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DESIGN AND IMPLEMENTATION OF INTELLIGENT LI-ION BATTERY CHARGER

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Abdulrahman Mahmood Faihan

ABSTRACT

DESIGN AND IMPLEMENTATION OF INTELLIGENT LI-ION BATTERY CHARGER

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Nowadays, Li-ion batteries are considered the best type of rechargeable batteries due to their high energy density, but they need a specific mode of charging to avoid their explosion. In this thesis, we have designed an intelligent battery charger that charges the Li-ion batteries by a constant current-constant voltage mode based on pic16f876 microcontroller. The charger can charge a variable number of Li-ion batteries that connected in series. The mode of charge has shown to the user by using two LEDs, one refers to the constant current mode and another one for constant voltage mode.

The voltage and current are detected in our design in order to make the necessary judgment on charging state of the batteries and also to present the values of charging current and charging voltage to the user in the LCD. Pulse Width Modulation signal was adjusted to obtain high-precision charging control. In addition, the Buck DC-DC converter has been used for producing positive regulated output voltage. The user could adjust the cutoff voltage and the charging current according to the number of series batteries that the user wants to charge. In addition to the cut-off voltage and charge current values, the value of input DC voltage which supplies the circuit also presented to the user on the LCD screen.

Keywords–Li-ion Batteries, PIC16F876, Intelligent Charger, PWM Controlling, DC-DC Buck converter.

ÖZET

Akıllı Li-ion Pil Şarj Aletinin Tasarımı ve Gerçekleştirilmesi

FAIHAN, Abdulrahman Mahmood

Yuksek Lisans Tezi, Elektrik ve Elektronik Mühendisliği

Danışman: Prof. Dr. Ergun ERÇELEBİ

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53 Sayfa

Günümüzde, Li-ion piller, yüksek enerji yoğunluğundan dolayı şarj edilebilir pillerin en iyi çeşidi olarak değerlendirilmektedir ancak patlamalarını önlemek için belirli bir şarj moduna ihtiyaç duymaktadır. Bu tezde, Li-ion pillerini sabit akım sabit voltaj moduyla şarj eden PIC16F876 mikro denetleyicisine dayanan akıllı bir şarj cihazını tasarladık. Şarj cihazı, seri bağlanmış çeşitli sayıda Li-ion pillerini şarj edebilir. Şarj modu iki LED kullanarak kullanıcıya gösterildi, biri sabit akım modunu, diğeri ise sabit voltaj modunu temsil etmektedir. Tasarımımızda, Akünün şarj durumu hakkında gerekli yargılamayı yapmak ve kullanıcıya şarj akımı ve şarj voltajı değerlerini LCD'de sunmak için voltaj ve akım tespit edilmiştir. Darbeli Genişlik Modülasyon sinyali, yüksek hassasiyetli şarj kontrolü elde etmek üzere ayarlandı. Buna ek olarak, pozitif düzenlenmiş çıkış voltajı üretmek için Buck DC-DC dönüştürücü kullanıldı. Kullanıcı, kesme voltajını ve şarj akımını kullanıcının şarj etmek istediği seri pil sayısına göre ayarlayabilir. Kullanıcı, kesme voltajını kullanıcının şarj etmek istediği seri pil sayısına göre ayarlayabilir. Kesme gerilimi ve şarj akımı değerlerine ek olarak devreyi besleyen giriş DC voltajının değeri de LCD ekranda kullanıcıya sunulmuştur.

Anahtar Kelimeler-Li-ion Pil, PIC16F876, Akıllı Şarj Aleti, PWM Kontrolü DC-DC Buck dönüştürücüler.

Dedicated to

"To Beloved parents, my mother and father"

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LIST OF SYMBOLS / ABBREVIATIONS

A	Ampere
AC	Alternative current
ADC	Analog to Digital Converter
C	Capacity
CC	Constant current
CCM	Continuous conduction mode
CV	Constant Voltage
D	Duty cycle
DC	Direct Current
DCM	Discontinuous conduction mode
DoD	Depth of discharge
DSP	Digital Signal processing
EMI	electromagnetic interference
FB	Feed back
IGBT	Insulated-gate bipolar transistor
I/O	Input/output
LCD	Liquid Crystal display
LDO	Linear drop out
mah	Millie ampere hour
MOSFET	Metal Oxide semiconductor field effect transistor Voltage

MCU	Microcontroller
PWM	Pulse Width modulation
PI	Proportional Integral
PIC	Peripheral interface controller
PID	Proportional Integral Deferential
SOC	State Of charge
SPI	Serial Peripheral interface
USART	Universal Asynchronous Receiver Transceiver
USB	Universal Serial Bus
Vgs	Gate to source voltage

Chapter 1

INTRODUCTION

1.1 Overview

Batteries nowadays considered the most desirable power source for the personal electronics such as the laptops, mobile phones, and music players as well as many other applications. To understand the impact of batteries on our lives, we see that all the persons monitor the amount of residual charge to see how much more they can use the I-pad or laptops or talk on the phone. In electrical power systems, there must be a balance between the two sides of production and consumption and when there is an imbalance in either of these two parts, as in renewable energy systems where the value of the generated voltage from solar cells or wind generators are variable and unstable. In this case, we need a storage side to store this variable energy and provide a stable power for the user even in the case of source voltage fluctuation. Factories produce many different types of batteries that can be classified according to their basic design. Although there are many ways to store energy, batteries are the best option in terms of performance, energy availability and reliability. The design of the battery determines the amount of stored electricity. Some batteries called primary batteries. It stops working and deactivated after consuming one of their constituent chemicals and must be disposed of. Other types of batteries can be reused after they have run out of energy by recharging them. This kind is called secondary batteries, or storage batteries.

Nowadays the peripheral electronic devices need batteries with a large capacity to work for a long time. In addition to capacity, the size of batteries is another important factor. The Li-ion batteries satisfy these two conditions with more extra advantages such as no memory effect, high operating voltage, and low self-discharge. If it were not used for a long time it would not lose its charge quickly. Li-ion cells are

suitable for the applications which need a big value of charge-discharge cycles. The small car with a 120-kilogram Li-ion battery can travel 150 kilometers. If the lithium-ion battery replaced by a nickel-metal hydride (NiMH) battery, the car can only walk 50 kilometers. Therefore, hopes are attached to the lithium-ion battery to operate the electric cars in the next stage. But on the other side, Lithium-ion batteries, due to their high density, are vulnerable according to short-circuiting and overcharging. It may explode and occur fire hazard if it could not charge safely unlike the other types of batteries which work safely even at overcharging and short-circuiting situations due to the fact that the other types use inflammable electrolyte and they have a low energy capacity. For this reason, we designed an intelligent lithium-ion battery charging system to control the charging current and the voltage. We have designed smart battery charger having several advantages, it is safer towards batteries damages and low-cost. The circuit is simple and all the components are available, it presents the voltage and current values on the LCD. In addition, it presents charging mode for the user and the best feature in our design that can charge a variable number of batteries in series from 3.7 V or from 4.2 types. But on the other hand, the feature of charging a variable number of batteries in series requires a balancing circuit to make equilibrium between the batteries. This is impossible in our design because in balancing circuit, we need to know the accurate number of batteries which connected in series and this is not available in our design.

1.2 Literature Review

In 2005, M.F.M. Elias, K.M. Nor and A.K. Arof have presented the basic concept of Li-ion batteries charging techniques, the equilibrium of a series connected Li-ion batteries, charging control circuits, protection and parameters monitoring in addition to design limitations. After a brief explanation in the theoretical literature of Li-ion batteries, the article presents the design of a practical charging circuit based on MCU. The circuit senses and presents the current and voltage values, starting and stopping the charging process and displaying a SOC value [1].

In 2012 Fei, Ma has used the AT89C51 MCU to develop an intelligent battery charger. The charger detects the voltage and the current of the battery. An intelligent control process applied in the design. The remaining time to complete the charge of

the battery is calculated automatically and all the parameters are adjusted to adapt to a variety of battery charging. Overcharge and over time protective functions added to the battery management system to prevent the damage of the battery [2].

In 2014, the main concept of battery charging of an EV has presented by Ying Zha, Shenzhen Hou, and Xu Fang. They have studied the intelligent charging system in terms of the hardware scheme and the working principle. They presented the desired characteristics of the charger based on the results of their study and the batteries performance [3].

In 2012, Wenjuan Wang, Guangxi Zheng and Weidong Lu have used the STC12C5AS2 microcomputer to perform a Li-ion battery charger with several properties. The system could detect the SOC as well as it could be connected to a PC to enable the user see the charging voltages and charging current values directly from the computer. The GUI on the PC also contains a voltage curve and current curve. The values of SOC and DOD presented for the user in the GUI. The photos of the real design and the circuit design are included in the article. The researchers found an active strategy to reduce the volume of calculation and save the CPU space. Two containers created to store calculated data inside it and plot the curves faster [4].

In 2006, Min Chen and Gabriel A. Rincón-Mora have designed battery charger for Li-ion batteries. The aim of the design was to get the maximum capacity and cycle life. The design presents the runtime. A power MOSFET transistor used to control the charging process. This MOSFET controlled by two linear feedback loops with high gain, the transition between feedback loops accomplished by a diode to get a smooth transition between these two loops. The charger charges the battery with constant current first and constant voltage later. The power losses were reduced in the design and power efficiency of the system improved by 27% by using an adaptive power effective charging structure. The system can charge a number of Lithium batteries until 0.43% of the full optimum charge of these batteries [5].

In 2011, Wencheng Wang used the AT89S51 SCM MCU to design a smart charger for lithium batteries. The flow chart, principle of work and the appropriate hardware components described in details. The SCM MCU creates the suitable Pulse width

modulation signal according to the Li-ion voltage and current charging curves. State of the charger is monitored by the system to detect the faults. The system displays the data for the user and provides the protection for the battery from overheating. The results show that the charging efficiency had been improved and battery life extended efficiently [6].

In 2015 Nguyen, D., Dao, C., Nguyen-Van, H., Nguyen, L., Lee, S. G., and Pham-Nguyen designed a wireless power system for Li-Ion battery charger including voltage doubler (AC-DC), voltage linear regulator (LDO) and charging control loop applying multi-charging phases method to minimize the battery effect. Proposed Li-ion battery charger with input voltage is 6Vp-p at frequency 4MHz, DC o/p voltage is 4.1V, maximum DC output current is 1.5mA is designed using TSMC 130nm technology for implanted biomedical devices [7].

K.M. Tsang and W.L. Chan in [2011] designed an adaptive charging system that can charge the lithium batteries with a strategy alike constant current-constant voltage, but without using the current sensor to sense the charging current. The design was low cost and simple. In addition, it performs the charging process quickly. The designers have used a double loop controller technique in their design to get a current sensorless circuit. The level of saturation increased in the main voltage control loop in order to shorten the charging time [8].

1.3 Organization of Thesis

We divide the thesis into five chapters as the following:

- Chapter One: In this Chapter, we make a short-term introduction to the developments of the different types of batteries and the Li-ion batteries and the importance of these batteries in daily life. Also, we make a literature review about the development of Li-ion charger design in the last few years
- Chapter Two: provides a general review of the different types of batteries and their advantages and disadvantages. The second section of this chapter discusses the batteries charging techniques and what is the most appropriate type for the Li-ion batteries.

- Chapter Three: illustrates the steps of the design and the used components in the design.
- Chapter Four: gives the results and discussion.
- Chapter Five: presents the conclusions and suggestions for the future work that may improve the performance of the project.

Chapter 2
The Theoretical Background

2.1 Overview

In this chapter, we will first discuss battery specifications and chemistries and show the superiority of lithium batteries over other types. After that, we will discuss the development of power electronic conversion circuits and power electronics elements, which considered the cornerstone for designing any type or topology of batteries charging systems. We will concentrate on the DC-DC converters and explain differences between them and their mechanisms. PWM converter's properties are discussed and explained in this chapter. PWM converters have many features and advantages. Such as relatively low cost, achieving high conversion ratios in buck and boost converter applications, the PWM converters could be operated with easy control circuits and high efficiency. A disadvantage of PWM DC-DC converters also will be described. In addition, we explain in details the different topologies for charging the different types of batteries, the advantages, and disadvantages of each type and the types of batteries that can be charged by these topologies.

2.2 Battery Specification

The word "battery" approved by the scientists in the 18's century. This expression used to act a group of electrochemical cells linked together to find an energy storage device. Two electrodes dunked by an electrolyte to promote the movement of ions and isolated by a separator could form the basic shape of the battery. The evolution of batteries was a bit slow in the past. New active materials made to improve the characteristics of batteries, but none of these attempts has given perfect Improvements to batteries. However, after the invention of lithium batteries, batteries developed and improved very quickly, whereas the capacity of the batteries increased by 8% each year in the last 20 year. However, this increase remains little and less than what production companies expect. In comparison with the transistor, for

example, we see that the number of transistors in single (IC) doubled every two years according to Moore's Law. Theoretical battery models hope to reach an energy level ten times more than what exists now. However, this is a theoretical target and may never achieve. The battery can be likened to a weak can that fills slowly, holds limited energy, and runs for a specific time after that it should be recharged or it will be a nuisance source. Batteries are available with a wide range of electrochemistry. Each of these varieties has its own special characteristics, which distinguish it from other species. It is used in certain applications and fields. In the next section, we will explain in detail each type, its pros, cons, and the areas where it is used.

2.2.1 Lead Acid Batteries

Lead-acid batteries represent the commonest type of batteries in the world. It acts about 40–45% of the overall global battery use. Lead-acid batteries are available in a variety of sizes and designs and in large quantities. Different sizes of lead-acid batteries are manufactured from smaller than 1 Ah to more than 2000Ah. The lead acid batteries can work with deep cycle applications and automobile starting applications, which needs high and enough discharge rates. In USA, California, the world's largest energy storage system has designed, it depends on a series and parallel connected lead acid batteries with different industrial-size. This system can store 40 MWh. This system has the ability to deliver energy into the utility grid at 2,000V and 8,000A for 4h. Lead-acid batteries are commonly used in the universal power supply systems, in renewable energy systems and distributed power stations. The typical method to charge the Lead-acid batteries accomplished with three charging stages, they are the constant-current bulk charge, equalization final charge, and finally float charge.

2.2.1.1 Advantages and disadvantages Lead Acid Batteries

The lead acid batteries are low-cost batteries. It could be manufactured with high rates of production in local foundations and this is the main reason for the admiration of lead-acid batteries. The open circuit voltage of the lead-acid cell is 2 volts and this is the highest open circuit voltage for aqueous electrolyte systems. The computation of SOC for a lead-acid battery is so easy because there is a linear relationship between the state of charge of the battery and the specific density of electrolyte bears. It provides good charge holding in the applications that do not provide

continuous charge for the battery. It is not harmful to the environment because it could be recycled easily.

Disadvantages include that Lead-acid batteries require maintenance frequently. One of the lead-acid problems is that it may lose their water during the operation so the water level should be checked continuously. Their weights are relatively heavy and not practical in applications that require portability because they employ lead in their construction. The life cycle of lead-acid batteries is between (50–500 cycles) and this number is low as compared with the other types.

2.2.2 Nickel-cadmium batteries

Nickel-cadmium considered a long-life, stable, very reliable battery. Nickel-cadmium batteries need little maintenance. Two major dissimilar shapes of Nickel-cadmium have been produced Depending on the nature of use. The first type is the cells with thick electrode plates, this type has a high-energy storage capacity, and its power to volume ratio is relatively high. The second type is the thin sintered plates. This type has low internal resistance. During the early years of the appearance of nickel batteries, most of battery failures and their problems caused by the "memory", a word derived from the term "cyclical memory", which means that the nickel batteries Remember how much power you spent during previous discharges and therefore do not deliver the remaining power as before. For unloading, it is a regular duty. Improvements in battery technology have virtually eliminated the "recycling memory" phenomenon. Battery manufacturers are recommended to charge these batteries 16 to 24 hours before use. Finally, the best method for charging unsealed Ni-Cd batteries is constant-voltage charging mode.

2.2.2.1 Advantages and Disadvantages of Nickel-cadmium batteries

Advantages include the temperature range of the operation is higher than the lead-acid batteries, for this reason, it is more appropriate for some devices in regard to temperature range. The life of the Ni-Cd batteries is longer than lead-acid batteries. If these batteries stored for long times, the SoC will not spoilage. It does not require continuous care and maintenance.

Disadvantages include that Nickel-cadmium batteries contain 6% cadmium in industrial batteries and 18% cadmium in commercial batteries. Heavy metals are toxic. Therefore, the disposal of this type of battery requires special care. In the

United States, part of the battery price is in the form of taxes to safely dispose of batteries after the end of its life. Under the so-called battery regulations, the sale of nickel-cadmium batteries in the EU is prohibited except for medical uses, alarms, emergency light bulbs and portable devices.

2.2.3 Nickel-metal hydride (Ni-MH)

NiMH batteries are the practical alternative to NiCd batteries where they have higher quality energy and less toxic metals. These batteries are used in medical equipment, hybrid cars, and industrial applications. This battery is in cells of AAA measurement. The advances in these batteries are impressive since 1990, and their energy has doubled and their life cycle has expanded. NiMH batteries outperform lithium batteries by two points, the price, and the safety. Lithium batteries outperform them in terms of specific capacity. NiMH batteries have become one of the most rechargeable batteries for portable devices. They are non-toxic and provide higher quality energy. It is used for consumer products such as mobile phones and computers.

2.2.3.1 Advantages and disadvantages of (Ni-MH) batteries

The capacity of these batteries is higher than NiCd batteries. The memory effect on the NiMH batteries is lower than in NiCd batteries. Simple transport and storage, not subject to regulatory control like Ni-cd batteries. Eco-friendly contains only moderate toxicity. The small proportion of nickel compounds makes recycling comfortable.

Disadvantages include that limited life cycle. Deep discharge reduces the life of its service. Serious consequences may happen if overcharging occurs. Hydrogen gas released when overcharging occurs due to the excessive temperature, fire risk increases in this case. It requires a more complex charging algorithm than NiCd batteries. Generate high heat during fast charging and high load discharge. High self-discharge, but this disadvantage could be reduced by adding some chemical additives, but this addition will lessen the capacity. The performance of Ni-MH degrades if it stored at elevated temperatures so it should be stored at a moderate temperature and up to 40% of the full charge. Other disadvantages of NiMH include a high self-discharge (around 50% greater than NiCd) [19].

2.2.4 Lithium-Ion Batteries

2.2.4.1 General Description

The first rechargeable Li-ion battery invented and produced by Sony in 1991. Lithium is lighter than all metals, has a high electrochemical voltage, and provides the greatest energy as compared with the weight. However, this battery was discovered in 1980. The specific energy of lithium batteries is twice than NiCd batteries. The nominal cell voltage of the Li-ion batteries is 3.60V. This could be considered a good feature as compared with nickel batteries that have 1.20V. Improvements in active electrode materials have evolved from the possibility of increasing energy density. The characteristics of the load are good, and the discharge curves provide effective energy storage at the desired voltage range of 3.70-2.80 compared to the nickel-discharge voltage curve between 1.0-1.25 V. In 1994, the cost of manufacturing the cylindrical 18650 lithium-ion batteries cells with a capacity of 1100 mah was about 11 $. In 2001 the price fell to two $ with a high capacity to 1900mah. Today, the energy density of the 18650 cells has become about 3000 mah with the biggest drop in price. Low cost, increased power and the absence of toxic substances have paved the way for the manufacture of globally accepted lithium-ion batteries used in portable devices, first in the consumer field and now in heavy industries [19].

2.2.4.2 Types of Li-ion Batteries

The architecture of lithium batteries is similar to that of nickel and lead-acid batteries. It uses a cathode (positive electrode) and an anode (negative electrode). The cathode is a metal oxide and the anode consists of perforated carbon. During discharge, the ions pass from the anode to the cathode via the electrolyte, while charging reflects the process where the Ions travel from cathode to anode. Figure 2.1 explains the process

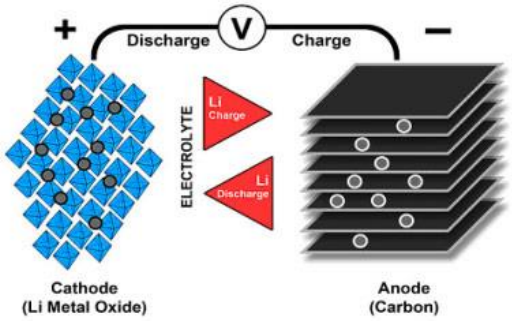


Figure 2.1 lithium-ion batteries and their Ions flow

The Sony Company used the coke as the anode in their original lithium-ion battery. Since 1997, most of the companies used graphite to get a flatter discharge curve. The difference between Li-ion batteries comes from the chemical materials, which used as an electrolyte of the battery. Other developments also took place in the anode and began attempts with several additions, including silicon alloys where it increases the specific energy by 20 %. Lithium batteries come in many variations, but all have the same "Li-ion" logo. Although there are many similarities when viewed at first glance, they vary in performance, and the choice of cathode material gives them a unique personality. The most famous types of lithium batteries are Lithium cobalt oxide“lithium cobalt”, lithium manganese oxide “lithium manganese”, lithium iron phosphate, Lithium Nickel Manganese Cobalt Oxide and aluminum nickel cobalt oxide, Lithium Nickel Cobalt Aluminum Oxide and Lithium Titanate. Figure 2.2 shows the energy density for these different types of Li-ion batteries. We make a brief comparison between these different types of Li-ion batteries and arrange it in table 2.1. The comparison shows the differences between these types in terms of charging voltage, charge rate (C-rate), energy density, discharge rate, cycle life, maximum allowed operating temperature, And applications where these types are used.

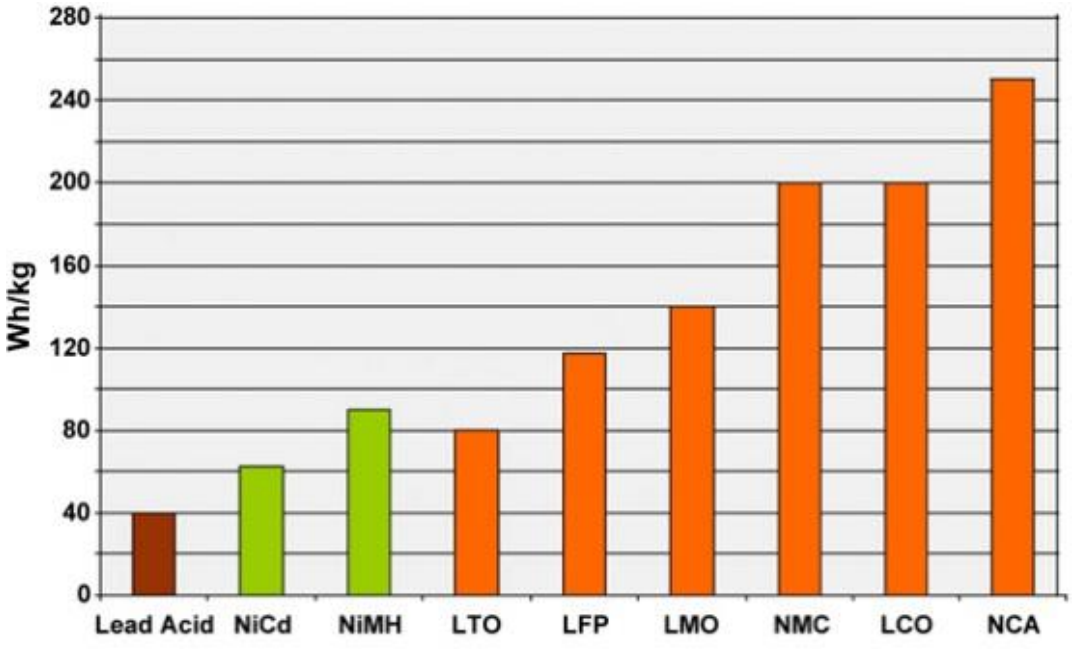


Figure 2.2 Typical specific energy of lithium-based batteries.

Table 2.1 Characteristics and properties of different lithium-ion batteries.

Type / Charecter	Lithium Cobalt Oxide LiCoO2	Lithium Manganese Oxide LiMn2O4	Lithium Nickel Manganese Cobalt Oxide LiNiMnCoO2	Lithium Iron Phosphate LiFePO4	Lithium Nickel Cobalt Aluminum Oxide LiNiCoAlO2	Lithium Titanate Li4Ti5O12
Voltages	3.60V nominal	3.70V (3.80V) nominal	3.60V, 3.70V	3.20, 3.30V nominal	3.60V nominal	2.40V nominal
Specific energy (capacity)	150–200Wh/kg	100–150Wh/kg	150–220Wh/kg	90–120Wh/kg	200-260Wh/kg	50–80Wh/kg
Charge (C-rate)	0.7–1C Charge current above 1C shortens battery life.	0.7–1C typical, 3C maximum	0.7–1C, charges	1C typical	0.7C, charges to 4.20V (most cells)	1C typical; 5C maximum
Discharge (C-rate)	1C; 2.50V cut off	1C; 10C possible with some cells	1C; 2C possible on some cells	1C, 25C on some cells	1C typical; 3.00V cut-off	10C possible
Cycle life	500–1000, related to DoD	300–700	1000–2000 (related to DoD)	1000–2000 (related to DoD)	500 (related to DoD, temperature)	3,000–7,000
Thermal runaway	150°C (302°F)	250°C (482°F) typical	210°C (410°F) typical	270°C (518°F) Very safe battery	150°C (302°F) typical	One of safest Li-ion batteries
Applications	Mobile phones, tablets, laptops, cameras	Power tools, medical devices, electric powertrains	E-bikes, medical devices, EVs, industrial	Portable and stationary needing high load currents and endurance	Medical devices, industrial,electric powertrain	UPS, (solar-powered street lighting

2.2.4.3 Advantages and Disadvantages Of Li-ions Batteries

Features include that the life cycle of a lithium ion is long. (3,000 cycles at 80% DoD).Hence, It is, therefore, suitable for applications requiring a lot of charging and discharging operations. They can operate in a wide range of temperature degrees. These batteries have the property of long shelf life because their self-discharge rate is low. The customers prefer this type of batteries because they have Fast charge capability. The energy efficiency of Li-ion batteries are high, it can reach up to 94% in terms of energy over a cycle. It has no “memory effect.” They have the best energy density value as compared with other types (300–400 kWh/m3, 0.13 kWh/kg). They are not harmful to the environment since they don’t contain toxic materials in their construction. Lithium-ion cells have a high coulombic density as compared with the lead-acid cells and this is one of the most important features in lithium cells. The new lithium-ion cell is characterized by approximately 94% of the columbic efficiency compared with the lead-acid battery, which offers approximately 80% columbic efficiency.

Disadvantages include that the initial cost of lithium-ion cells is expensive as compared with the other types. The increase in the energy density of lithium-ion batteries causes instability and possibly fire risk occurs. This conduct of lithium-ion cells leads to the need for more complex protection circuits. The lithium-ion battery system must be able to block overcharging since the happening of this problems may lead to thermic escape and then the risk of fire. Crushing the cells leads to ventilation and fugitive heat.Sometimes Li-ion batteries connected in series and this connection requires a charge equilibrium system. Li-ion cells do not work with low cost, passive cell balance circuits which are easy to perform. The lithium-ion cells are made in non-charging mode, therefore they must be charged before use. The Li-ion cells are charged using either constant-current or a constant-current constant-voltage (CC-CV). Exceeding the rated values may cause permanent damage to the battery. On the other hand, the capacity of the battery may reduce if it is charged with a voltage lower than the rated value. Advanced aging, even if not in use (aging occurs in all batteries. Modern lithium systems have a lifespan similar to other chemicals). Subjected to transport restrictions when transported in bulk. If a group of i-ion batteries connected together, the charger must monitor the temperature of the internal battery as well as the voltage of each cell. Because of these limitations, it needs a special control circuitry for the administration of charge and discharge. In spite of that Lithium-ion batteries have a flat voltage profile, it has been recognized that cell open-circuit voltage provides a good estimate of the state of charge (SoC) ranging from 20% to 100%.

2.2.4.4 Comparison between Li-ion batteries and other types

We conclude from the previous sections which discussed above the different types of batteries that lithium-ion batteries are getting ahead of other batteries in several points like the energy density, size, weight and many other features. The following table lists the main advantages of lithium on other types. We concluded the main characters of these types and arranged it on the table (2.1).

Table 2.2 General comparisons between the famous types of batteries

Battery type	Lead acid	Ni-Cd	Ni-MH	Lithium-ion
Energy density [a] (Wh/Kg)	35	40-60	60	120
Power density (W/kg)	180	150	250-1000	1,800
Cycle life [c]	500-1500	2,000	2,000	3,500
Cost ($/kWh)[d]	269	280	500-1,000	Consumer electronics: 300-800 Vehicles: 1,000-2,000
Battery characteristics	High reliability, low cost	Memory effect	Currently, best value and most popular battery for HEVs	Small size, light weight
Application	Car battery, forklift, golf cart, backup power	Replacement for flashlight battery	HEVs, replacement for flashlight battery	Consumer electronics

2.3 Charging Techniques

The appropriate charge of the battery can improve the performance of the battery and life cycle of the battery. Therefore, many factors such as good quality of charging current, fast charging, avoid undercharging and overcharging should be considered in battery charging system design. In particular, reducing the charge can reduce its power density while overcharging can damage the physical components of the battery. Therefore, suitable control technology should be taken in the charging process. The battery voltage (and/or) the battery current should be fed to the charger control circuit. The charging current and charging voltage path of the battery defined by a curve known as characteristic charging curve. This curve defines the (V_{Bat} vs. I_{Bat}) through the charging period. We will present different battery charging techniques in this section, discusses the operating principle of the controller which controls battery charge for each technique, and depicts the block diagram of the controller.

2.3.1 Constant current charging (CC)

Constant current charging is the most traditional battery charging technique. In the charging property curve shown in Figure 2.3. The voltage of the battery growths

through charging process while the battery current remains constant until it is charged up to the maximum allowable value (battery rated voltage). The current and voltage characteristics in constant current mode are shown in the Fig 2.3a. In order to evade The battery failure and the battery failure of the battery, the controller of the charger should disconnect the charging voltage when it reaches the rated voltage of the battery. It is not necessary for the voltages of the battery to be linear during the charging and discharging periods, and depend on the battery type.

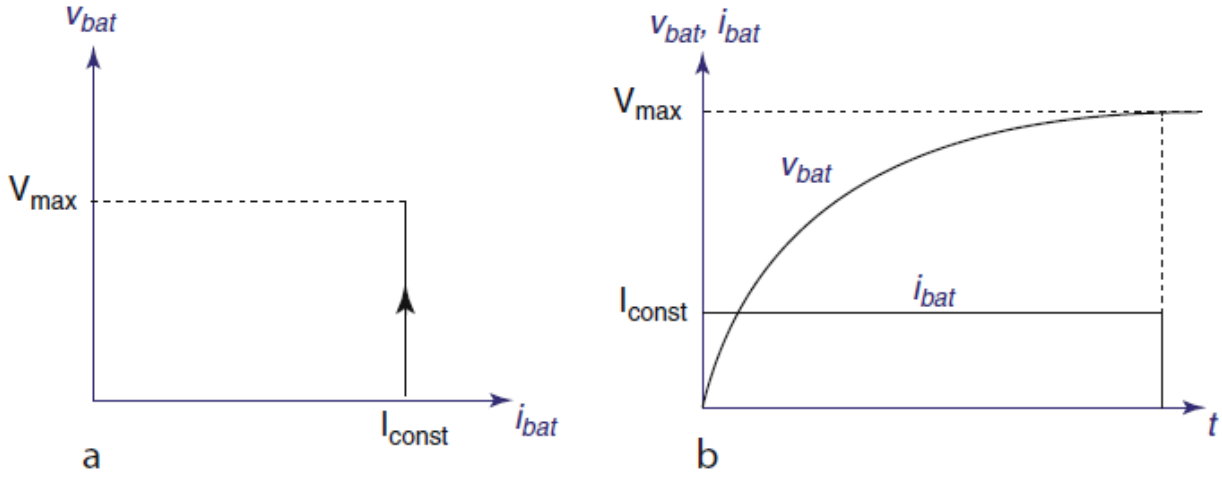


Figure 2.3 a Charging characteristic curve for CC topology

Figure 2.3 b battery‘s current and voltage behavior during the charging process

In order to apply this type of charging, we need charging control circuit. In this circuit, the value of the reference current is compared with the output current (charging current) value to generate an error signal. The fault signal is carried into a (PI) controller to create the command signals and eliminate the fixed error. We can realize fast charging just by using components holds large current amounts, but anyhow this may cause a breakdown of the chemical elements of the battery. Instead, the slow current charging lengthens the charging time. Therefore, proper selection of the charging current is so important to increase the life of the battery and enhance the charging performance. The simplicity is the main advantage of this method. This conversion circuit could be done by using an AC-DC or DC-DC conversion depending on the type of the input. Moreover, we can drop the output capacitor because it is not required to regulate the output voltage in this technique whereas regulating the output current is enough. O/P capacitor elimination makes the output

converter circuit from first-order current filter type which can be simply examined and performed easily.

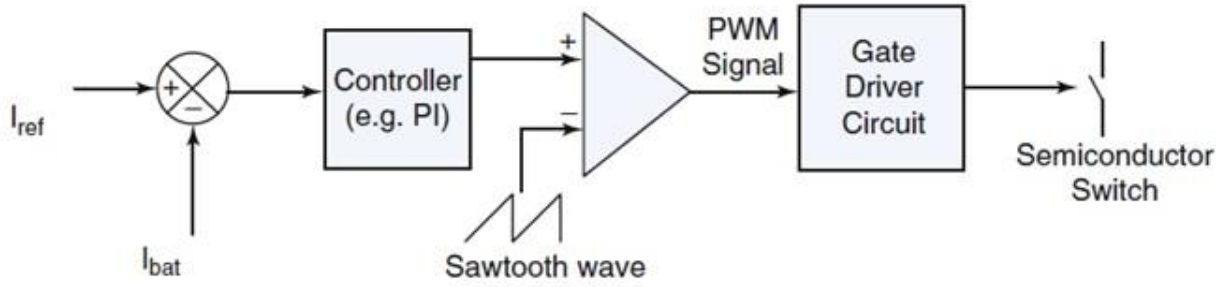


Figure 2.4 Block diagram of Constant current controlling circuit

2.3.2 Constant Voltage Charging technique (CV)

Constant Voltage Charging is another traditional technique for charging the different types of batteries. In this technique, the voltage of the battery stays constant, whereas the current of the battery goes down and eventually becomes very low as shown in Figure 2.5. But in this technique, the temperature of the battery increased because of the initial high current which can damage the battery, depending on the chemistry. The battery-charging unit separates the battery from the charger circuit when the current reaches a certain amount (I_{min}) as shown in Figure 2.5. Another disadvantage of CV charging is the long charging period as a result of the little current that passes through the final stages of charge. However, it is simple for low-cost applications.

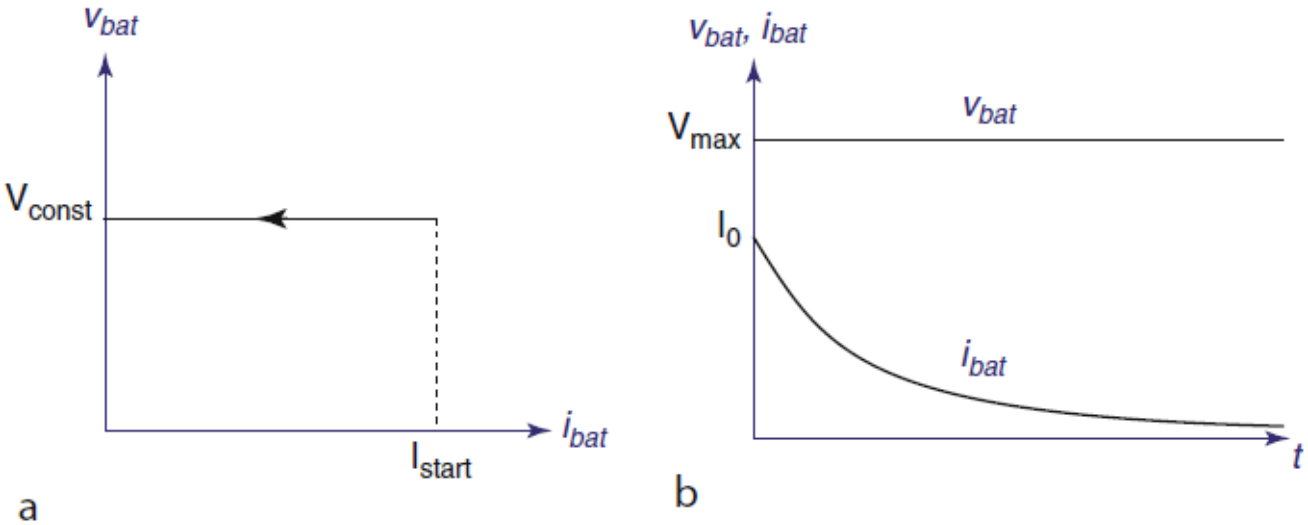


Figure 2.5a the characteristic curve of the constant voltage topology
Figure 2.5b voltage and Current behavior during the charging process

Figure 2.6 shows the control block diagram, where the sensed signal is the battery voltage and reference signal is the reference voltage. As in constant current method, the implementation of CV technique is clear and easy. But the controller design process is a little more complicated than CC, whereas the system order will increase because the capacitive output is required to regulate the output voltage which.

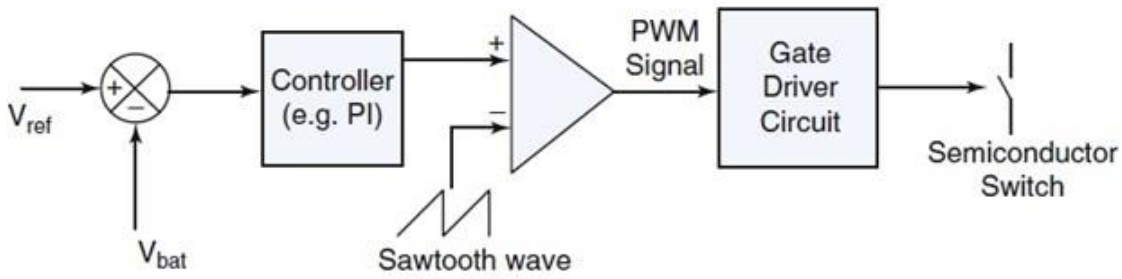


Figure 2.6 Block diagram of Constant Voltage controlling circuit

2.3.3 Constant Current – Constant Voltage Charging technique (CC-CV)

The constant current-constant voltage charging topology employs together the CV charging and CC. The mechanism of this technique illustrated in the current-voltage profile curve and charging characteristic curve that showed in Figure 2.8 and Figure 2.7. The charging process is done in two steps. In the First stage, the current of the battery stays constant until the battery voltage becomes equal to the rated voltage (V_{bat}). Then, the current of the battery fall gradually until it reaches to the specified value (I_{min}). During this stage, charging voltage keeps constant. Since the current stays constant at the first stage of charge, the drawback of high initial current flow in constant voltage topology eliminated here. Since the constant voltage topology is applied here in the second step, the overcharging problem that appeared in CC method is also avoided here. These vantages of CC-CV technology make it so ideal for applications that require high-performance. The main disadvantage of this technique is the complexity of the design, which makes this option more expensive as compared with CC or CV techniques. Going back to lithium batteries, we notice that exceeding the maximum voltage can result in many dangers, including the risk of fire and battery explosion. Also at the same time, applying the charging voltage to the battery less than the rated voltage reduces the battery life cycle. Therefore, the

best way to charge lithium batteries is this technology as we will ensure the safe charge of the battery while maintaining the battery life.

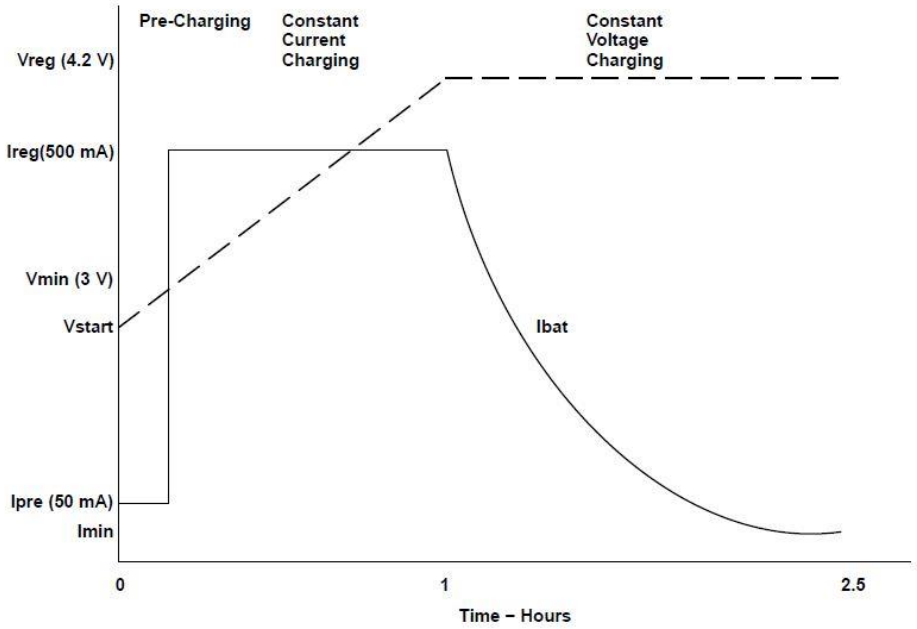


Figure 2.7 current- voltage profiles curve

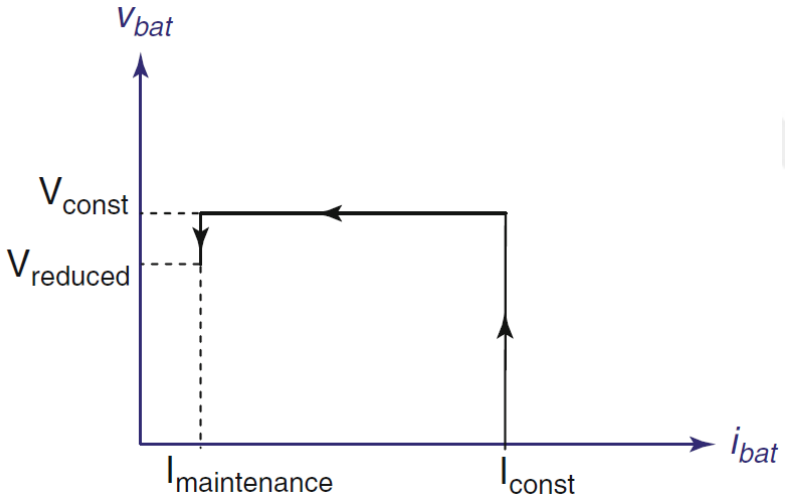


Figure 2.8 charging characteristic curve

2.3.4 Other Charging topologies

In the previous section, we refer to the main techniques used for charging the battery packs, but there are other techniques that can also be used in the charging process. For example; trickle charging which usually used for storing batteries which are not used but must be kept in full charge condition. It compensates for self-discharge. This technique is exercised in the float-charging phase by applying a low rate of

continuous charge in order to maintain the battery at its fully charged state. Also, there are pulse chargers which charge the battery with pulses of current. In this technique, the width of the pulses controls the charging rate (calculated depending on the average current), the width of these pulses generally about 1 second. The charger gives small breaks from 20 to 30 msec between every two pulses. These breaks give stabilization to the internal chemical materials of the cell by achieving the equal reaction thru the bulk of the electrode before recharging. This permits the chemical reactions to stay on the same level with i/p rate of electrical energy. The undesirable chemical reactions like the crystal growth, passivation, and passivation reduced by this charging technique. Also of the open circuit voltage of the battery could be sampled battery over the remaining period in this method.

Table2.3 Comparison between charging strategies

Charging technique	Advantages	Disadvantages
Constant current (CC)	• Simplicity of implementation • First order open-loop transfer-function • Simplicity of the controller	• Overcharging risk if high charging current is used • Prolonged charging time if low current is used
Constant voltage (CV)	• Simplicity of implementation	• Battery temperature rise during the initial stages of charging • Prolonged charging time due to low current during the final charging stages • Second order open-loop transfer-function
Constant current – constant voltage (CC – CV)	• Protecting the battery against overcharging • No current rush at the beginning stage of charging • Enables float charging after the battery is fully charged • High performance	• Requires both voltage and current sensor for closed-loop control
Pulse current	• Even distribution of ions throughout the electrodes and inside the battery • Prolonged battery life due to maximizing chemical performance • Charging rate can be controlled by the duty cycle of the battery current	• Requires fast control-loop • Requires high bandwidth current-sensor • Expensive
Taper characteristic	• Gradual current decrease during the charging • Protection against overcharging	• Requires both voltage and current sensor for closed-loop control • Complexity of implementation
Assembled constant current	• Eliminates overcharging property of CC charging • Eliminates prolonged charge time property of CC charging • Takes other advantages of CC charging	• More complicated control scheme than CC charging
Assembled taper characteristic	• Different adjustment of characteristic curve is possible to satisfy different design requirements • Enhanced charging performance	• Requires both current and voltage sensors for closed-loop control • Most complex control scheme

The other type of charging is taper charging; in this type, neither battery voltage nor battery current stays constant. Instead of that, a combination of battery current and battery voltage maintained. The main drawback of this technique that it is obligatory to sense battery voltage and current and sensors are usually the most expensive part in the conversion circuits, increasing the number of sensors definitely will increase the design's cost.

2.4 Charger Types

Chargers usually include a form of voltage regulation to control the applied charge voltage to the battery. In the next section, we will review the most important electronic circuits used for applying the charging techniques that were presented and explained in the previous section. Generally, there are two main techniques in power electronics. The first type is linear mode voltage regulators. The implementation of this type is easy and it does not need for complex components or triggering circuits. On the other hand, it has relatively high power dissipation and its efficiency is low. This type used usually in the simple charging circuits. The other type of chargers depends on the switching mode voltage regulating in its construction. Switching mode circuits are more complex than the linear voltage regulator and need for triggering circuits and driving circuit for the gate of the switch, but on the other hand, it has low power dissipation and its efficiency is high.

2.5 DC-DC converters

Power electronics is divided into four main sections

- AC to DC converting called rectifiers
- DC to AC converting called (inverters/converters)
- AC to AC converting called converters
- DC to DC converting called chopper

DC-DC converters used in many applications from small laptops and computers to large power systems and DC drives. In general, DC-DC converters take the unregulated DC voltage and produce a regulated DC voltage. This output voltage can have either a different polarity or a different magnitude, or both [9]. DC-DC converter circuits are one of the best options for implementing the aforementioned charging techniques. Especially for lithium-ion batteries and their special charging specifications, DC-DC converter circuits are the best and most accurate method for fast and safe charging. In general, DC-DC converters have several purposes, they are:

1. These circuits convert unregulated DC voltage into a regulated DC voltage
2. Adjust and regulate load and line variations in the DC output voltage.
3. AC o/p ripples on the DC o/p voltage Reduced below the required level.
4. Provide separation or isolation between the input supply and the load (isolation is not mandatory).
5. Electromagnetic interference (EMI) does not affect the supplying system and the input source.
6. Various international and national safety standards satisfied with this type [9].

Generally, DC-DC converter circuits contain several different topologies. Each topology gives a specific result. In this section, we will explain these different topologies and what is the most appropriate type of our design. Also, we will explain the semiconductor power electronic switches, which used in OFF and ON cases.

High energy conversion efficiency could be achieved by switching regulators. Modern power electronic switches can operate at high frequencies.

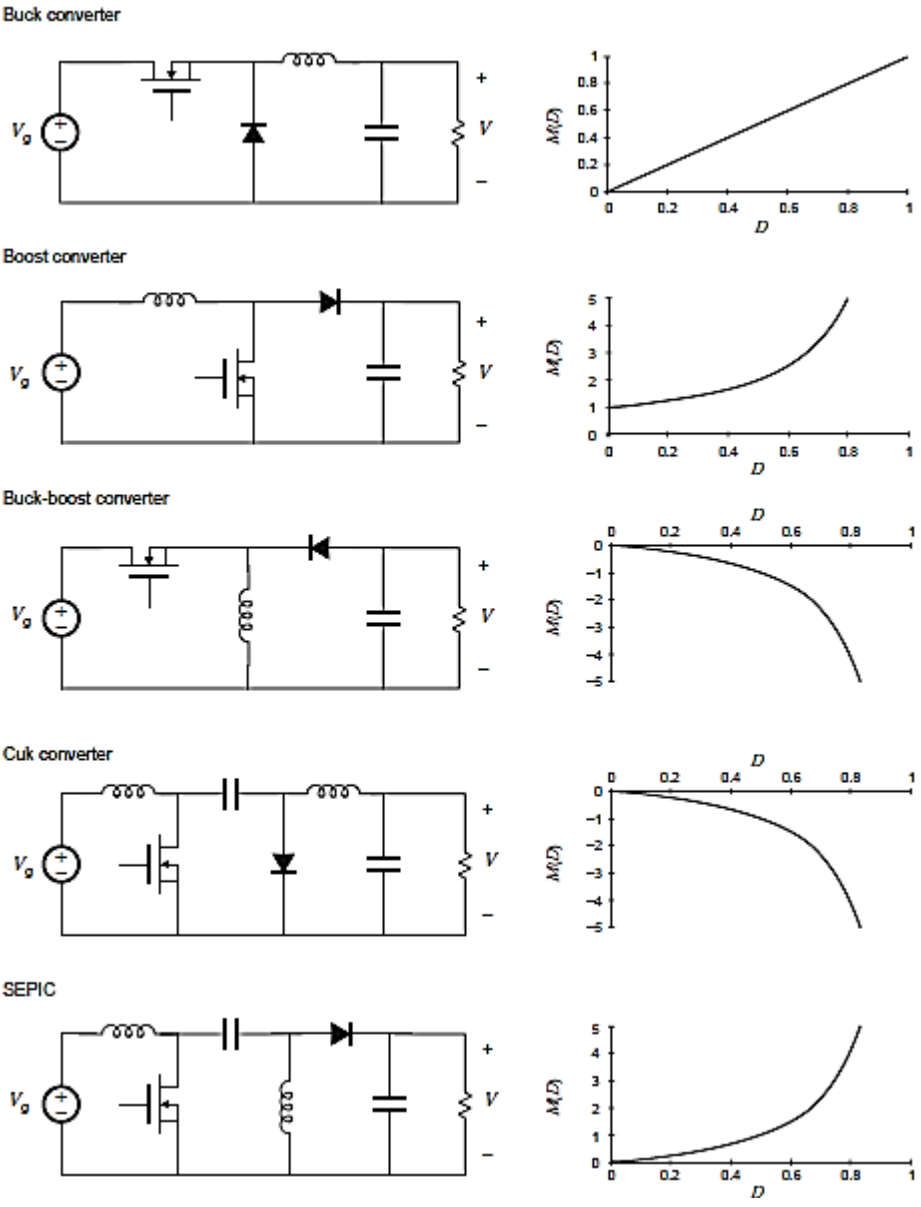


Figure 2.9 DC conversion ratio and circuit diagram for some basic DC-DC converter type

2.5.1 The Buck Converter

Buck Converter is the synonym name for the step-down converter. Figure 2.10 shows the components of the buck circuit. The source of the circuit should be DC voltage and one of the power electronics switching elements like the (MOSFET,

IGBT, and Power BJT) are used as a controlled switch with a freewheeling diode, filter capacitor C, filter inductor L, and load resistance R [11].

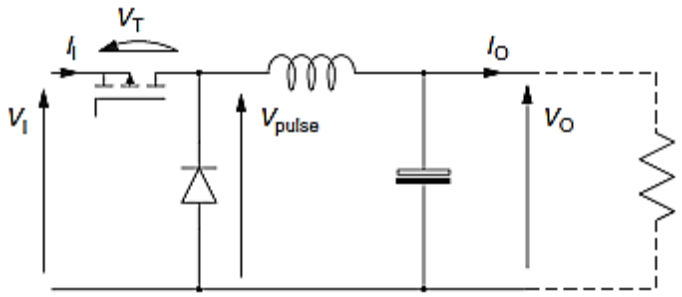


Figure 2.10 Buck (step-down) DC-DC converter

Working principle of the buck converter depends on the storage and discharge of energy in the inductor. Figure 2.12 shows the cases of storage and discharge in buck converter where (V_o) is the output voltage, V_{in} is the input voltage. I_{in} and I_{out} is the input current and outputs current respectively.

The duty ratio (duty cycle) is the ratio between the ON time of the switch and the total switching period defined by D is shown in Figure 2.11.

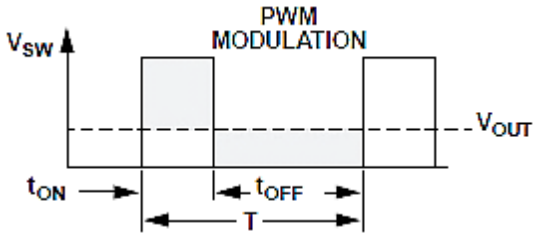


Figure 2.11 Ton and Toff in PWM waveform

The working principle of the circuit summarized in two states. The first state when the switch is ON which known as ***ON state.*** Figure 2.12a shows the state of the circuit and the direction of the current, in this case, the switch is turned on and the diode is reversed biased, the current flows through the load.

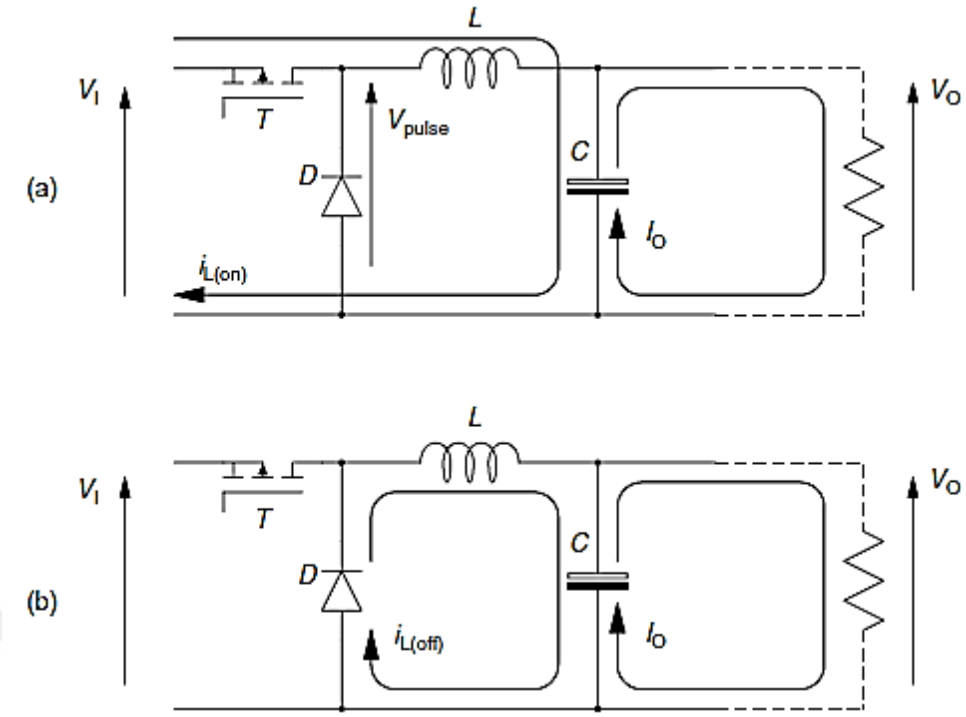


Figure 2.12a voltage and current paths when the switch in (ON) state

Figure 2.12b voltage and current paths when the switch in (OFF) state

The injected voltage through the inductor is calculated according to the following equation

$$V_L = V_I - V_{DS(on)} - V_o \tag{2.1}$$

$$V_L \approx V_I - V_o \tag{2.2}$$

Moreover, the increase of inductor current occurs according to the following equation

$$\frac{diL}{dt} = \frac{V_i - V_o}{L} \tag{2.3}$$

OFF State

The current is saved as a stored energy when it is passed through the inductor at the ON state, so when the switch is OFF (A) must be provided a path for the current the diode is forced into conduction. A voltage is forced through the inductor is:

$$V_L = -V_{DS(on)} - V_o \tag{2.4}$$

$$V_L \approx -V_o$$

The current of the inductor reduces according to the following equation:

$$\frac{diL}{dT} = \frac{V_i - V_o}{L} \tag{2.5}$$

As the stored energy in the inductor continues to decrease, this energy goes to the output side (the capacitor and load).

This means that the ripple of the current increases and decreases. So it will return to the same initial state. After this understanding, it is important to notice that buck converter has two different situations according to the value of the inductor. The first is (CCM) continuous conduction mode. The charging current does not reduce to zero in this mode. The main current and voltage waveforms of this mode are displayed in Figure 2.13. The Second mode is the Discontinuous Conduction Mode (DCM), where the inductor loses all its stored energy while the switch is not turned on so the discharging current will drop to zero. Figure 2.14 shows the current and voltage waveforms of this mode.

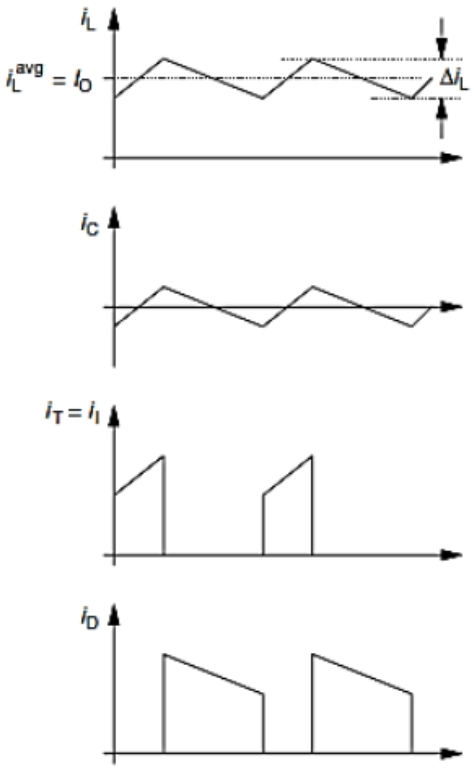


Figure 2.13 buck converter waveforms in CCM mode

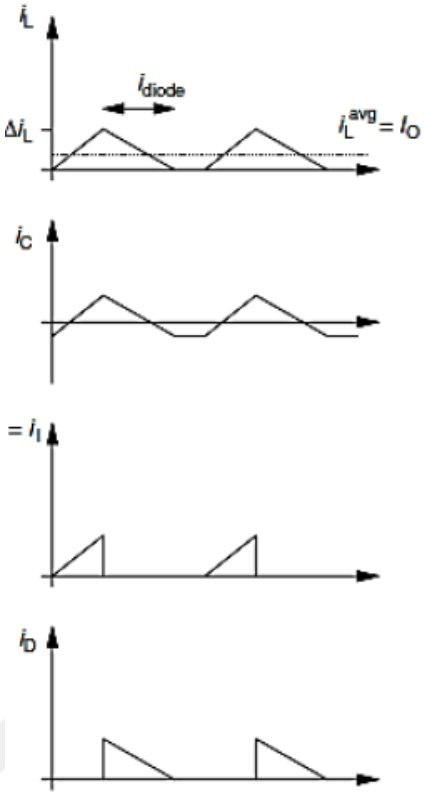


Figure 2.14 buck converter waveforms in DCM mode

2.5.2 Boost DC-DC converter

Boost Converter is the synonym name for the step-up DC-DC converter. This type of DC-DC converters is mainly used in applications that need to convert DC voltages from a certain level to a higher level than the input voltage. The Figure 2.15 shows the main components and the structure of this topology [11].

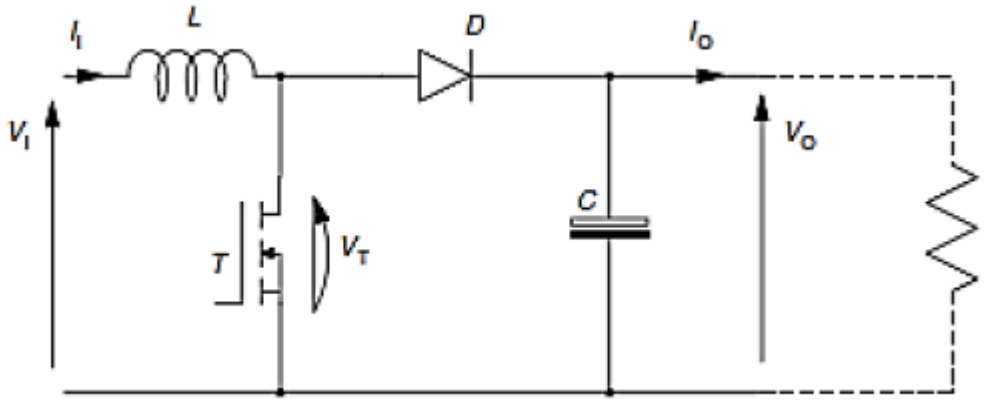
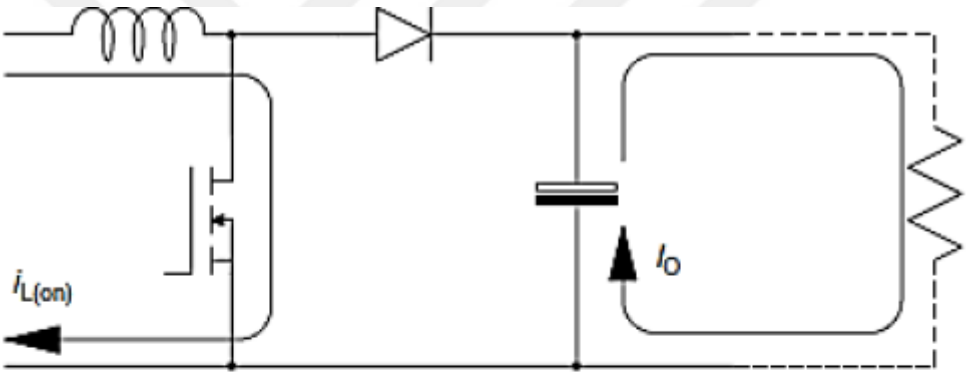


Figure 2.15 the circuit diagram of boost (step up) converter

When the switch is ON state, the diode will be reverse biased, and the o/p stage of the converter will be isolated by the diode. During this period, the inductor takes the energy from the source and stores it as shown in Figure 2.16a. When the switch is in the OFF state, the diode will be forward biased and thus the energy stored inside the inductor will move to the output as well as the energy coming from the source so the voltages on the ends of the output will be higher than the input voltage as shown Figure 2.16b. The equation 2.6 gives the ratio between the output voltages to the input voltage.

$$\frac{V_0}{V_{in}} = \frac{1}{1-\delta} \tag{2.6}$$

Where the symbol (δ) refers to the ratio between the ON time of the switch to the total switching time.



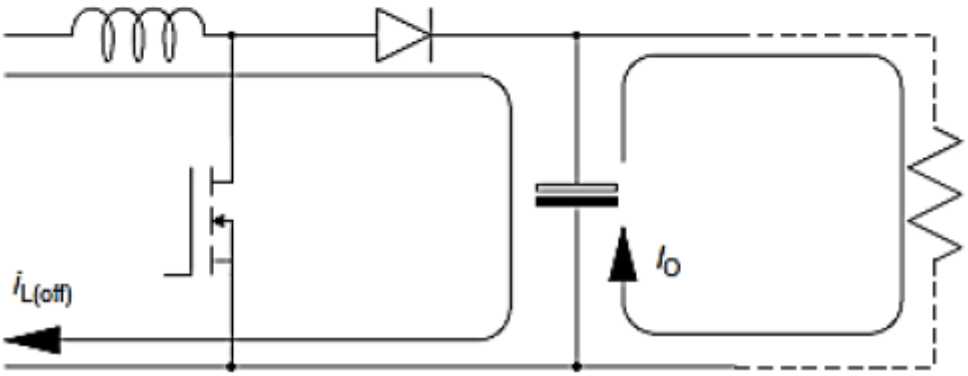


Figure 2.16a the boost converter and current path During ON State of the switch

Figure 2.16b the boost converter and current path During OFF State of the switch

We can summarize the principle of work for this converter by two states and this is a brief explanation of each state

ON state

As shown in Figure 2.16a. The input current is forced to pass through the inductor only,

$$V_L = V_I - V_{DS(ON)} \tag{2.7}$$

Since $V_{DS(on)}$ value is so small, we can neglect it

The increase of current happens according to the following equation

$$\frac{diL}{dt} = \frac{Vi}{L} \tag{2.8}$$

In this state, when the diode is reverse biased and the saved energy in the inductor increases, then the capacitor fed load only.

OFF State

In this case, when the switch is in OFF mode, the diode will be forward biased.

When the switch is opened, the current will decrease as the impedance is higher. The magnetic field which created previously will be drawn to sustain the current towards the load. Thus the polarity will reverse (left side of the inductor will be negative). As a result, two sources will be in series causing a higher voltage to charge the capacitor through the diode.

The voltage across the inductor determined by the following equation

$$V_L = V_i - V_{DS(on)} - V_o \tag{2.9}$$
$$\approx V_i - V_o$$

$$\frac{diL}{dT} = \frac{V_i - V_o}{L} \tag{2.10}$$

As a result of discharging process from the inductor to the capacitor and inductor charging process from the source to the inductor, a ripple in the current of the inductor will occur. The ripple form specifies topologies for the Boost converter, the first is the continuous conduction mode (CCM) in this mode the current through the inductor current (I_L) never drops to the zero. The second topology is the Continuous conduction mode (DCM). This case happened if there is too high ripple amplitude in the current. The inductor may be totally discharged before the end of the commutation cycle. In this case, during part of the period, the current through the

inductor will fall to zero. Hence, the relationship between the switching time of the operation, o/p voltage and the i/p voltage is

$$\Delta iL_{(on)} + \Delta iL_{(diode)} = 0 \tag{2.11}$$

$$\Delta iL_{(on)} + \frac{diL}{dt} t_{(on)} = \frac{V_I}{L} t_{(on)} \tag{2.12}$$

$$\Delta iL_{(diode)} = \frac{diL}{dt} t_{(diode)} = \frac{V_i - V_o}{L} t_{(diode)} \tag{2.13}$$

$$\frac{V_o}{V_{in}} = \frac{t_{(on)} + t_{(diode)}}{t_{(diode)}} \tag{2.14}$$

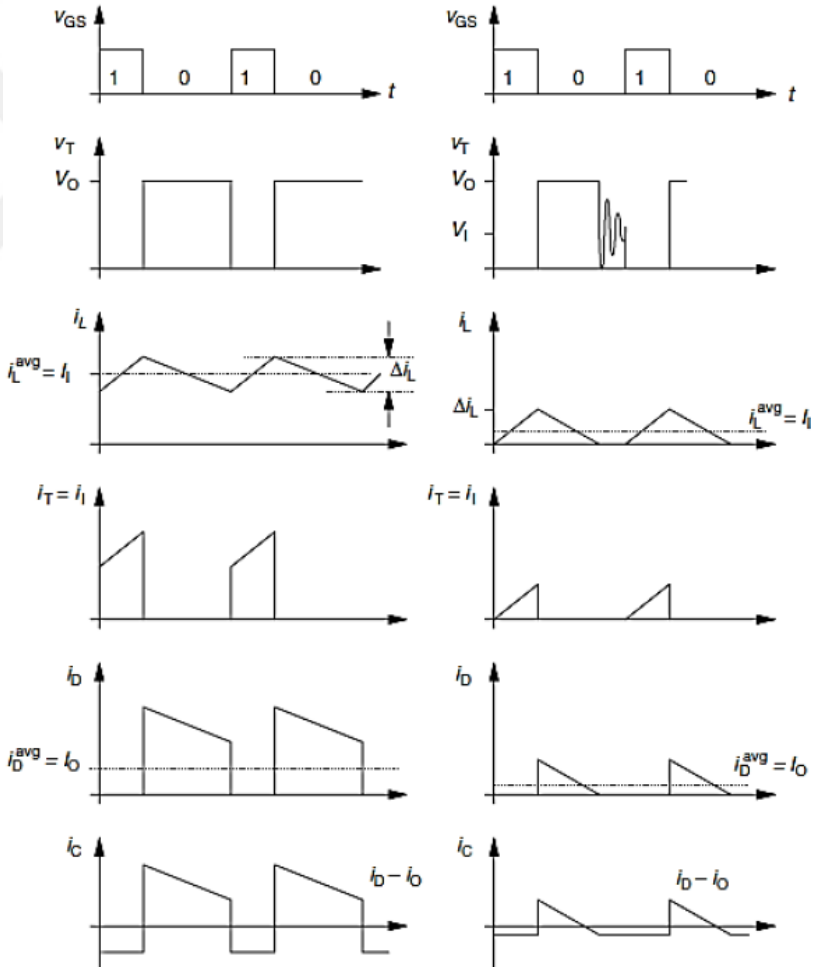


Figure 2.17a boost converter inductor's current and voltage waveforms in CCM mode
Figure 2.17b boost converter inductor's current and voltage waveforms in DCM mode

The relationship between the output voltage and input voltage at the continuous conduction mode is simple when the diode equal to T_{off}, but this relationship nonlinear relation and it is a function of the duty cycle (δ) [23].

$$\frac{V_o}{V_i} = \frac{1}{1-\delta} \tag{2.15}$$

$$V_{CA} = \frac{\sqrt{3}}{2} V_{dc} M \sin(\omega t - \frac{5\pi}{6}) \tag{2.16}$$

$$V_{AB} = V_{DC} - M \sin(\omega M t) \tag{2.17}$$

In the discontinuous conduction mode, the equation of the output/input relationship can be expressed by the average current pass through the inductor (equal to the input current) in terms of the diode (t_{on}) operation time.

$$\frac{V_O}{V_I} = \frac{1}{1 - \frac{V_I \delta^2}{2 I_I L f}} \tag{2.18}$$

2.5.3 Buck-Boost DC-DC

In the Buck-Boost DC-DC converter the output voltage could be below(Buck), greater than(boost) or equal to the i/p voltage, but the polarity of the voltage on the o/p side is always negative with reference to the input voltage. Figure 2.18 shows the buck-boost converter's circuit diagram.

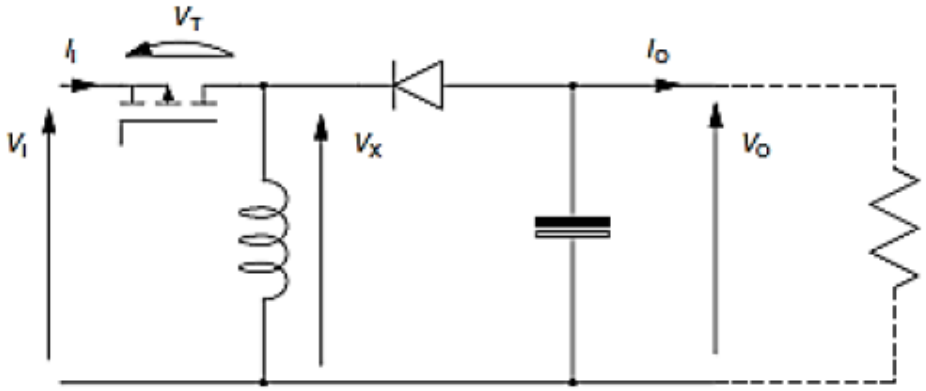


Figure 2.18 the buck-boost converter circuit diagram.

As in buck converter and the boost converter, there are two modes of operation for Buck-Boost Converter. Figure 2.19 shows the operating modes of this converter and below a brief explanation for these two modes

Mode 1: ON State

In this mode, the diode is reverse-biased and the current passes through the inductor and the transistor (switch) which is ON state. The energy transfers from i/p voltage source and stored in the inductor. In this step, the capacitor supplies energy to the o/p load.

In the On state, the voltage through the indicator is calculated in the form of the linear change of the current from I_1 to I_2 during a specific time.

$$V_s = L\frac{I_2 - I_1}{t_1} = L\frac{diL}{dt} \tag{2.19}$$

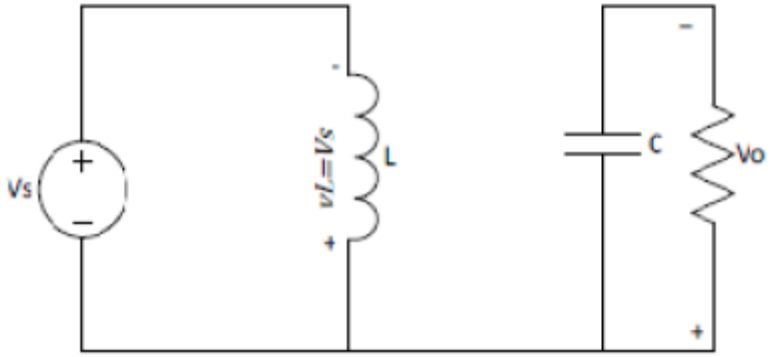


Fig 2.19 The behavior of the Buck-boost converter during ON state

Mode Two OFF State

In this mode, the diode is forward bias so the inductor current will get a path to flow through the diode to the capacitor and the load. In this mode, the stored energy in the inductor will be converted to the load and the capacitor and the inductor current will continue in decreasing until the next ON state.

In this mode, the inductor current decreases from I_2 to I_1 linearly during a specific time t2, thus the output voltage equation is

$$V_o = -L\frac{I_2 - I_1}{t_2} = -L\frac{diL}{dt} = -L\frac{\Delta I}{t_2} \tag{2.20}$$

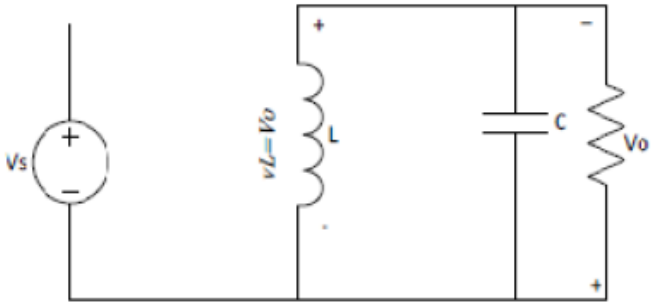


Figure 2.20 The behavior of the Buck-boost converter during OFF state

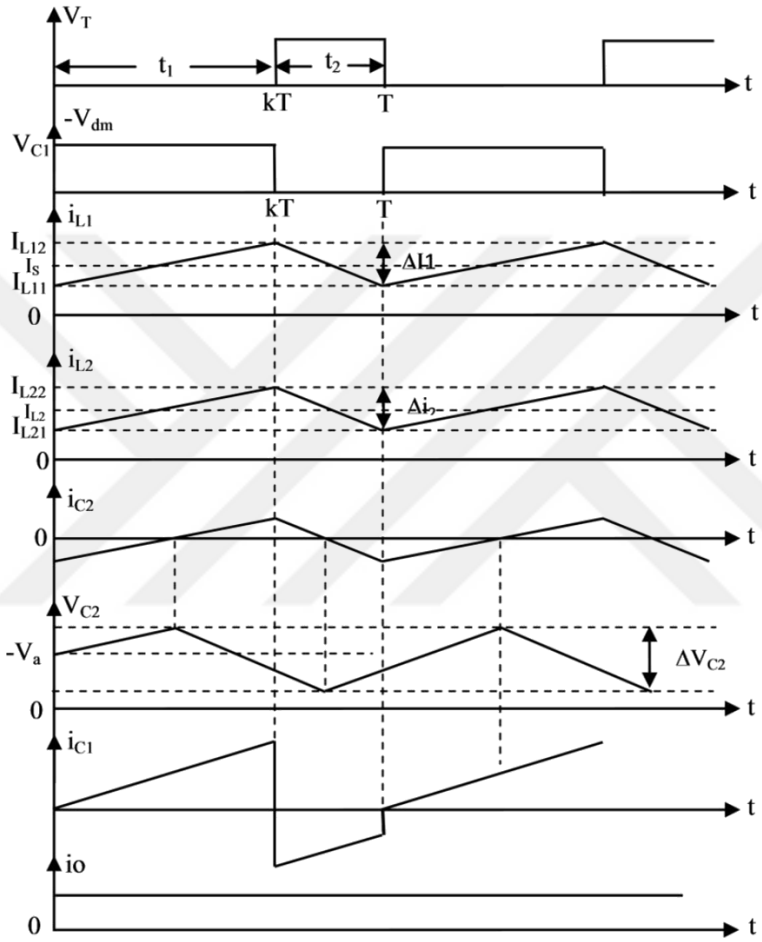


Figure 2.21 The waveforms Of Buck-Boost DC-DC Converter

The Buck-Boost converter's conversion ratio is:

$$M(D) = \frac{-D}{(1-D)} \tag{2.21}$$

Where D is the duty cycle and the negative sign refer to the opposite polarity of the output voltage with reference to the input voltage. From the equation, we see that if the PWM duty cycle equal to 0.5 we will get an o/p voltage equal to the i/p voltage and if the duty cycle is greater than 0.5 we will get a boost converter and vice versa.

As in the two previous types of DC-DC converters, the buck-boost converter also works in two modes they are (CCM and DCM) according to the value of the inductor. The Equation 2.20 specifies the value of the critical inductance (L_c) which determines the boundary between the continuous conduction mode (CCM) and discontinuous conduction mode (DCM) [25].

$$L_{critical} = \frac{(1-D)R}{2f} \tag{2.22}$$

2.5.4 Cuk converter

The cuk converter contains two inductors the first one connects in series with the converter input and the second one with the output port. The switch network OFF and ON connects a capacitor to the inductors input and output. The conversion ratio M(D) is identical to that of the step up and step down converter. Hence, this converter also reverses the voltage polarity, while either decreasing or increasing the voltage magnitude.

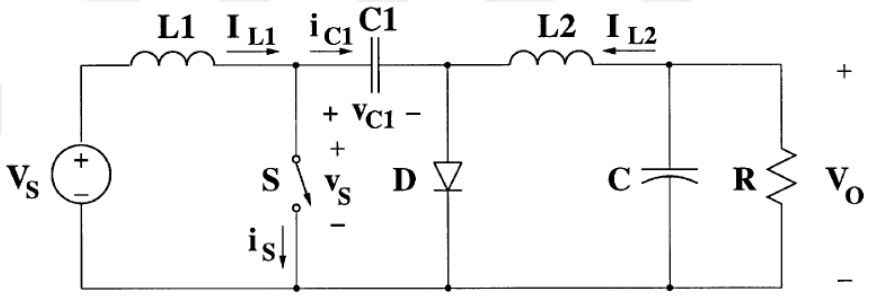


Figure 2.22 The circuit diagram of the Cuk converter

An important advantage of this topology is a continuous current at both the input and the output of the converter. The basic circuit of the cuk converter is shown in Figure 2.22. In this topology, the output voltage may be greater than, equal or less than the input voltage, but the polarity of the output voltage is negative with respect to the input voltage. In the cuk converter, there are two modes of operation.

The Cuk converter's conversion ratio is:

$$M(D) = \frac{-D}{(1-D)} \tag{2.23}$$

2.6 Power electronics switching devices

In the previous part of this chapter, we explained the DC-DC converters, their characteristics, methods of operation, and their respective equations. We mentioned in the previous section that the main part of these circuits is the electronic switching device. In general, there are several types of power electronics switching devices all of them could be used in the DC-DC converters, but each one of these devices has its special characteristics, advantages, and disadvantages. In this section, we will review the most famous And most frequently used device. An insulated-gate bipolar transistor (IGBT) is a three-terminal power semiconductor device primarily used as an electronic switch which, as it was developed, came to combine high efficiency and fast switching. It switches electric power in many applications: variable-frequency drives (VFDs), electric cars, trains, variable speed refrigerators, lamp ballasts, air-conditioners and even stereo systems with switching amplifiers. The IGBT is a semiconductor device with four alternating layers (P-N-P-N) that are controlled by a metal-oxide-semiconductor (MOS) gate structure without regenerative action. A power MOSFET is a specific type of metal oxide semiconductor field-effect transistor (MOSFET) designed to handle significant power levels. Compared to the other power semiconductor devices, for example, an insulated-gate bipolar transistor (IGBT) or a thyristor, its main advantages are high switching speed and good efficiency at low voltages. It shares with the IGBT an isolated gate that makes it easy to drive. They can be subject to low gain, sometimes to degree that the gate voltage needs to be higher than the voltage under control.

The design of power MOSFETs was made possible by the evolution of CMOS technology, developed for manufacturing integrated circuits in the late 1970s. The power MOSFET shares its operating principle with its low-power counterpart, the lateral MOSFET. The power MOSFET is the most widely used low-voltage (that is, less than 200 V) switch. It can be found in most power supplies, DC to DC converters, and low voltage motor controllers.

Chapter 3
Hardware Design for the Intelligent Battery Charger

3.1 Overview

The previous chapter discussed the different types of batteries, the difference between them, advantages and disadvantages of each type. Then we proved through that section that lithium batteries are the best now, the most developed and Keep pace with scientific in all areas and the need for batteries with high storage density. Then we discussed the different techniques used to charge the batteries and we knew that the best technology to charge the Li-ion batteries is Constant current-Constant voltage technique. The previous chapter discussed also the power electronics circuits which used to perform these charging techniques. And we mentioned some kinds of power electronics switches. Now we will select the best charging method, circuit topology and the switching device and all other required components to complete the design and we will explain the step of the design in this chapter. Generally, there are several methods to charge various types of batteries, but for Li-ion batteries, not all the methods are suitable for the charging process. The constant current-constant voltage technique is the best method for Li-ion batteries. In this technique, the charging process is accomplished by two steps. The first one, we apply a regulating current (constant current) for the batteries, the battery current will be kept constant while the battery voltage increases during charging until it reaches the maximum allowable value (predetermined value Vconst). The second one, the charger starts the voltage regulation phase, the applied charging voltage remains constant while the battery current decreasing and ultimately becoming very low until it reaches the end-of-charge current I_{end}. To perform this technique, we need a current feedback loop and a voltage feedback loop to adjust the duty cycle of the PWM wave to get the smooth and proper transition between the current and voltage mode.

3.2 Overall design

To perform the CC-CV charging technique, two topologies of DC-DC converters could be used. The first technique is the boost converter, this technique used at the application that contains a large package of serially connected Li-ion batteries so the example TESLA electric car which contain 90 Li-ion cell connected in series to get 324 VDC so with the disadvantages of using the transformers in the large power electronics application it is preferred to use a boost converter that step-up the voltage from 220 VDC to a 324 VDC. The other used topology of DC-DC converter is Buck converter this technique used when we have a number of cells need charging voltage less than the i/p voltage and This is the technique that we will use in our design because it is the most common technique as the number of applications like laptops and electric bicycle that need to a step-down the voltage is more than the applications that need to step-up the voltage. To enable the user charging a variable number of batteries in series, we connected two variable resistors. By changing the value of the first resistor (voltage resistor) we will adjust the full charge voltage limit in the (Constant voltage mode) for example if we have two groups of serially connected Li-ion batteries we will adjust the value of charging voltage on 7.4 V. Taking into consideration the value of the input DC voltage (AC\DC converter). In our design, we used a 12-volt AC\DC converter so the maximum possible number of charged batteries will be 3. The second variable resistor adjusts the value of the supplied current to the batteries in (CC mode). According to the C value of the batteries taking into consideration the maximum available Continuous Drain Current value which determined by the type of the switching device which used in the design, anyhow it is Preferable to use slow charging for lithium batteries. It is about 0.3 of the Crate value of the battery.

The microcontroller (MCU) used in the charger is the PIC16F876 from microchip. We fed the overall circuit by a 12V AC\DC converter and we fed the microcontroller and the LCD by a linear dropout LDO circuit. We used the GPIO p2 as an input for the battery current feedback sensor, p4 for the battery voltage feedback sensor and the GPIO p3 as an i/p for the AC/DC converter voltage measurement sensor. This MCU provides 16-bit timer used to get a high precision PWM wave. The output accuracy can achieve 1/65535 when outputs PWM. Two LEDs are connected to the microcontroller, the first one will work the charging process in constant current mode

and the second one will indicate the constant voltage mode. The 16x2 LCD is connected to port B, It will present four values for the user. The first value will be presented the i/p voltage which comes from the AC\DC converter. This value gives an indication to the user about the maximum acceptable number of charged batteries in series. The second value is the cutoff voltage which determined by the user according to the number of batteries, the third value is the instantaneous charge voltage while the fourth value is the charging current which determined by the user also. Figure 3.1 shows the block diagram of the hardware connection.

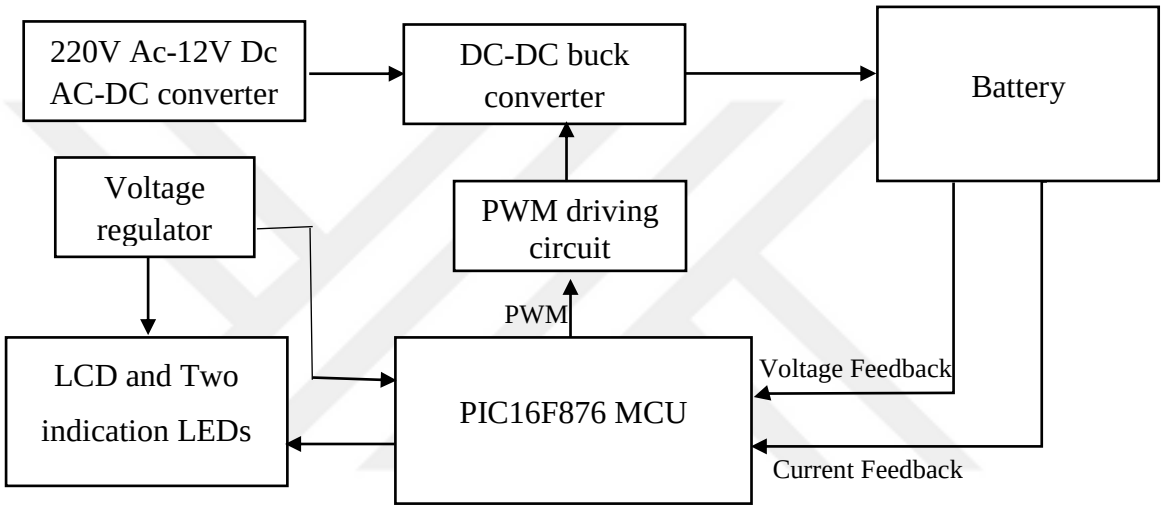


Figure 3.1 the block diagram of the hardware connection

3.3 DC-DC Buck Converter and PWM Circuits

Since the input voltage of the AC\DC converter is 12V and the charge input voltage of the lithium battery is lower than the input voltage which is supplied by the source, it is necessary to set the step-down circuit. DC-DC Buck converter is used to convert a higher DC voltage to the required voltage value. We used the IRFZ44N power MOSFET for switching operation. It is low on-resistance, a fast switching device and passes up to 35A Continuous Drain Current at 100°C with a freewheeling diode and LC network, acts as a low-pass filter. When the PWM wave becomes at the high level, the switch is ON. BUCK circuit charges the battery through the inductor and capacitor. When the capacitor is charging, the inductor's current and stored energy are gradually increasing. At this time, the diode is in reverse blocking state. The transistor switches are off when the PWM wave at the low level, inductor's current

decreases gradually. The induced electromotive force, which is produced by the inductor, it makes a current flow through the diode. Current passes energy to the battery through the inductor and diode. When battery's voltage is lower than capacitor's voltage, the capacitor starts by releasing the energy to the battery. The values of the capacitor and inductor are chosen to make the cutoff frequency lower than the PWM frequency in all the time. This can help the capacitor to effectively reduce the output voltage ripple and maintaining a DC voltage level. The capacitor value is 220 µF and the inductor is 75 μH, the cutoff frequency is 1.2 kHz. DC-DC BUCK circuit is shown in Figure 3.2.

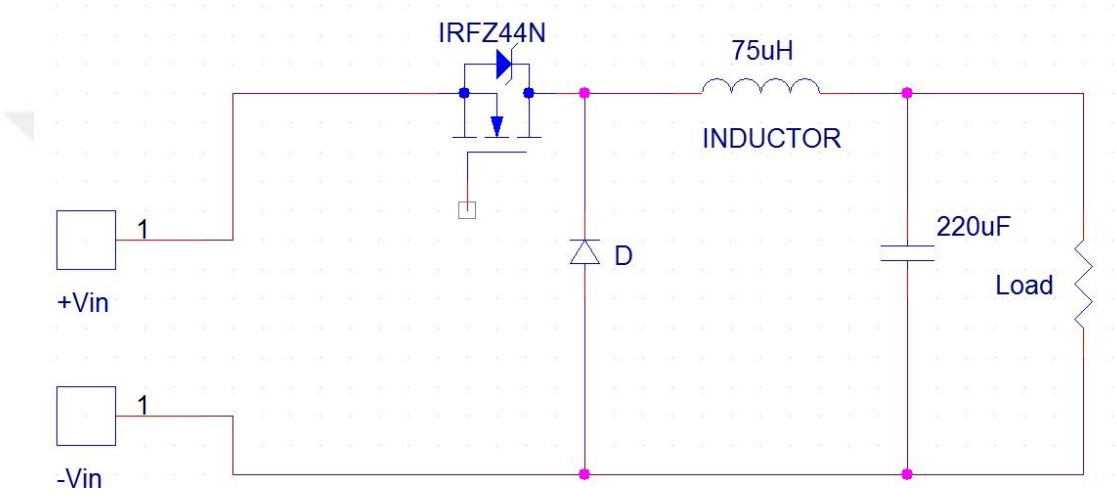


Figure 3.2: DC-DC Buck Converter

3.4 Voltage, Current Sensing Circuit Design

The microcontroller i/p ports cannot read the values of the voltage directly so in order to convert the large voltage values into smaller values we will use a voltage divider. It is a simple circuit. Just using two series resistors and an input voltage, we can create an o/p voltage that is a fraction of the input. C1 is a filter capacitor used to remove high frequency 'noise' in the signal. High precision resistance has employed in the charging loop to sample current values. Current values can be measured in MCU by sampling voltage values. An amplifier was added to the current sensing circuit to amplify the measuring voltage because the charging current value and the precision resistor's voltage both of them are low. Figure 3.3 shows the voltage and current sensing circuit design.

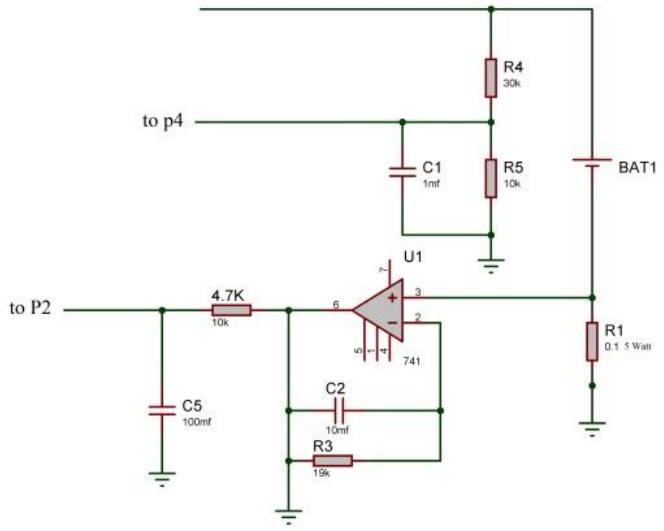


Figure 3.3 : voltage and current Sensing Circuit

3.5 The power source of the circuit

The components of the circuit such as the microcontroller and the LCD should be supplied by a DC regulated voltage as well as the supply voltages of the OP-AMPs, so we should add low dropout (LDO) linear voltage regulator. We used LM7805 linear voltage regulator from Texas Instrument. It can give up to 1.5 A maximum o/p current and this is so enough for the components of the design. It accepts an input voltage from 7 to 25 volts and gives a regulated o/p voltage from 4.8 to 5.2V. We connect the regulator to Fixed-Output Regulator mode. Figure 3.4 shows the connection diagram of the voltage regulator.

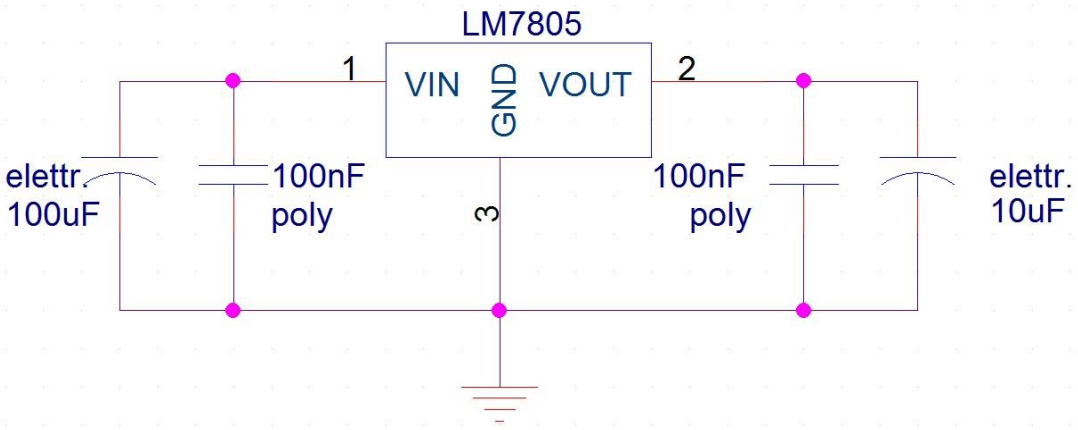


Figure 3.4: the connection diagram of the voltage regulator.

3.6 The processing Unit

The microcontroller (MCU) used in our design is the PIC16F876 from microchip. It is an 8-bit microcontroller, it has 5 channels with 10-bit resolution dedicated for the analog to digital converter(A\D converter) and it has 2 capture/ compare/ PWM functions. The power consumption of this microcontroller is very low. The frequency of operation is 20 MHZ. It has an 8 KB FLASH Program Memory (14-bit words). Data memory of this type is 368 bytes. The serial communications protocols of this microcontroller are MSSP and USART as well as to the other different on-chip peripherals such as SPI, Comparators, USB, I2C, weak pull-ups, Timers.

The controller will perform the following tasks

- It will read the values of current and voltage by the internal A/D converters of the microcontroller
- It will produce the PWM signal to drive the MOSFET of the buck circuit
- It will send the values of the Voltage and current to the 16x2 LCD interfaced with the microcontroller
- It will provide the protection to the battery Packages from the overcurrent and the overvoltage cases.

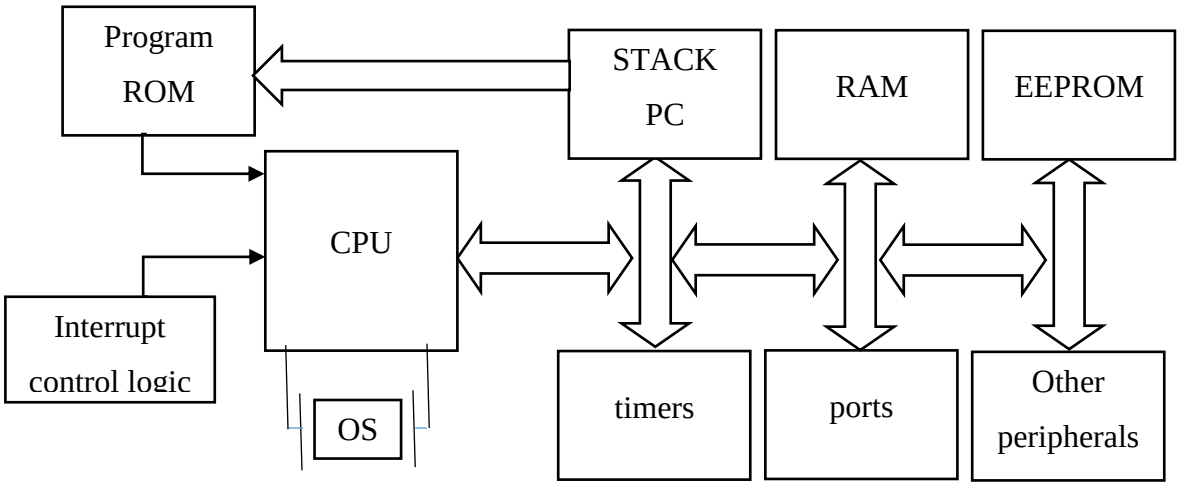


Figure 3.5: The block diagram of the PIC16F876

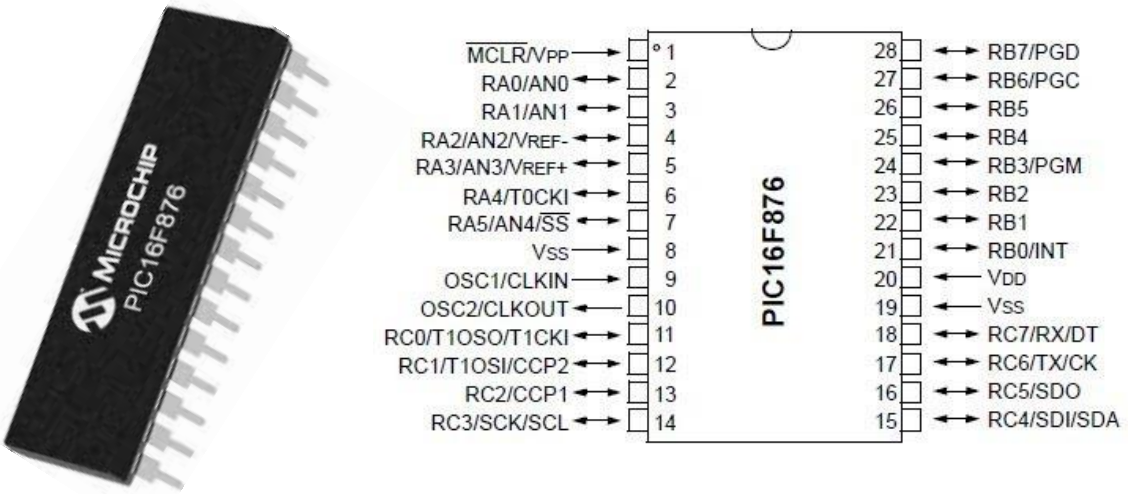


Figure 3.6: PIN diagram of PIC16F876

3.7 Software

C language was used to write the code of the charger using MicroC compiler. The following flow charts show the sequence of processes. At the start of the program, it will initialize the LCD and A/D converter pins that will take the reading of the input DC voltage and the Charging DC voltage and the charging current. The program also will initialize PWM

The first flowchart shows the necessary initializations that will be done at the start of the program, the second flowchart explains the code of the constant current mode and the third flowchart shows the constant voltage mode

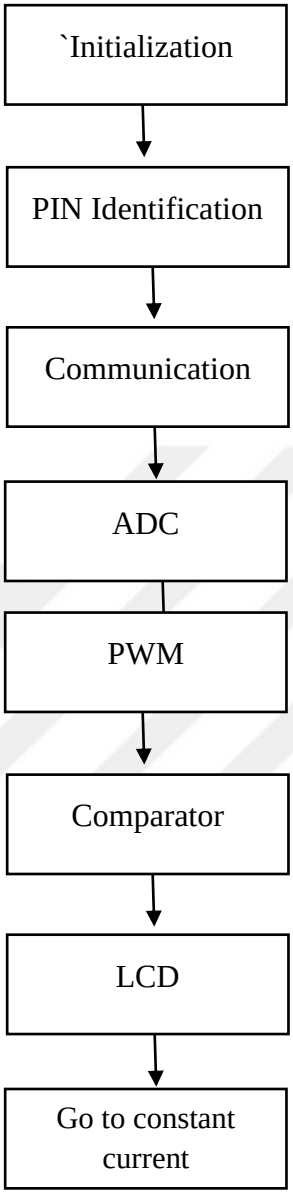


Figure 3.7: Program startup

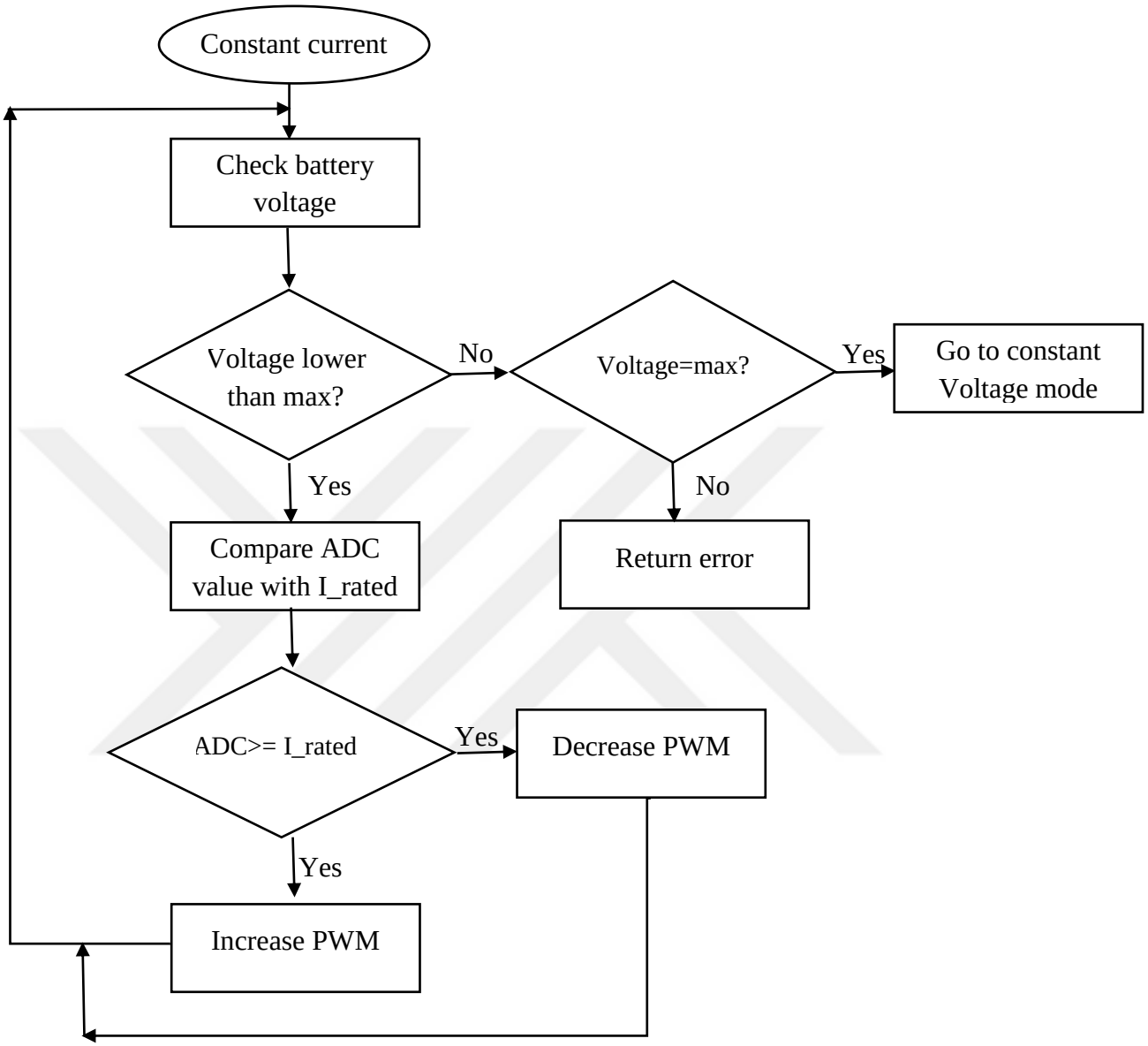


Figure 3.8: constant current mode flowchart

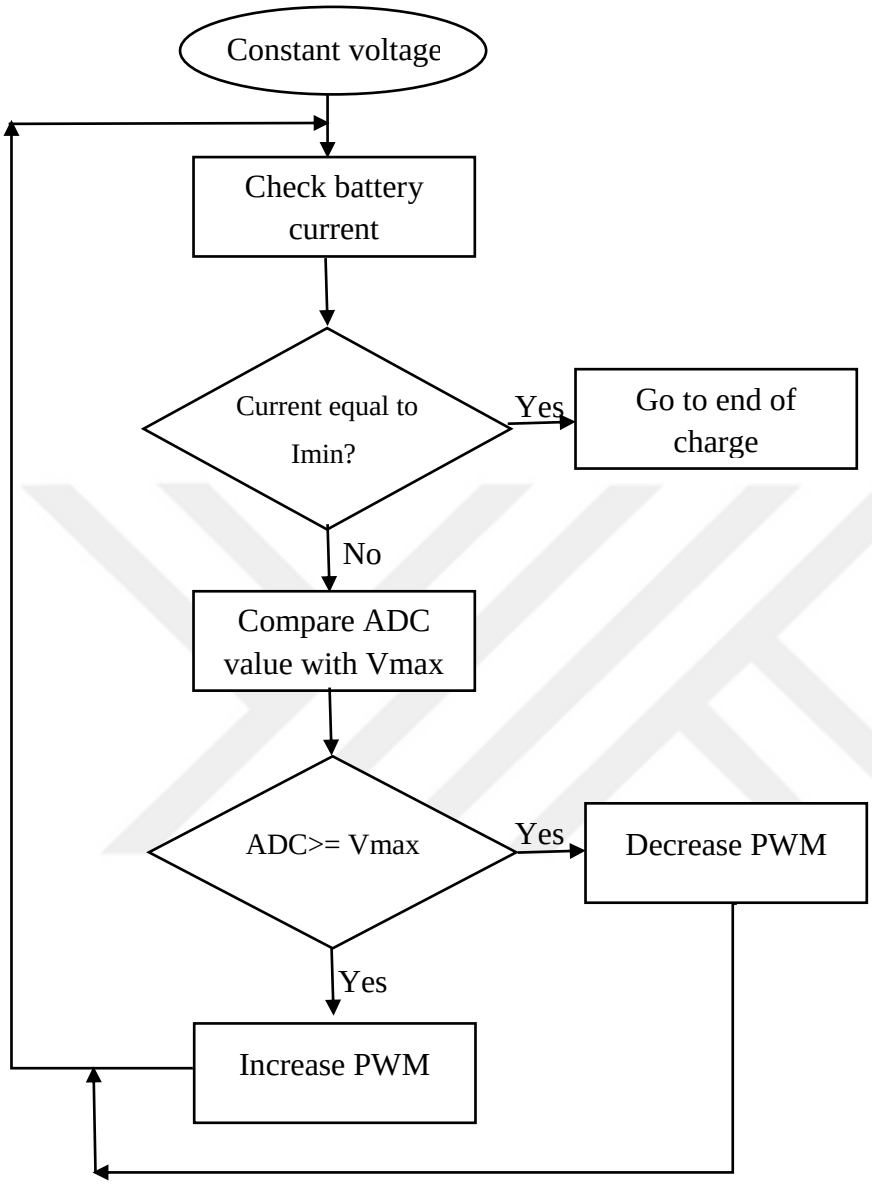


Figure 3.9: constant voltage mode flowchart

Chapter Four
The Results and Discussions

4.1 Introduction

This chapter presents experimental results that show the practical aspect of the work. First, the system performance was tested by charging different groups with different numbers of batteries to verify that the system implements the constant current-constant voltage modes, change between the constant current mode and constant voltage mode smoothly, and compare the reading of the LCD with the authorized power measurement tool.

4.2 System results

In order to test the charger performance, we charged at the first single Li-ion battery. Figure 4.1 shows an experimental board operation, the voltmeter used to measure the charging voltage and also to show the accuracy of measurement. Fig 4.1 shows the result of charging 1 Li-ion battery. The first voltage reading is the input DC voltage from the AC\DC converter, it was 13.88V. The second voltage reading (Vb) is the cutoff voltage which is determined by the user using the variable resistor, we adjust it on 3.6 V because we have one battery with rated voltages 3.7V. The third voltage reading is the instantaneous charging voltage and the fourth reading is the charging current which is determined by the user also using the variable resistor. We adjust it on 310 mA (0.3C). We notice that the reading of the voltmeter is 3.472 V and the reading of the LCD is 3.47 V. Since the charging voltage is still 3.47 the red LED is ON, it indicates that the charging in CC mode.

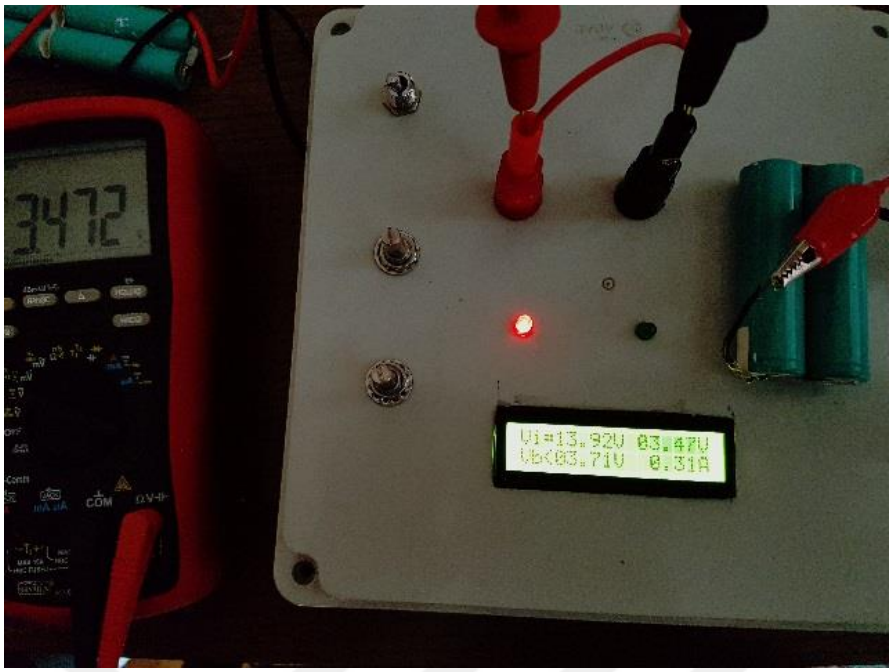


Figure 4.1: The results in case of one battery and CC mode

Figure 4.2 shows the single Li-ion battery in constant voltage mode. The charging voltage reaches the specified limit which is 3.7 in this case. The voltage stays constant and the charging current becomes 260mA. The current decreases gradually until it reaches the end-of-charge current (I_{end}). The green LED is ON, it indicates that the charging in CC mode.

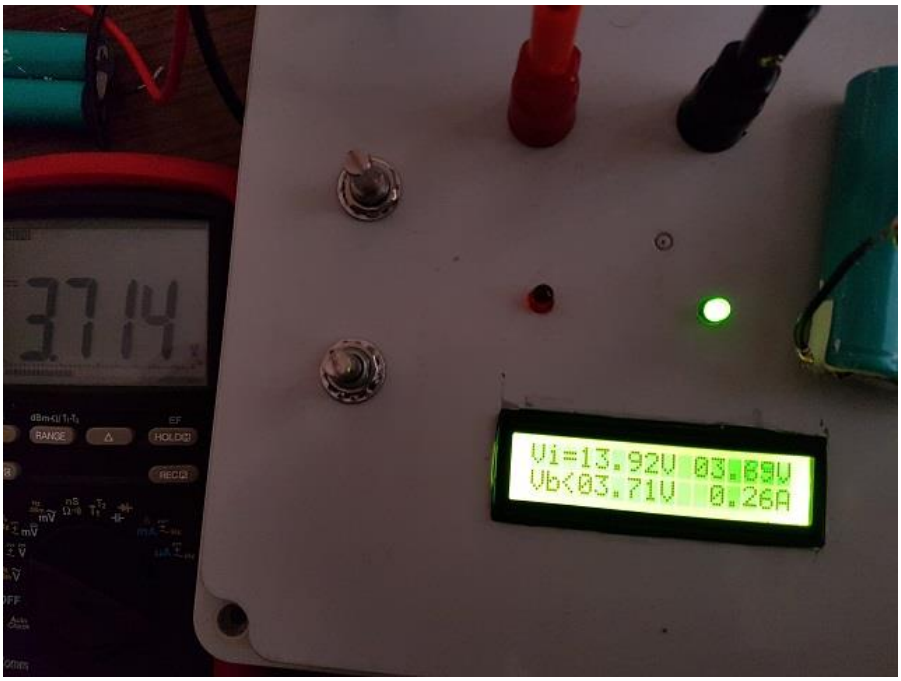


Figure 4.2: The final results in case of one battery and CV mode

In Figure 4.3 we charged three groups of Li-ion batteries connected in series. Figure 4.3 shows an experimental board operation; we adjust the charging voltage on 11.1V because we have three batteries with 3.7V for each one. The third voltage reading is the instantaneous charging voltage and the fourth reading is the charging current. We adjust it on 1300 mA. The red LED is ON, it indicates that the charging in CC mode.

Figure 4.3: The charging process of 3 Li-ion batteries in CC mode

Figure 4.4 shows that the instantaneous voltage of the batteries becomes 11.1V. While the green LED is ON, it indicates the constant voltage mode and the drawn current is 0.84 A.

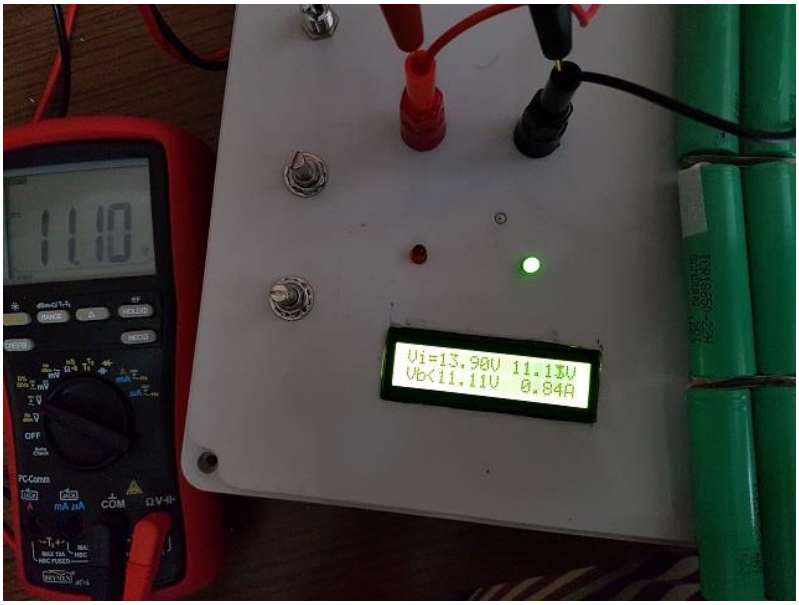


Figure 4.4: The charging process of 3 Li-ion batteries in CV mode

In Figure 4.5 we notice that the drawn current becomes 0.44A, that means the charger still in constant voltage mode and the current will decrease until it reaches to the end-of-charge current I_{end}.

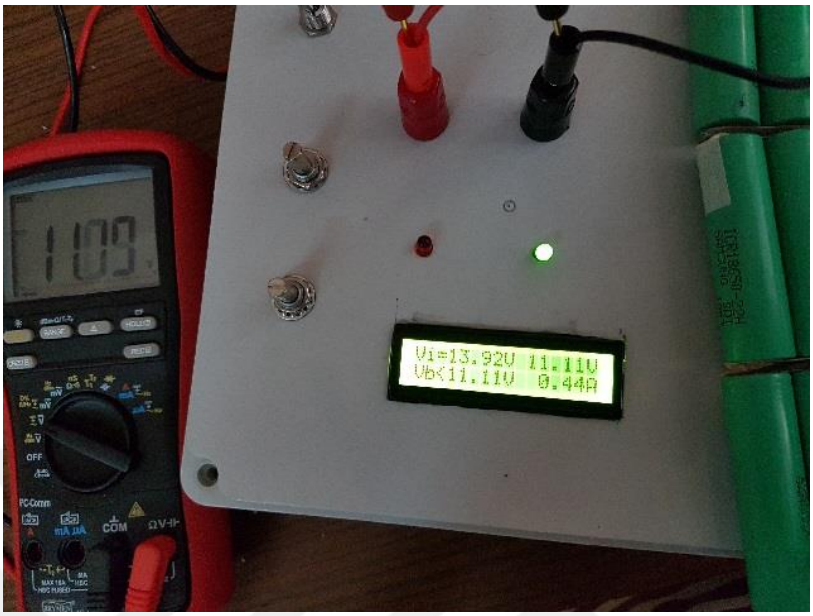


Figure 4.5: The charging process of 3 Li-ion batteries in CV mode

Finally, we recharged three groups of Li-ion batteries connected in series again and we connect an oscilloscope to show the charging curve. Figure 4.6 shows the voltage charging curve. The battery voltage before the charging process is 6.5 V, so the charging curve starts from this point Then the voltages are gradually increased. The Voltage scale of the oscilloscope is 5V and the maximum available timescale is 50 Sec so it is not possible to present all the curve in one graph

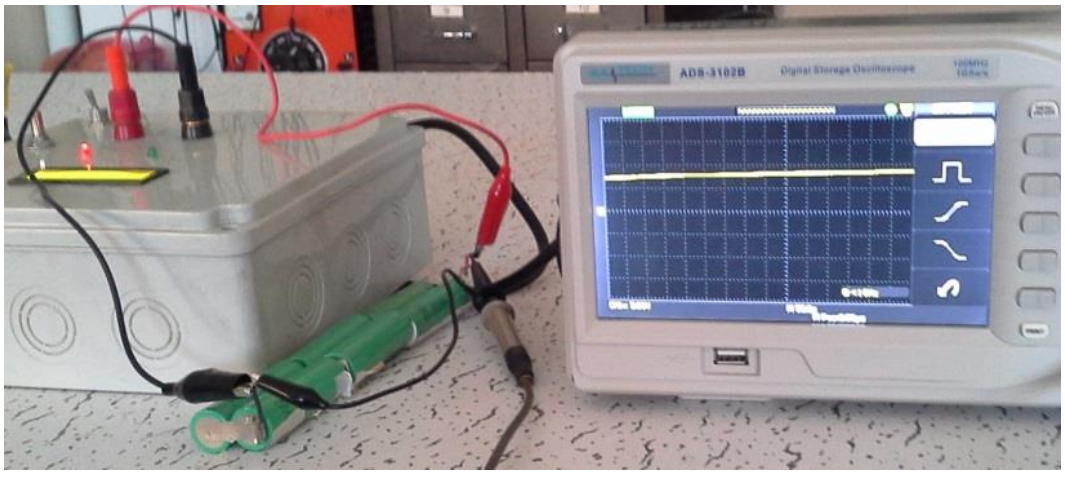


Figure 4.6: Voltage charging curve

Figure 4.7 Shows how the charging voltage reaches the setpoint voltage which is 11.2 V in this case. It will stop the increase and stay constant while the current decrease. Voltage scale is 5V and timescale 50 Sec.

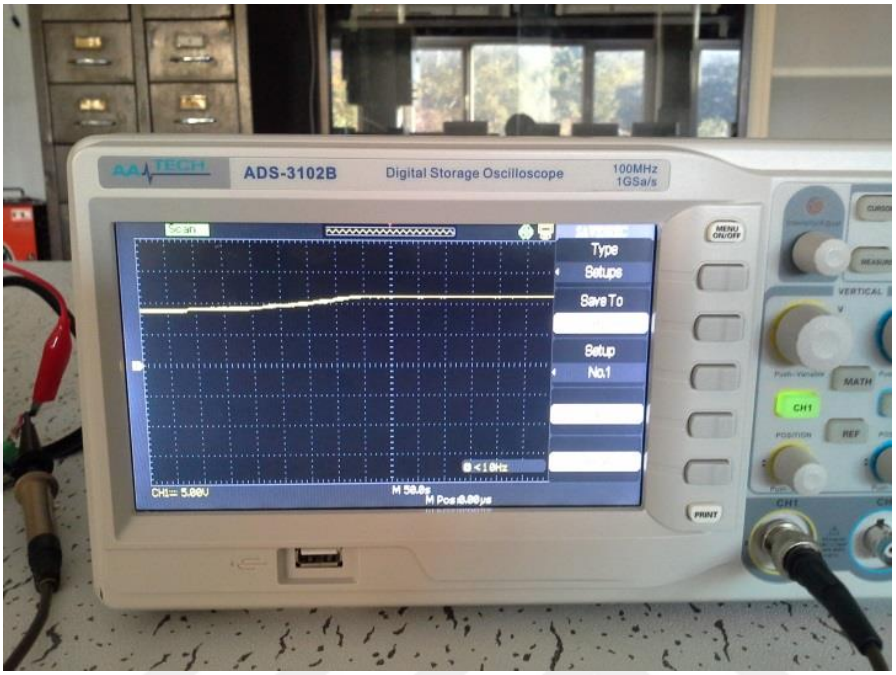


Figure 4.7: Voltage charging curve

Then the charging voltage will settle at a constant level while the battery current is decreasing. Figure 4.8 shows the charging voltage when the charger in constant voltage mode.

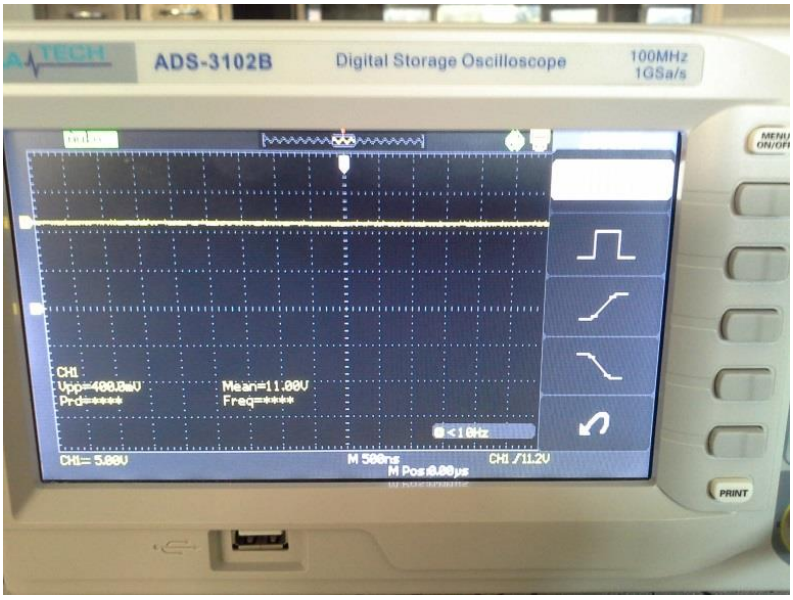


Figure 4.8: the charging voltage curve when the charger in CV mode.

Chapter Five
Conclusion and Future work

5.1 Conclusion

In this thesis, an accurate small size, low-cost intelligent battery charger had been designed based on a PIC16f876 microcontroller to implement a safe and a quick charge operation for a variable number of serially connected Li-ion batteries. This charger designed to be a switched mode power supply. First AC-DC converter designed to get unregulated 12 VDC. Next, a buck DC-DC converter was designed to step-down this unregulated DC voltage into a specific voltage according to the number of charged batteries. The power MOSFET switch (IRFZ44N) was selected in the design to perform the switching operation. Two variable resistors used to enable the user to choose the number of the charged batteries, one to determine charging voltage and the other to determine to charge current. The LCD presents four values for the user; the first voltage reading is the input DC voltage from the AC\DC converter. The second voltage reading (Vb) is the cutoff voltage, which is determined by the user using the variable resistor. The third voltage reading is the instantaneous charging voltage and the fourth reading is the charging current. Finally, the result shows that the system has high accuracy. Moreover, the charging curve performed correctly.

5.2 Suggestion for Future Works

We can summarize the suggestion for the future development by the following points

- The design can be developed to charge larger numbers of serially connected batteries by changing the AC-DC converter o/p value
- Use 3-ph power source for large packages li-ion batteries especially in public charging stations for the hybrid electric vehicle.

- Add a Wi-Fi module to the design to connect the circuit to the internet of things (IOT) and display the voltage and current readings displayed on the LCD screen on a mobile application

- Add an adaptive battery management system to the design to make the equilibrium between the different numbers of batteries

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