DEVELOPMENT OF REPETITIVE CURRENT CONTROL FOR LEAD ACID BATTERY USING ARDUINO

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ABSTRACT

This project focused on development of repetitive current control for lead acid battery using Arduino. The project uses Buck-Boost converter circuit with reference voltage of 14V from lead acid battery. The range of buck operation input voltage is between 18V to 15V while boost operation input voltage range is between 10V to 13V. The current sensor uses in this project is to measure the output current with rating 50 A versions and 40 mV/A output sensitivity. The results of simulation output current slightly increase with the minimum value of 0.11A and the maximum value of 0.26A. While the hardware output current is constant at1.71A for 10V to 18V. This project uses MATLAB R2013b and Arduino UNO microcontroller with specification of ATmega328 processor. A repetitive current controller is been developed using MATLAB Simulink Toolbox which communicates with Arduino Support Package library in order to generate the pulse width modulation (PWM) signals.The project with the aid of MATLAB software and Arduino is able to develop repetitive current control for lead acid battery.

ABSTRAK

Projek ini memberi tumpuan kepada pembangunan kawalan arus berulang-ulang untuk bateri asid plumbum menggunakan Arduino. Projek ini menggunakan Buck-Boost penukar litar dengan voltan rujukan 14V bateri asid plumbum. Julat voltan masukan bagi operasi Buck adalah diantara 18V hingga 15V manakala julat voltan masukan bagi operasi Boost adalah diantara 10V hingga 13V. Pengesan arus yang digunakan dalam projek ini adalah untuk mengukur keluaran arus dengan spesifikasi versi 50Amp dan sensitivity 40mV setiap arus keluaran. Keputusan simulasi arus keluaran dengan nilai minimum adalah 0.11A dan nilai maksimum ialah 0.26A. Manakala arus keluaran perkakasan adalah 1.71A berterusan dari 10V hingga 18V. Projek ini telah menggunakan perisian MATLAB R2013b dan Arduino UNO mikropengawal dengan spesifikasi pemproses ATmega328. Pengawal arus berulang-ulang telah dibangunkan dengan menggunakan MATLAB Simulink Toolbox yang berkomunikasi dengan perpustakaan Arduino Pakej Sokongan untuk menjana modulasi lebar denyut (PWM) isyarat. Projek dengan bantuan perisian MATLAB dan Arduino mampu untuk membangunkan kawalan arus berulang-ulang untuk bateri asid plumbum.

TABLE OF CONTENTS

LIST OF FIGURE

LIST OF TABLE

LIST OF SYMBOLS AND ABBREVIATIONS

V   -   Voltage

A   -   Ampere

AC   -   Alternating Current

DC   -   Direct Current

PWM   -   Pulse Width Modulation

USB   -   Universal Serial Bus

MOSFET   -   Metal Oxide Semiconductor Field Effect Transistor

PbO_2 -   Plumbum Oxide (Positive electrode)

Pb   -   Plumbum (Negative electrode)

H_2SO_4 -   Sulfuric acid

SO_4 -   Sulfate substance

DSP   -   Digital Signal Processing

ADC   -   Analog Digital Converter

LED   -   Light Emitting Diode

PCB   -   Printed Circuit Board

CHAPTER 1

INTRODUCTION

1.1   Background

Battery is been rapidly increasing used in a variety of subject areas, such as power sources for telecommunication equipment, car starters, hybrid electrical vehicles, renewable energy storage systems and etc. Furthermore, battery has also been employed as a standby power source when the main power having disturbance of electricity.

Battery as the most popular energy storage device has two different types, primary battery and rechargeable battery.Primary battery also known as disposable battery which have higher density than rechargeable battery. Also have a lower self discharge. The primary battery is not suitable for the energy storage systems since the battery intended to be used once and then discarded. Rechargeable battery which also known as a secondary battery because electrochemical reactions are electrically reversible. Many different rechargeable battery technologies but only four of these batteries are leading the world market : Nickel Cadmium, Nickel Metal Hydride, Lead acid and Lithium-Ion.

Converters have a wide range of applications and becoming increasingly important especially in power semiconductor devices. DC to DC converters convert a DC voltage to a different DC voltage level. Nowadays, DC to DC converter circuits can be found in diverse applications such as switching power supplies, variable speed drives, and PWM rectifiers, where conversion of the DC voltage source to different levels is required [1].
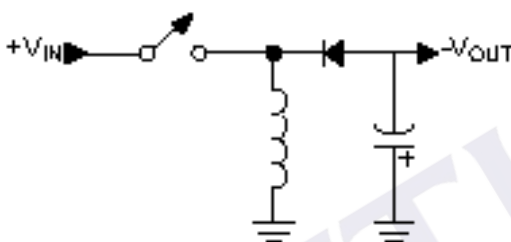
Figure 1.1 : The Buck-Boost converter circuit

The conventional Buck-Boost converter circuit in Figure 1.1 consists of two modes of operation, Buck and Boost. The Buck operation convert a voltage source into a lower regulated voltage while the Boost operation used to obtain an output voltage higher than the input.

The battery charger controller has been developed to improve charging rate, optimize battery performance and reduce the internal resistance of the battery. The previous controllers for battery charger are using Intelligent Fuzzy Controller, Digital Signal Processing based Fuzzy Logic Controller and Robust Local Controller.

This project uses software MATLAB as a control while the Arduino is served as a signal processing controller. MATLAB has been chosen for this project due to accessibility this software and can easily modify and improve the code provided. While, Arduino has been selected due to affordable cost and has an easy programming language based on ready C/C++ libraries. The Arduino is an open source microcontroller board has digital input/output pins and simply connected to a computer with a Universal Serial Bus (USB) cable to get started.

The block diagram for this project as shown below.
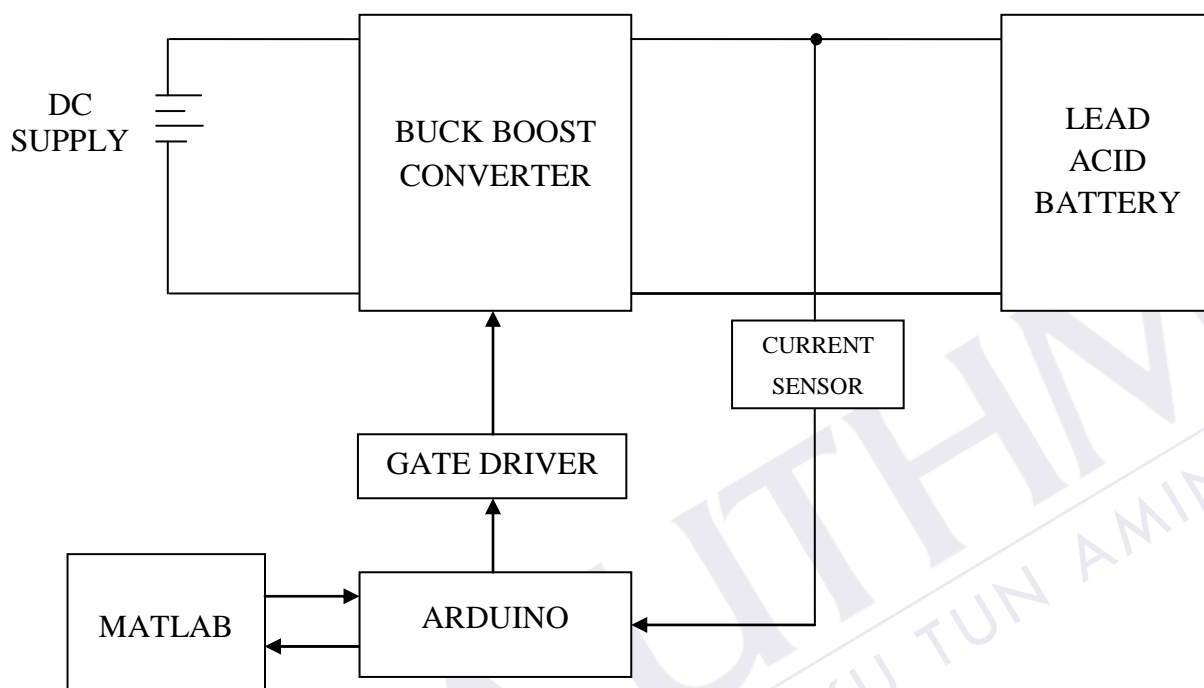
Figure 1.2 : Block diagram of the project

The block diagram of the project in Figure 1.2 starts with DC supply input voltage to the Buck-Boost converter circuit. The output voltage of the converter start charging the lead acid battery. Current sensor detects the current and send output signal to the Arduino. The Arduino generates PWM output signals and send through gate driver to control switching on the Buck-Boost converter circuit.

1.2   Problem Statement

The potential problems that encountered in the battery is the charging technical problem which led to longer charging time that causing the quality of the battery become poor and shorten the life of the battery [2]. The battery charger requires a converter that able to charge the battery with the variable input voltage and a constant output voltage for charging process. Therefore, the Buck-Boost converter is a suitable converter used in this project. Otherwise, according to [14], the conventional battery charger experiences a low power factor and distorted current harmonic waveform. Since many controller was applied in the battery charger such as fuzzy controller, PID, time delay and etc, thus, the battery charger with a controller will improve the line power quality and able to deliver maximum allowable output power to the battery.

1.3   Objectives

The main objectives of the project are :

i)   To communicate between MATLAB &Arduino software.

ii)   To develop repetitive current controllers for a Buck-Boost converter.

iii)   To design gate driver for Buck-Boost converter circuit.

iv)   To design Buck-Boost converter circuit for the lead acid battery.

1.4   Scope

The project scope concentrates on the development of hardware and software according to the objectives of the project.

- This project uses MATLAB R2013b and Arduino microcontroller software. The software should be able to communicate each other in order to receive input and output signal.

- The purpose of MATLAB R2013b software is to develop repetitive current controller block diagram to create a PWM input signal.

- Design gate driver with single phase two input four output to meet the MOSFET used in the converter.

- The type of converter circuit that has been selected in this project is a Buck-Boost converter.

CHAPTER 2

LITERATURE REVIEW

2.1   Lead Acid Battery

Nowadays, several industries such as automobiles, vehicles and renewable energy storage system are rapidly increasing use the battery for an energy storage element [4], [5] & [6]. For this reason, lead acid battery is one of the most admired elements for supporting those products. The lead acid battery most popular utilized especially for energy storage system.

Energy can be charged and discharged in the lead acid battery through a chemical reaction between the positive electrode (PbO_2) and negative electrode (Pb) using sulfuric acid (H_2SO_4) solution electrolyte shown in [7].

$$PbO_2 + 2H_2SO_4 + Pb \Leftrightarrow PbSO_4 + 2H_2O + PbSO_4 \tag{2.1}$$
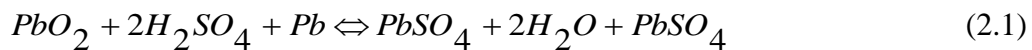
As chemical reaction shown in [8], every charge and discharge process in lead acid battery will have sulfate substance (SO_4) collected at both positive and negative plates (electrode) known as "sulfation". The sulfation occurs because sulfate substance (SO_4) cannot complete reversible reaction to be sulfuric acid. Consequently, the battery cannot complete chemical reaction process and then the battery eventually is depreciated.

The sulfation is the main reason of worn out batteries that a charging process would directly affect with a battery capacity and lifetime. Thus, the incorrect charging process could result to deteriorate alead acid battery due to sulfation. Hence, the battery charging process is quite significant for battery lifetime and capacity.

Table 2.1 : Properties of the rechargeable batteries

	Lead Acid	Nickel Cadmium	Nickel Metal Hydride	Lithium Ion
Cell Voltage (V)	2	1.2	1.2	3.6
Specific energy (Wh/kg)	1-60	20-55	1-80	3-100
Specific power (W/kg)	<300	150-300	<200	100-1000
Maximum cycles	200-700	500-1000	600-1000	3000
Discharge time range	>1min	1min-8hr	>1min	10s-1hr
Cost ($/kWh)	125	600	540	600
Cost ($/kW)	200	600	1000	1100
Efficiency (%)	75-90	75	81	99

The properties of the rechargable batteries are shown in Table 2.1 consists of lead acid battery, nickel cadmium battery, nickel metal hydride battery and lithium ion. One of the reason the lead acid battery selected is by comparing the cost between the batteries.

2.2   Charging Method

Charging Lead-Acid battery is an interesting control problem, especially during the charging process due to exponential current-time relationship. However, the conventional charging methods of lead acid battery used for charging is reducing the battery life such batteries unprotected from overcharging. The methods also waste a lot of energy and do not have built in battery charged to prevent the self discharge.

The main charging processes for a lead acid battery can be accomplished by various methods; constant current method (CC), constant voltage method (CV), constant current-constant voltage method (CC-CV) [9], pulse charging and Reflex™ charging [10]. Constant current method (CC) does not change appreciably in magnitude, regardless of battery voltage or temperature. The battery is charged at the lower charging rate. This charging scheme may prolong the charging time. In the constant voltage method (CV), the initial charging current is normally high. The heating effect may damage the plate and shorten the battery life.

Another charging method is called constant current-constant voltage method (CC-CV) composed of two charging modes. In the initial charging, the battery chargers provide constant charging current until the battery voltage reaches the upper voltage threshold. Once it reaches the upper voltage threshold, the charging current decreases until the battery is completely charged.
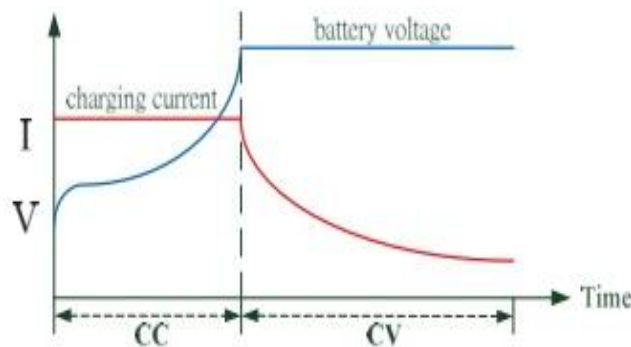
Figure 2.1 : Constant current-constant voltage method.

Pulse charging method has been studied in [9] & [10] and a pulse current is applied to the battery periodically provides the battery a relax time in charging process. Using a large pulse current will shorten the battery charging time. The Reflex™ charging method is an improvement on the pulse charging. A charging period consists of a positive pulse, a negative pulse and a relax interval.

Table 2.2 : Comparison charging method

Method	Advantages	Disadvantages
Constant current method	Has ability of limited current to prevent the over current of initial charge.	Easy to overcharge in later stage.
Constant voltage method	Has ability of limited voltage to prevent the over voltage.	Easy to overcurrent in initial stage.
Constant current-constant voltage method	Can limit voltage and current.	Charge time is too long.
Pulse charge method	Can reduce the polarization to prevent the battery temperature rise.	Control is complex.
Reflex™ charge method	Can reduce the polarization to prevent the battery temperature rise.	Control is complex.

The comparison between 5 types of charging methods are shown in Table 2.2 consists of constant current method, constant voltage method,constant current-constant voltage method, pulse charge method and Reflex™ charging method.

2.3   Converter

Many power semiconductor devices that are commercially available categorized into four categories : AC to DC converter (rectifier), DC to DC converter, AC to AC converter and DC to AC converter (inverter). Three basics DC to DC converter topologies : Buck converter, Boost converter and Buck-Boost converter [11].
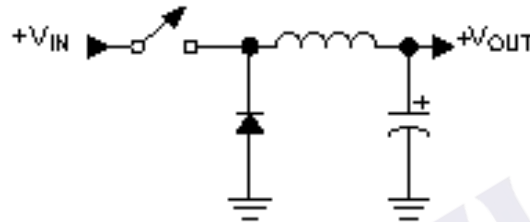
Figure 2.2 : Buck converter circuit

The Buck switching converter in Figure 2.2, convert a voltage source typically 8V to 25 V into a lower regulated voltage typically 0.5 V to 5 V. This step down converters using a switch, a diode, an inductor and several capacitors. Thus, the Buck converters offer higher efficiency in most cases.
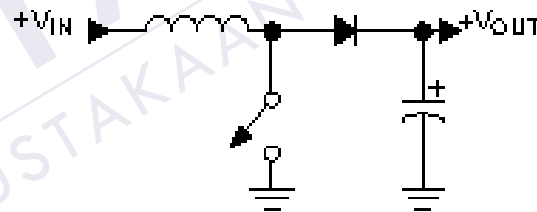
Figure 2.3 : Boost converter circuit

The Boost converter in Figure 2.3, used to obtain an output voltage higher than the input. This step up converters also using a switch, a diode, an inductor and several capacitors.

2.4   Intelligent Fuzzy Controller

The previous controllers for lead acid battery charger are using Intelligent Fuzzy Controller [12] where implies an intelligent two step charging method. The first step is when the battery is almost 70% of full charging charges with a high current fast charge fuzzy algorithm. The second step is when the battery current is left to decrease exponentially and the battery voltage is maintained at a set value.
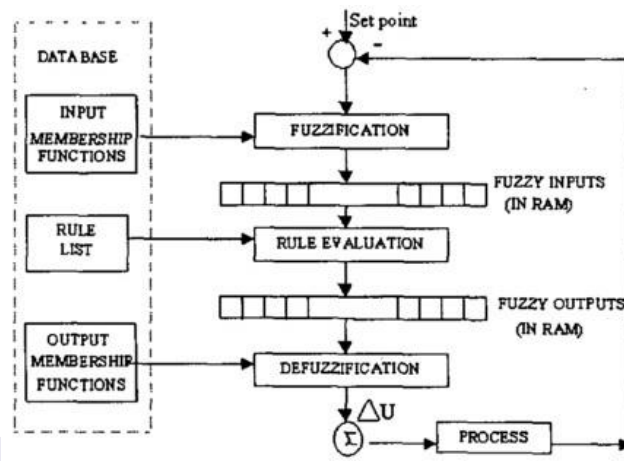
Figure 2.4 : Block diagram of Fuzzy Controller

The block diagram of Fuzzy Controller in Figure 2.4 shows that the Fuzzy controller has three basic steps : Fuzzification, Rules evaluation and Defuzzification. By applying Fuzzy controller to the battery charging systems can reduce the charge time and improve the charge efficiency [13]. The Digital Signal Processing (DSP) based Fuzzy Logic Controller is used for battery charger to supply the pulse width modulation (PWM) waveforms and perform fuzzy control feedback [14]. Hence, reducing the need for extra components. The DSP based fuzzy logic control provides an excellent alternative method of controlling the battery charger. The battery charging system is able to achieve the desired output at a better dynamic performance and easier implementation. According to [14], the conventional battery charger experiences a low power factor and highly distorted current harmonic waveform. Thus, the battery charger with a fuzzy logic controller will improve the line power quality and able to deliver maximum allowable output power to the battery.
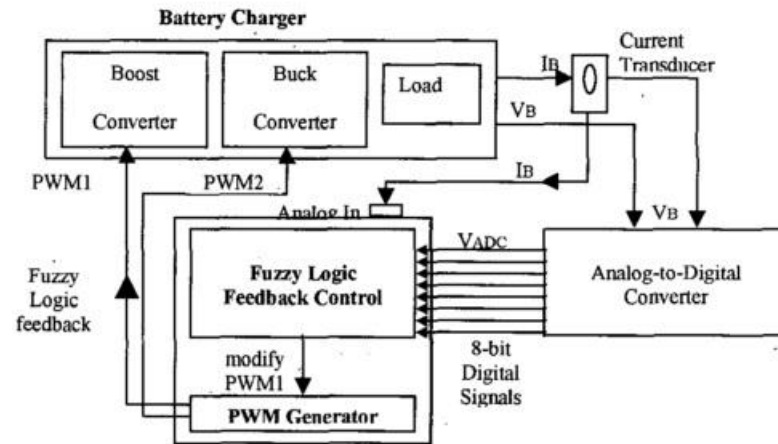
Figure 2.5 : The Fuzzy feedback control system

The Fuzzy feedback control system in Figure 2.5 is designed to detect the charging current from the Analog In and battery voltage variation. The duty cycle of the boost converter will be determined according to the input battery voltage and charging current level.

2.5   Repetitive Controller

Many signals in engineering disciplines are using periodic signal. For example most signals associated with engines, electrical motors, converters performing a task over and over again. In practical applications, the control tasks are often of a repetitive nature. For example, in industrial manipulators executing operations of picking, placing or painting, machine tools and magnetic disk or CD drives [15]. The control systems are usually required to track or reject periodic exogenous signals.

The feature of a repetitive controller contains an internal model of a periodic signal with harmonics at angular [16]. In a basic repetitive control system, the repetitive controller consists a pure delay positive feedback line with a repetition period, T which is used to carry out self learning in the following way. By referring the Figure 2.6, at the control input v(t), the previous period is added to the control input of the present period to regulate the current control input. Due to ease implementation and high control precision of repetitive control is now widely used in many fields from aerospace to public welfare systems.
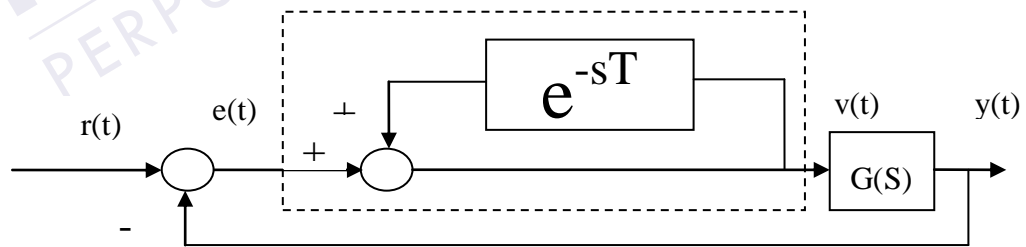

Figure 2.6 : Configuration of repetitive control system.

The transfer function of repetitive control system is [17]:

$$\frac{v(t)}{e(t)} = \frac{e^{-sT}}{1 - e^{-sT}} \tag{2.2}$$
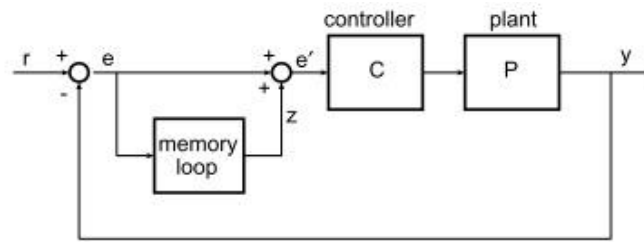
Figure 2.7 : Block diagram of a control loop including a repetitive controller

Block diagram of a control loop including a repetitive controller in Figure 2.7 shows a block diagram of a closed loop system including a repetitive controller. The reference signal r, acting on the system is assumed to be a periodic signal with known and fixed period time.

Repetitive control is a method of tracking a periodic reference input signal that exhibit repetitive behaviour [18]. The usual repetitive problem handles three situations which is when the objective is to track with zero error a periodic command. Second is when the desired output is a constant but there is a periodic disturbance. Third is aims to get zero tracking error to a periodic command in the presence of a periodic disturbance [19].

Only reference or disturbance signals within certain frequencies need to be tracked or rejected. Therefore, the external model repetitive control is usually to establish a signal generator including the harmonics of interest. This approach is called basis function based repetitive control [15]. The basis function method can greatly save the storage size for the implementation of the repetitive controller. Furthermore, stability analysis of repetitive control systems becomes easier due to the stability of the basis function.

2.6   Software

MATLAB use as a control and visualization environment, while the Arduino is serves as a signal processing controller. The Arduino is an open source microcontroller board that has digital input and output pins and simply connected to a computer with a Universal Serial Bus (USB) cable to get started. The Arduino also recommended for those who just starting involved with develop electronic projects.

The research on MATLAB and Arduino controller increasing widely synchronous with the latest technology development particularly in industrial, engineering, education field and etc. One of the great initiative that involve MATLAB and Arduino is for the development of low cost educational platform [20]. MATLAB has been selected due to most widely used software also almost accessible in all educational institutions generally. Thus, students able to modify and improve the code provided.

In vision research has proposed an inexpensive system to control light intensity for research application also involve usage of Arduino [21]. The pulse width modulation (PWM) signal was shown in a good quality provided by the Arduino controller, thus leading the irradiance output of LEDs to be linear as a function of the duty cycle of a PWM signal. The application easily implement for students, educational purpose and universities with limited infrastructure.

MATLAB also involve in research of design current control for multi module bidirectional battery charging or discharging [22] and almost related to this project. Researcher use MATLAB in order to design current and voltage feedback compensation. Also identify accuracy of the modeling and validity of control design by MATLAB simulation.

CHAPTER 3

METHODOLOGY

3.1 Methodology

Chapter 3 consists of methodology used for the project including software and hardware developments. The software part will discuss about MATLAB simulation as well as repetitive controller. Usage and properties of Arduino board also discussed further in this chapter. The part of hardware development consists of design converter circuit, gate driver circuit, current sensor and project assemble. For both software and hardware development consists of open loop and close loop operation.

3.2   Software

The software use in this project is MATLAB R2013b and Arduino UNO microcontroller which features a maximum clock rate of 16 MHz with 32 KB Flash Memory. The Arduino has 14 digital input and output pins which 6 pins can be used as PWM outputs and another 6 pins used as analog inputs. For this project, Pin 9 & Pin 11 used as PWM outputs which connected to input gate driver while Pin A1 used for input voltage and Pin A2 used for current sensor. The Figure 3.1 shows the Arduino UNO board microcontroller used in the project.

Figure 3.1 : Arduino UNO board microcontroller

A repetitive current controller has been developed using MATLAB Simulink Toolbox in order to generate the pulse width modulation (PWM) signals. The Arduino receives PWM output signals and send through gate driver to control switching on the Buck-Boost converter circuit.

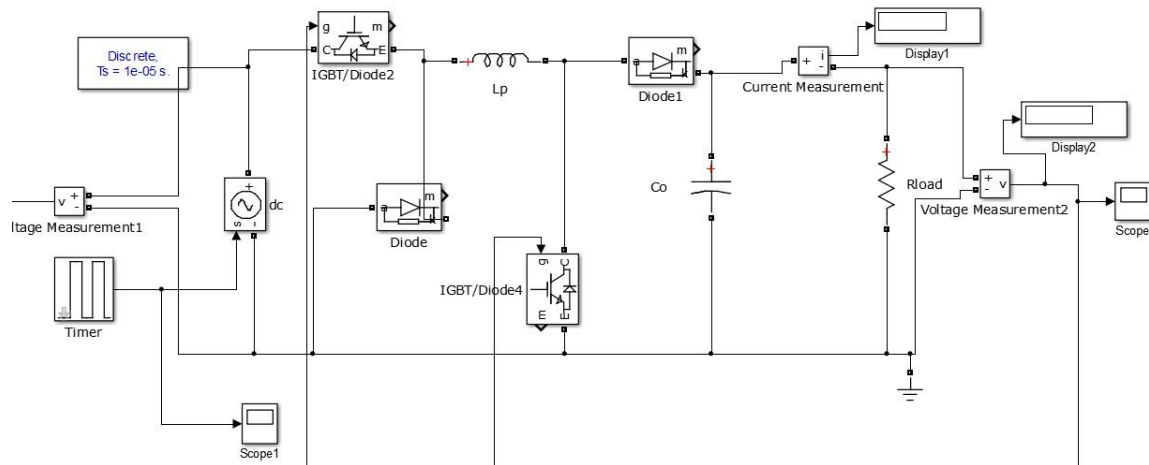Figure 3.2 : MATLAB simulation diagram of Buck-Boost converter circuit

The MATLAB simulation diagram of Buck-Boost converter circuit in Figure 3.2 shows the components for Buck-Boost converter circuit is a pair of switches, two controlled MOSFET (IRF540) and two uncontrolled diodes (IN4001). The converter also use one capacitor (47uF), one inductor (10mH) and one resistor (100ohm).
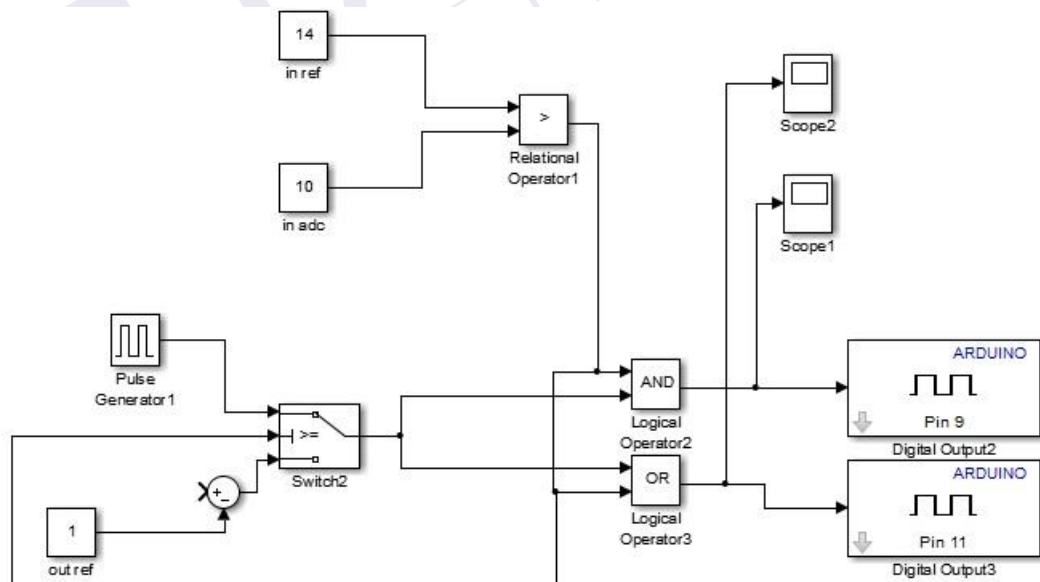

Figure 3.3 : Open loop simulation diagram

The open loop simulation diagram in Figure 3.3 is for Boost operation. Input voltage for Boost operation is 10V and will compare in relational operator with reference voltage 14V. If the input voltage is lower than reference voltage, the output signal becomes 1.
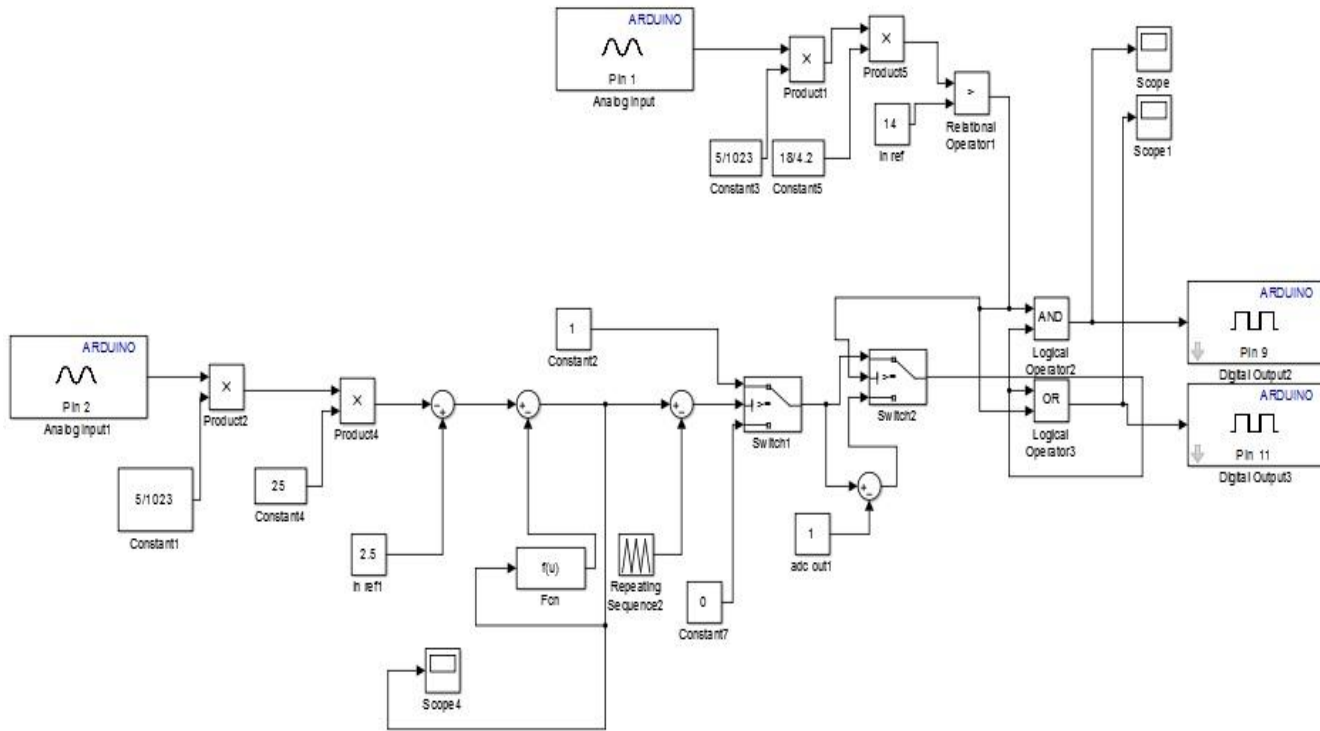

Figure 3.4 : Close loop simulation diagram

The close loop simulation diagram with repetitive current controller shows in Figure 3.4. The repetitive current controller in equation (2.2) is used in this project [17]. By referring to Figure 3.4, Pin A1 used for input voltage and Pin A2 used for output current sensor. The input voltage at Pin A1 is in analog signal and have to convert through Analog Digital Converter (ADC) since Arduino only able to read in digital signals. The input voltage will compare in relational operator with input reference of 14V. If the input voltage is higher than input reference, the output signal becomes Buck operation. While, if the input voltage is lower than input reference, the output signal becomes Boost operation. The Pin A2 used for output current sensor and also have to convert to digital signals. The digital signal then need to combine with repetitive equation to generate PWM signals.

3.3   Hardware

The hardware development consists of designing the Buck Boost converter circuit, gate driver circuit, current sensor and overall connection of the project.

3.3.1   Converter

Buck-Boost converter circuit has been decided to use in this project since the converter consists of two modes of operation, Buck and Boost. For Buck mode, operation acts to buck voltage from 18V to 15V while Boost mode, operation acts to boost voltage from 10V to 13V.
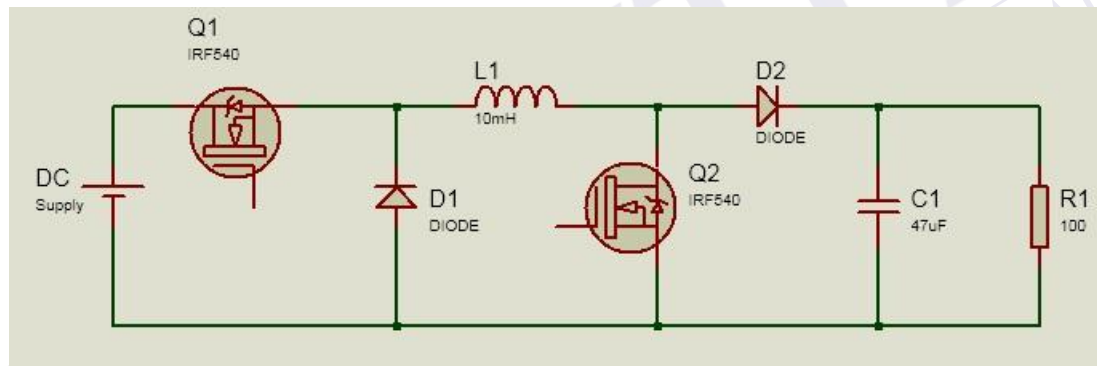

Figure 3.5 : Circuit of Buck-Boost converter

The Buck-Boost converter in Figure 3.5 was designed to receive the single phase input dc supply and convert to output dc voltage which is 14V that compatible with properties of lead acid battery.
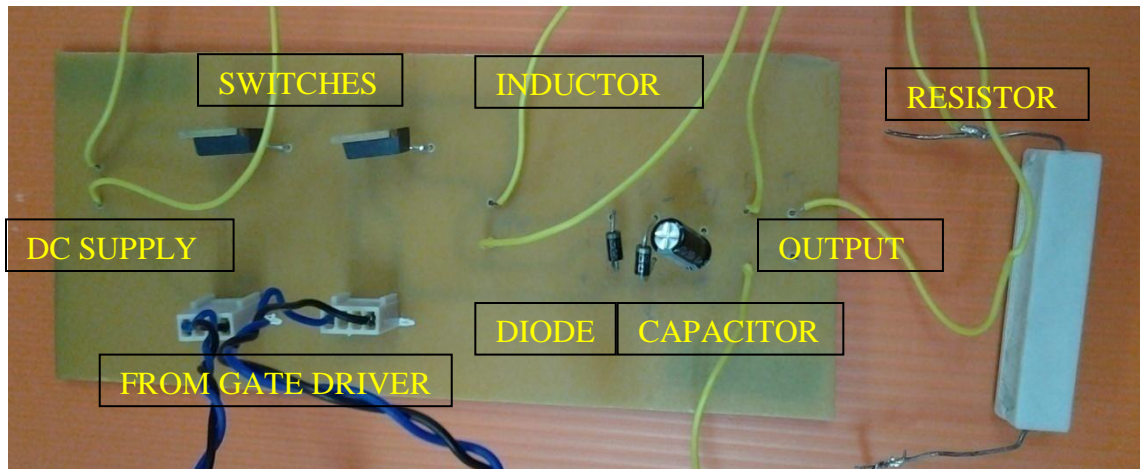
Figure 3.6 : Buck-Boost converter circuit

The Buck-Boost converter circuit in Figure 3.6 shows the circuit used to achieve unidirectional power flow from input to output, the converter use a pair of switches,two controlled MOSFET (IRF540) and two uncontrolled diodes (IN4001).The converter also use one capacitor (47uF), one inductor (10mH)and one resistor (100ohm) to store and transfer energy from input to output also filter or smooth voltage and current. All the circuit and PCB layout are designed using the Proteus 8 Professional software.

The circuit analysed in two operations: Buck operation and Boost operation. In Buck operation (18V to 15V), switch 1 (SW1) is in PWM mode and switch 2 (SW2) is opened. While in Boost operation (10V to 13V), switch 1(SW1) is closed and switch 2 (SW2) is in PWM mode.

First state in Buck operation : When the switch 1 (SW1) is closed, the diode D2 becomes forward biased (short circuit), the switch 2 (SW2) is open (open circuit) and the circuit formed in Figure 3.7.

Figure 3.7 : Switch 1 (SW1) is closed

By using Kirchoff's Voltage Law, the voltage across the inductor, V_L is given by the difference between voltage supply, Vs and output voltage, Vo.

$$V_L = V_S - V_O \tag{3.1}$$

The inductor voltage, V_L is related to the change in current flowing through it according to the relation.

$$V_L = L\frac{di_L}{dt} \tag{3.2}$$

Equating V_L in both equation (3.1) and (3.2),

$$V_L = V_S - V_O = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{Vs - Vo}{L} \quad . \tag{3.3}$$

Since $\frac{di_L}{dt}$ is constant, the equation can rewrite as below:

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t_1} = \frac{Vs - Vo}{L} \tag{3.4}$$

Figure 3.8 : Inductor current versus time

The duty cycle, D of the switch is defined as follows:

$$D = \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T}$$

(3.5)

From equation (3.5), the equation can be rewritten as below:

$$\frac{\Delta i_L}{DT} = \frac{V_S - V_O}{L}$$

$$\Delta i_L = \left(\frac{V_S - V_O}{L} \right) DT$$

(3.6)

Second state in Buck operation : When the switch 1 (SW1) is reopened, the diode D1 becomes forward biased (short circuit), the switch 2 (SW2) is open (open circuit) and the circuit formed in Figure 3.9.
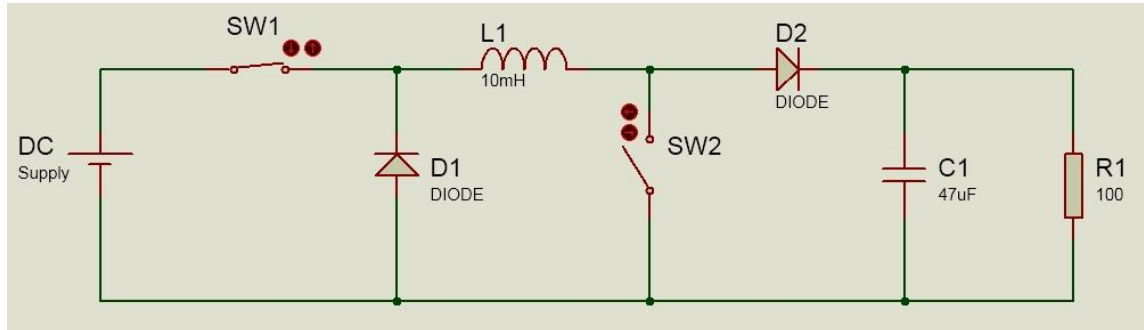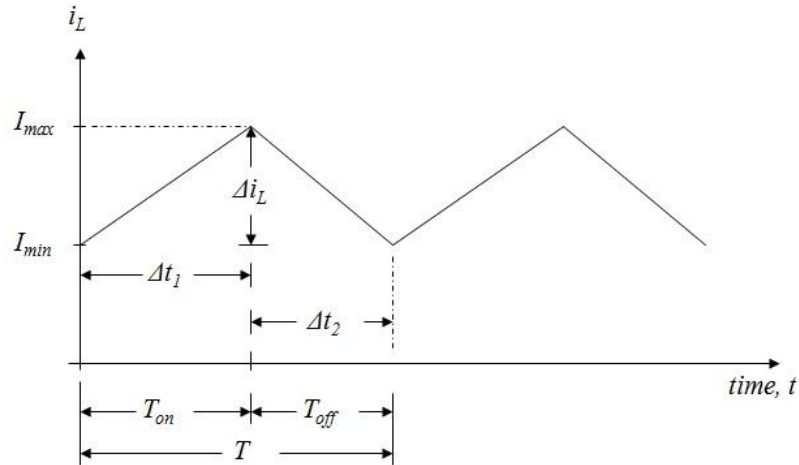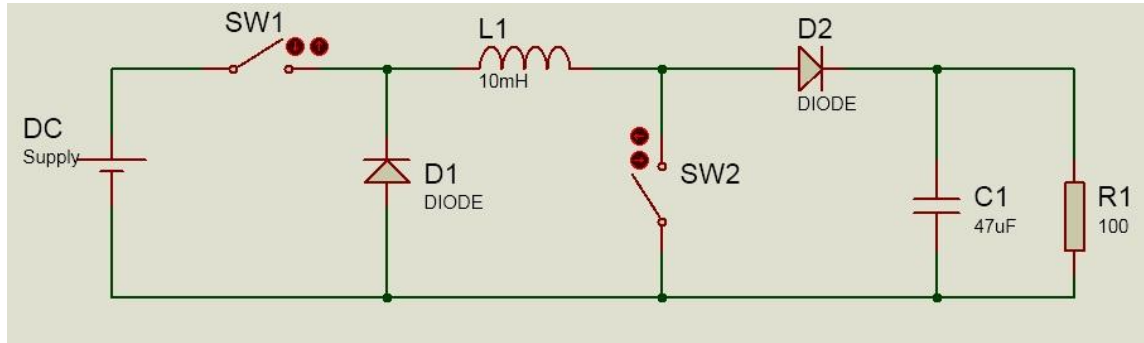

Figure 3.9 : Switch 1 (SW1) is reopened

By using Kirchoff's Voltage Law, the voltage across the inductor, V_L is given by the difference between voltage supply, Vs and output voltage, Vo.

$$V_L = -V_O \tag{3.7}$$

The inductor voltage, V_L is related to the change in current flowing through it according to the relation.

$$V_L = L\frac{di_L}{dt} \tag{3.8}$$

Equating V_L in equation (3.7) and (3.8),

$$V_L = -V_O = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{-Vo}{L} \tag{3.9}$$

Since $\frac{di_L}{dt}$ is constant, the equation can rewrite as below:

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t_2} = \frac{-Vo}{L} \tag{3.10}$$

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