will summarize on how the project is developed, from components selection, software selection, PWM programming, circuit construction and simulation result.

3.1 Components selection

Basic components to build a simple buck converter are chosen. They are DC input voltage source, controlled switch, diode, filter inductor, filter capacitor, and load resistance.

For the switching action, several components must be considered. These include the switch to the load and the switching controller. For switch, MOSFET is chosen. IR2101 is selected to drive the MOSFET. The input signal for the driver come from PWM signal generated by Microchip PIC18F4550 microcontroller. This PWM output is not capable of driving the MOSFET. Driver is used to amplify the PWM output and is connected to the gate of the MOSFET [7].

3.1.1 DC voltage source

This is the main DC source for buck converter operation. For a buck converter, input DC voltage source is higher than the output DC voltage. The buck converter will reduce or step down the higher input voltage to lower output voltage.

3.1.2 Inductor

An inductor is a passive element designed to store energy in its magnetic field. An inductor will resist the change in current flowing through it. The current through inductor cannot change instantaneously.

An ideal inductor does not dissipate energy. The energy stored in it can be retrieved at a later time. The inductor takes power from the circuit when storing energy and delivers power to the circuit when returning previously stored energy.

A practical nonideal inductor has a significant resistive component. This is due to the fact that the inductor is made of a conducting material such as copper, which has some resistance. This resistance is called the winding resistance, and it appears in series with the inductance of the inductor. The presence of winding resistance makes it both an energy storage device and an energy dissipation device. Since the winding resistance is usually very small, it is ignored in most cases.

The nonideal inductor also has a winding capacitance due to the capacitive coupling between the conducting coils. Winding capacitance is very small and can be ignored in most cases, except at high frequencies.

3.1.3 Capacitor

A capacitor is a passive element designed to store energy in its electric field. The capacitor resists an abrupt change in the voltage across it. The voltage on a capacitor cannot change abruptly.

The ideal capacitor does not dissipate energy. It takes power from the circuit when storing energy in its field and returns previously stored energy when delivering power to the circuit. A real, nonideal capacitor has a parallel-model leakage resistance. The leakage resistance may be as high as 100 MQ and can be neglected for most practical applications.

3.1.4 Diode

Since the current in the inductor cannot change instantaneously, a path must exist for the inductor current when the switch is off (open). This path is provided by the freewheeling diode (or catch diode).

The purpose of this diode is not to rectify, but to direct current flow in the circuit and to ensure that there is always a path for the current to flow into the inductor. It is also necessary that this diode should be able to turn off relatively fast. Thus the diode enables the converter to convert stored energy in the inductor to the load.

3.1.5 MOSFET

MOSFET is an acronym for Metal Oxide Semiconductor Field Effect Transistor and it is the key component in high frequency, high efficiency switching applications across the electronics industry.

MOSFET (either N−channel or P−channel) that passes the voltage supply to a specified load when the transistor is on. The selection of a P−channel or N−channel load switch depends on the specific needs of the application. The N−channel MOSFET has several advantages over the P−channel MOSFET. For example, the N−channel majority carriers (electrons) have a higher mobility than the P−channel majority carriers (holes). For high current applications the N−channel transistor is preferred.

3.1.6 IR2101

The IR2101 are high voltage, high speed power MOSFET and IGBT drivers with independent high and low side referenced output channels. The logic input is compatible with standard CMOS or LSTTL output, down to 3.3V logic. The output drivers feature a high pulse current buffer stage designed for minimum driver cross-conduction. The floating channel can be used to drive an N-channel power MOSFET or IGBT in the high side configuration which operates up to 600 volts.

3.1.7 PIC18F4550 microcontroller

PIC is a family of modified Harvard architecture microcontrollers made by Microchip Technology. The name PIC initially referred to Peripheral Interface Controller. PIC18F4550 is an 8-bit microcontroller of PIC18 family. PIC18F family is based on 16-bit instruction set architecture. PIC18F4550 consists of 32 KB flash memory, 2 KB SRAM and 256 Bytes EEPROM.

This is a 40 pin PIC Microcontroller consisting of 5 I/O ports (PORTA, PORTB, PORTC, PORTD and PORTE). PORTB and PORTD have 8 pins to receive/transmit 8-bit I/O data. The remaining ports have different numbers of pins for I/O data communications.

PIC18F4550 can work on different internal and external clock sources. It can work on a varied range of frequency from 31 KHz to 48 MHz. PIC18F4550 has four in-built timers. There are various inbuilt peripherals like ADC, comparators etc in this controller. PIC18F4550 is an advanced microcontroller which is equipped with enhanced communication protocols like EUSART, SPI, I^2C, USB etc. Figure 11 shows the PIC18 family and their characteristics. Figure 12 shows pin of PIC18F4550.

Device	Program Memory		Data Memory		I/O	10-Bit A/D (ch)	CCP/ECCP (PWM)	SPP	MSSP		EUSART	Comparators	Timers 8/16-Bit
	Flash (bytes)	# Single-Word Instructions	SRAM (bytes)	EEPROM (bytes)					SPI	Master I^2C^{TM}			
PIC18F2455	24K	12288	2048	256	24	10	2/0	No	Y	Y	1	2	1/3
PIC18F2550	32K	16384	2048	256	24	10	2/0	No	Y	Y	1	2	1/3
PIC18F4455	24K	12288	2048	256	35	13	1/1	Yes	Y	Y	1	2	1/3
PIC18F4550	32K	16384	2048	256	35	13	1/1	Yes	Y	Y	1	2	1/3

Figure 11: PIC18 family

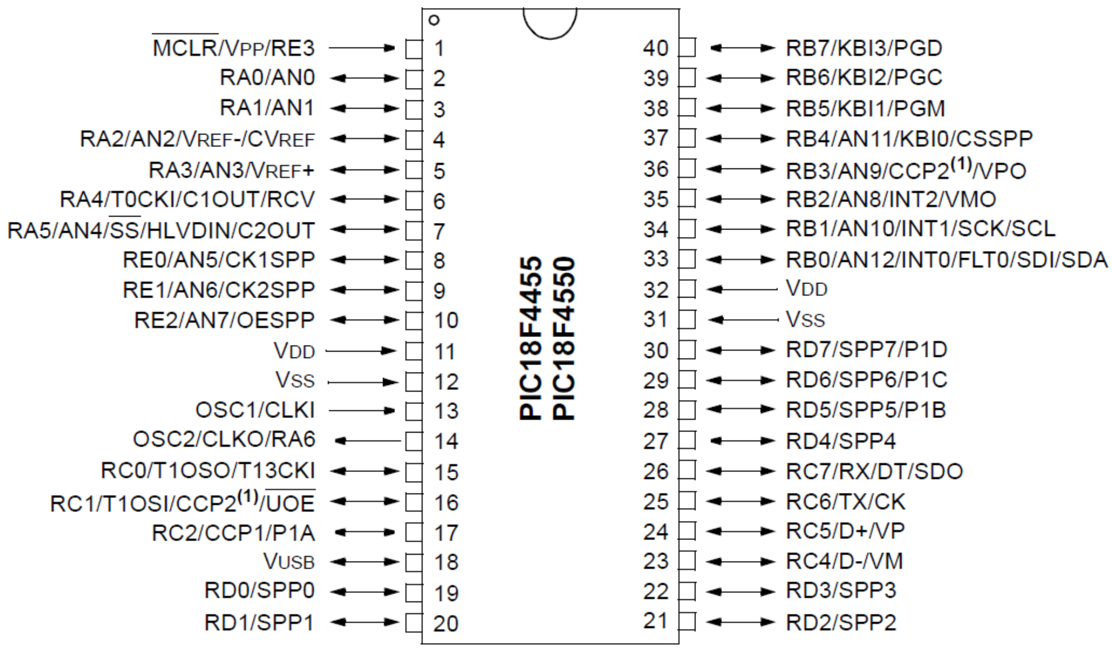

Figure 12: PIC18F4550

3.2 Software selection

C language is chosen to write the PWM program for the PIC18F4550 microcontroller. The C programming is written in MPLAB Integrated Development Environment (IDE) software. The circuit for the buck converter is designed in Proteus software.

3.2.1 MPLAB IDE

MPLAB IDE is a software program that runs on a PC to develop applications for

Microchip microcontrollers. It is called an Integrated Development Environment, or IDE, because it provides a single integrated environment to develop code for embedded microcontrollers. Figure 13 shows MPLAB window.

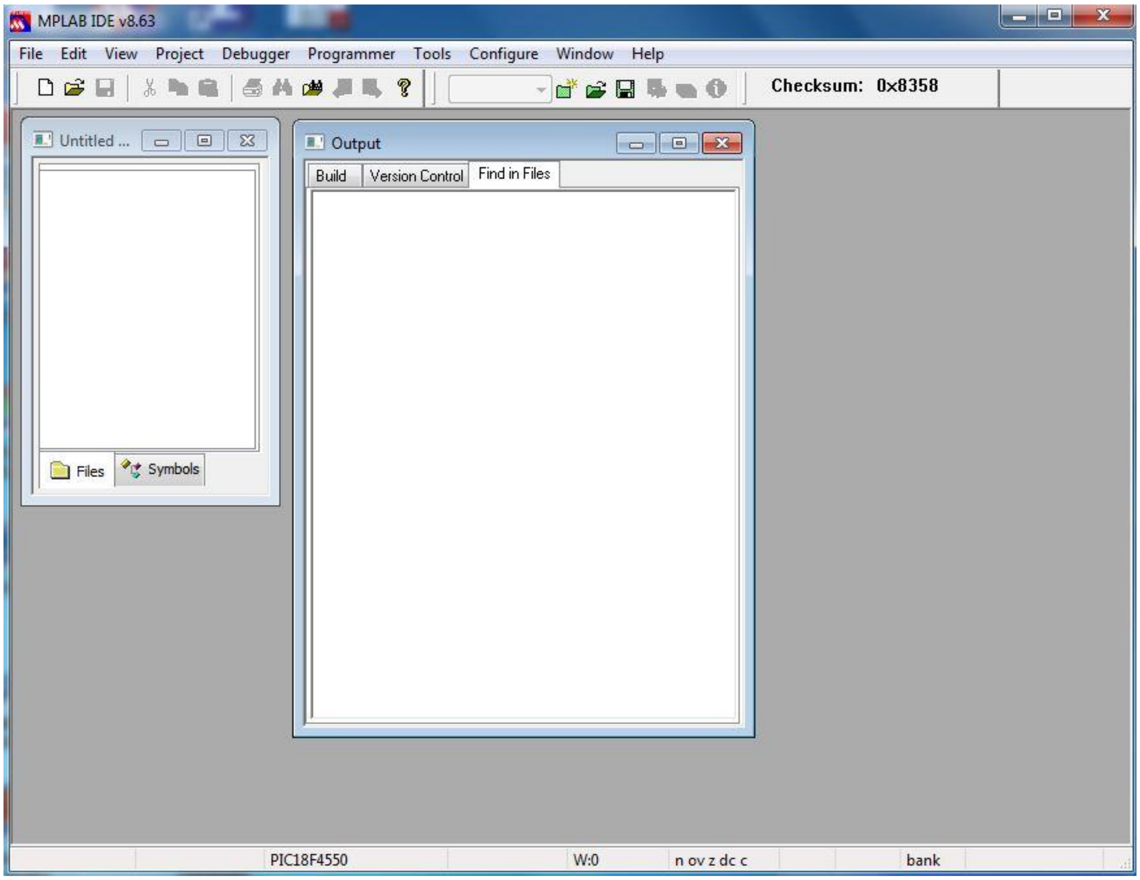

Figure 13: MPLAB window

3.2.2 Proteus

Proteus is software for microprocessor and microcontroller simulation, schematic capture, and printed circuit board (PCB) design. It is developed by Labcenter Electronics. Figure 14 shows Proteus window.

Proteus consists of a single application with many modules such as ISIS Schematic Capture, PROSPICE Mixed mode SPICE simulation, ARES PCB Layout and VSM (Virtual System Modeling). This project will use ISIS Schematic

Capture to design the buck converter circuit and VSM mode to simulate the buck converter circuit.

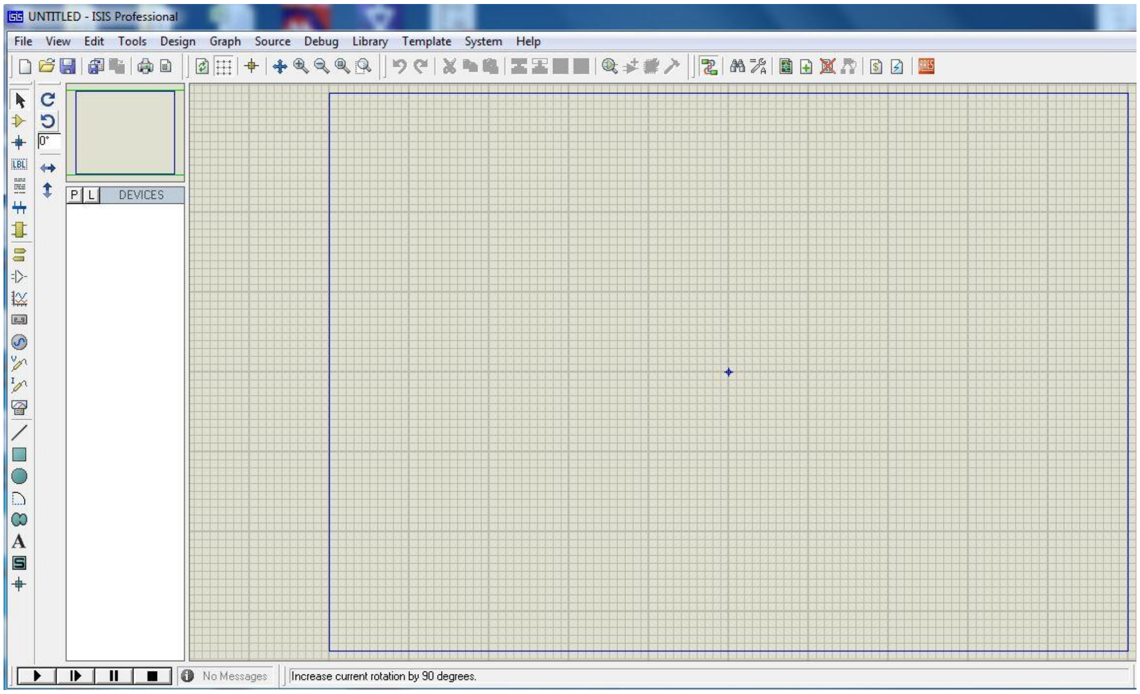

Figure 14: Proteus window

3.3 PWM Programming

The PWM signal to drive the MOSFET is generated from PIC18F4550 microcontroller. PIC18F4550 microcontroller has two CCP (Capture/Compare/PWM) modules. These modules are used to create the PWM signal. Pin RC2 is used to output the PWM signal.

3.3.1 Capture/Compare/PWM (CCP) modules

Each Capture/Compare/PWM module is associated with a control register (generically, CCPxCON) and a data register (CCPRx). The data register, in turn, is comprised of two 8-bit registers: CCPRxL (low byte) and CCPRxH (high byte). All registers are both readable and writable.

The CCP modules utilize Timers 1, 2 or 3, depending on the mode selected. Timer1 and Timer3 are available to modules in Capture or Compare modes, while Timer2 is available for modules in PWM mode.

In Pulse-Width Modulation (PWM) mode, the CCPx pin produces up to a 10-bit resolution PWM output. Since the CCP2 pin is multiplexed with a PORTB or PORTC data latch, the appropriate TRIS bit must be cleared to make the CCP2 pin an output. Figure 15 shows a simplified block diagram of the CCP module in PWM mode.

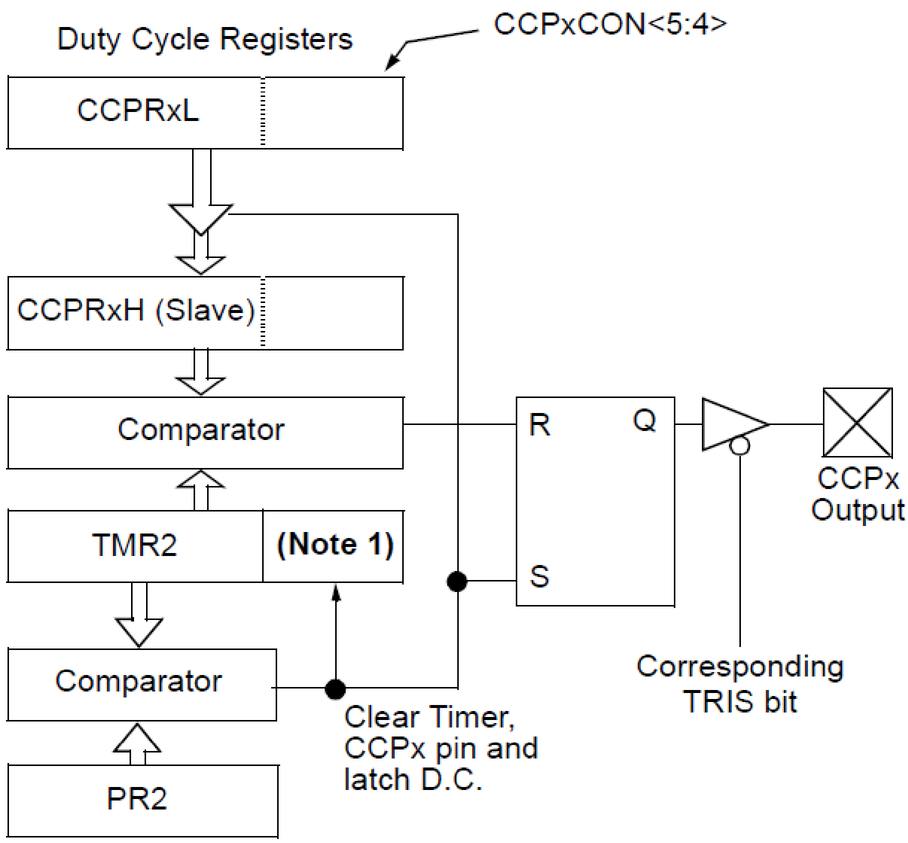

Figure 15: CCP module in PWM mode.

A PWM output (Figure 16) has a time base (period) and a time that the output stays high (duty cycle). The frequency of the PWM is the inverse of the period (1/period).

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