CELL BALANCING FOR ELECTRIC VEHICLE APPLICATION

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DECLARATION

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

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"CELL BALANCING FOR ELECTRIC VEHICLE APPLICATION"** was prepared by KUAN TEIK HUA has met the required standard for submission in partial fulfillment of the requirements for the award of the degree of Master of Engineering (Electrical) at Universiti Tunku Abdul Rahman.

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Thank you.

Kuan Teik Hua

ABSTRACT

CELL BALANCING FOR ELECTRIC VEHICLE APPLICATION

Kuan Teik Hua

Green energy is becoming more and more important worldwide as environment pollution worsen. On transportation sector, the electric vehicle is currently considered the best choice to address the environment pollution issue. The electric vehicle is powered by renewable green energy is using a rechargeable battery cell to operate. To efficiently operate and provide sufficient torque to the electric vehicle, the battery cell needs to condition so that it could run and accelerate smoothly. This paper reviews the commonly available storage system, different types of rechargeable battery, the different terminology used in battery specification and its health conditions. As cell balancing is an important part of battery control system, therefore, different types of cell balancing method together with its challenges will also be discussed.

In order for the electric vehicle to have a reliable and consistent performance, the output voltage to power the electric vehicle needs to maintain at a fixed voltage. It should not be affected by the fluctuation voltage of the individual battery cell. This is accomplished by using a buck-boost converter. Therefore the operation of buck-boost converter is being discussed in detail. The report also presented a conceptual design of the electric vehicle.

A downscale experiment to test the conceptual design is being carried out. The test parameter will be:

- Output voltage maintains when battery voltage fluctuates
- Battery could be recharged with AC supply inlet via an AC to DC converter
- Battery health diagnostic.

The downscale experiment shows that the regulation is 99.06% when is powered by AC inlet (using AC to Dc converter) with 10A load current and 99.54% when is powered by batteries at 48V output.

Charging and discharging of the battery is very time-consuming. To speed up the design testing, normally battery simulation will be used. Battery simulation using Simscape is also included in the discussion. The report ends with a recommendation for the future improvement.

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LIST OF ABBREVIATIONS / GLOSSARY

BEV	Battery Electric Vehicle
C	Battery Capacity, in ampere-hours [Ah]
CO_2	Carbon Dioxide
C-rate	Rate of discharge (or charge)
DOD	Depth of Discharge
DTSC	Double-Tiered Switched Capacitor balancing
EV	Electric Vehicle
EPNGV	Extended Partnership for a New Generation of Vehicles
HEV	Hybrid Electric Vehicle
ICE	Individual Cell Equalizer
Li-ion	Lithium-Ion
Li-Po	Lithium-Polymer
MOSFET	Metal-oxide-semiconductor field-effect transistor
MSC	Modularized Switched Capacitor balancing
MSI	Multi-Switched Inductor balancing
MpT	Multiple Transformer balancing
MWT	Multi-Winding Transformer balancing
NiMH	Nickel-metal hydride
NiCad	Nickel-cadmium
OCV	Open Circuit Voltage
PWM	Pulse Width Modulation
RUL	Remaining Useful Life
SC	Switched Capacitor balancing

SLI	Starting-lighting-ignition
SOC	State-of-charge [%]
SOH	State-of-Health [%]
SR	Switched Resistor balancing
SSC	Single Switched Capacitor balancing
SSI	Single Switched Inductor balancing
ST	Shared Transformer balancing
SWT	Single Winding Transformer balancing

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Environmental concern on pollution and the continuous depletion of fossil fuel reserves has triggered significant interest in green energy worldwide. Various research work on the use of green energy has been carrying out and it becoming more and more important worldwide. For transportation segment, an electric vehicle which is using green energy is considered the best choice to address the environment pollution issue.

An electric vehicle is an automobile that is powered by electric motors, using electrical energy generally stored in rechargeable batteries. Electric motors provide the vehicle instant torque to move around and smooth acceleration. Usually, a number battery cells together with the regulator and controller are needed so that the power to the electric motor can be regulated and controlled for the smooth running of the vehicle. The use of regulator and controller also prolong the lifetime of the battery and recharge the batteries. The regulator is to provide cell balancing and regulate the output voltage to the electric motor to achieve reliable performance. Cell balancing also is known as redistribution. It is referred to the method that maximizes the capacity of a battery pack with multiple cells connected together in series to make all of its energy available for use and to increase the battery usable lifetime.

Major functional components for an electric vehicle can be simplified to the following: an electric motor, a motor controller, a traction battery with a battery management system, a plug-in inlet charger, a wiring system, a regenerative braking system, a vehicle body and a frame (Hu, 2011).

1.2 Objectives

The objective of this project is to assemble and design a system that could provide the features stated from (i) to (iv) and is able to evaluate its performance. The evaluation can be done by downscale design.

Depict a control system of the electric vehicle with the following components:

i. AC inlet for charging the battery
ii. AC to DC converter to convert the AC inlet to DC supply
iii. Rechargeable batteries pack
iv. Controller to regulate the output voltage and provide battery diagnostic signal.

1.3 Problem Statement

For electric vehicle application, the prime source of energy is coming from the battery cell. Therefore it is important to have a constant and reliable voltage supply when the state-of-charge (SOC) of the battery is changed during charging and discharging. The challenge will be as follows:

- How to maintain the terminal voltage at the electric motor?

  To obtain 144Vdc supply we need to connect twelve pieces of 12Vdc batteries in series. When the battery is new, the output voltage of a fully charged battery can be as high as 13.5Vdc (data obtain from Trojan 27 AGM data sheet per Appendix 2). Twelve pieces of this battery will have 162Vdc. This voltage will need to bring down to 144Vdc. On the hand, due to discharge and aging, a 12Vdc battery might not be able to provide 12Vdc output. In this case, the total twelve pieces of this battery might not be able to supply 144Vdc. This voltage will need to bring up to 144Vdc.

  In practice, not all battery will be having the same voltage level. Therefore an individual buck-boost converter is needed for every battery unit to bring the voltage level to consistently 12Vdc. In other words, when any of the series connected battery voltage go below or above 12Vdc the system will self-adjust to maintain a constant 12V dc.

- Detect the state-of-health (SOH) of the individual battery.

  The battery is the prime energy source of the electric vehicle system. When any of the battery cells malfunction the circuit should be able to isolate it and bypass the respective battery cell.

- Charging and discharging time.

Charging and discharging of a battery is taking a long time and it is time-consuming to set up the test. Therefore to determine the electrical system capacity design of the EV could be very costly due to the required long and repetitive testing. Battery modeling and simulation could be applied to reduce the physical testing requirement for component selection (Jackey, 2007). To design battery management system (BMS), a battery can be modeled using Simscape with parameter include battery characterization, specific battery algorithm, estimation on state-of-charge (SOC) and state-of-health (SOH), optimization on system-level with real-time simulation.

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CHAPTER 2

LITERATURE REVIEW

2.1 Types of Energy Storage

There are many ways to store energy which primarily depends on the source of energy. They are:

2.1.1 Chemical Energy Storage in the form of potential energy. Gasses such as hydrogen, oxy-hydrogen (a mixture of oxygen and hydrogen), liquid nitrogen and hydrogen peroxide are the medium used to store chemical energy which when ignited can be used for refrigeration and cooling or to generate electricity

2.1.2 Electrochemical Energy Storage which involves the conversion of chemical energy into electricity such as a battery (a device that converts stored chemical energy into electricity) and fuel cell (a device which converts chemical energy into electricity through a chemical reaction with feature a cathode, anode and an electrolyte). There are two basic types of batteries namely rechargeable (can be used multiple times) and non-rechargeable (only used one time).

2.1.3 Electrical Energy Storage which used capacitor and supercapacitor (or superconducting magnetic energy) to store electric charges. The capacitor is used as temporary backup power, while supercapacitor is used to backup power for larger engines including electric vehicles. Sometimes people also use supercapacitor as a battery bank to power low energy requirement device such as portable media players.

Superconducting magnetic energy storage (SMES) can be used to stores electrical energy from the grid within its magnetic field created by the current flowing in the coil.

2.1.4 **Thermal Energy Storage** has used the stored thermal energy for cooling or heating up buildings due to temperature different between the building and the energy in the stored object.

- Hot water storage tank. Commonly provided by wood furnaces and solar thermal collectors. The water tank is used to stores hot water for bathing, washing and space heating applications.

- Storage heater. Turn on the electric heater to generate heat during low tariff period. Store the heat using heat retention material such as ceramic or clay bricks. Use or release the heat during high tariff period to save cost.

- Steam accumulator uses a steel tank that contains steam under pressure. Accepting steam when the supply is greater than demand and to release it when demand exceeds the supply.

2.1.5 Mechanical Energy Storage

Mechanical Energy Storage is a method that store energy produced by motion such as a hydraulic accumulator and flywheel energy storage.

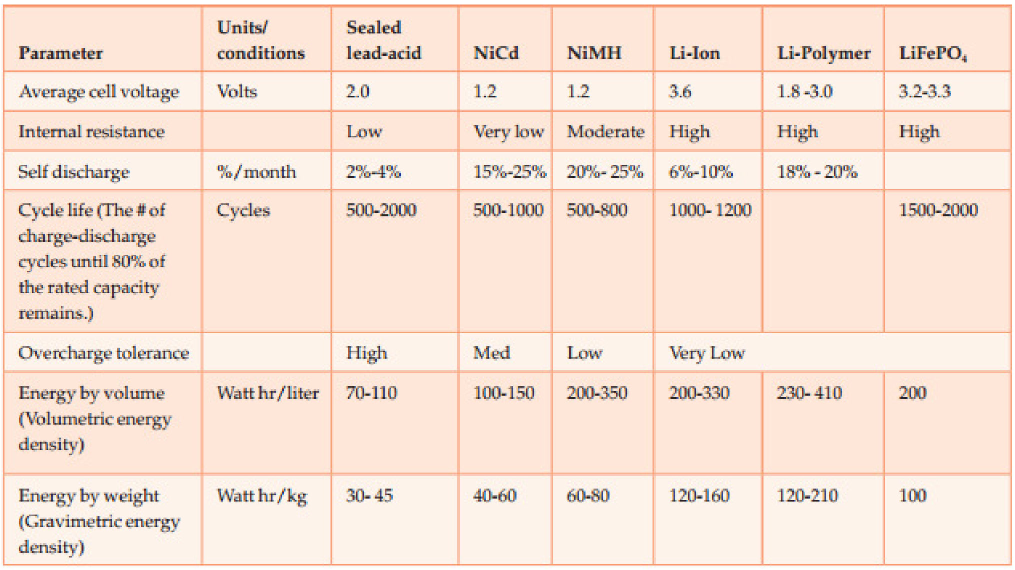
- Hydraulic accumulator or compressed gas accumulator. It is a storage reservoir which stores non-compressible fluid (usually nitrogen) under pressure.

- Flywheel energy storage is a method that stores energy through a flywheel. It is used to store grid energy and energy that is generated by wind farms.

Out of the five types of energy storage described in section 2.1.1 to 2.1.5, electrochemical energy storage is most commonly used for the electric vehicle. Therefore the current project shall concentrate on electrochemical energy storage cell mainly rechargeable battery.

2.2 Battery

A device that could produce electricity from chemical reactions is known as a battery. Batteries could come with different chemicals in it. Figure 2.1 shows a common rechargeable battery available in the market (Kularatna, 2011). The choice of rechargeable battery technology limited to the weight, size, cycle lifespan, energy density, power density, operating temperature range and the cost.



Parameter	Units/ conditions	Sealed lead-acid	NiCd	NiMH	Li-Ion	Li-Polymer	$LiFePO_4$
Average cell voltage	Volts	2.0	1.2	1.2	3.6	1.8 -3.0	3.2-3.3
Internal resistance		Low	Very low	Moderate	High	High	High
Self discharge	%/month	2%-4%	15%-25%	20%- 25%	6%-10%	18% - 20%	
Cycle life (The # of charge-discharge cycles until 80% of the rated capacity remains.)	Cycles	500-2000	500-1000	500-800	1000- 1200		1500-2000
Overcharge tolerance		High	Med	Low	Very Low		
Energy by volume (Volumetric energy density)	Watt hr/liter	70-110	100-150	200-350	200-330	230- 410	200
Energy by weight (Gravimetric energy density)	Watt hr/kg	30- 45	40-60	60-80	120-160	120-210	100

Figure 2.1: Common rechargeable batteries available in the market (Kularatna, 2011)

A battery is consist of three main components: the anode made of lead dioxide and the cathode made of sponge lead; and the electrolyte, which separates these terminals. The electrolyte is a chemical medium that allows the flow of electrical charge between the cathode and anode (MIT School of engineering, 2012). When a device is connected to a battery chemical reactions occur on the electrodes that create a flow of electrical energy to the device. For energy storage purpose, especially for electric vehicle application, the rechargeable energy generated by green energy sources that are rechargeable such as solar and wind energy will be considered as relevant.

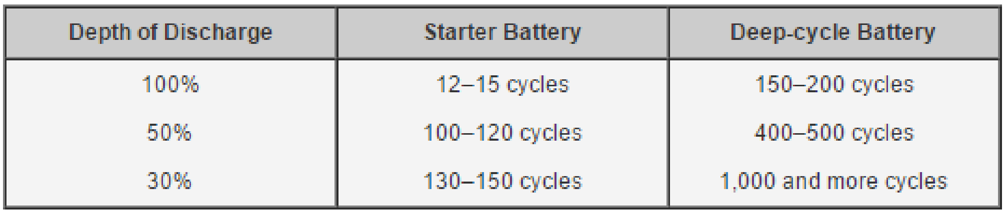
2.2.1 Lead-Acid Batteries

The oldest type of battery technology which is rechargeable was invented during 1859 by the French physicist Gaston Planté is the lead-acid battery (Oberhofer and Meisen, 2012). Lead-acid battery concept is already over 150 years old but it is still known for its cost-effectiveness today. There are two types of lead acid batteries namely Starting-Lighting-Ignition type (SLI – use it as a starter battery for the car) and Deep Cycle (use it in marine, golf carts, and wheelchairs).

Working Concept

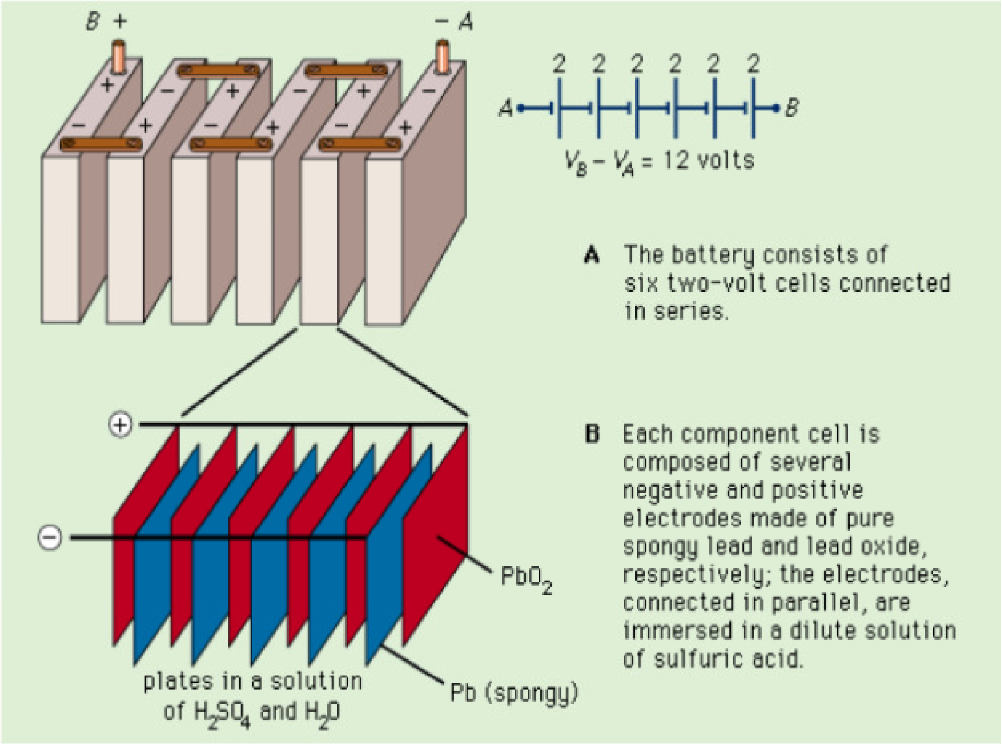
A 12V lead-acid battery will have six two-volt cells connected in series. Each cell delivering 2 volts and each component cells is composed of several positive and negative electrodes made of spongy pure lead and lead oxide. The electrodes connected in parallel are immersed into diluted sulfuric acid electrolyte as shown in Figure 2.2. The dilution is 20 to 40%. When discharged, both the anode and the cathode react chemically that produce electricity. The chemical reaction also converts the electrolyte into lead sulfate that produces electrical energy. This process can be reversed by charging the battery with electricity. The cycle lifespan and the ability to withstand the deep discharges level depending a lot on the type of battery. Starting-lighting-ignition batteries (SLI) are designed to deliver quick bursts of energy used in starting engines. It has a greater plate count. They are not designed and cannot handle more than 50% of deeply discharged because they have thinner lead plates with somewhat different material composition. Frequent discharged to more than 50% will reduce their cycle life dramatically and may cause permanent damage.

Table 2.1: Cycle performance of starter and deep-cycle batteries (Buchmann, 2011)



Depth of Discharge	Starter Battery	Deep-cycle Battery
100%	12–15 cycles	150–200 cycles
50%	100–120 cycles	400–500 cycles
30%	130–150 cycles	1,000 and more cycles

Deep cycle batteries with thicker plates hence it is heavier and bulkier. It can survive a number of discharge cycles. Deep cycle batteries can provide greater long-term energy delivery. Therefore it is advisable to have a deep cycle discharge protection when designing a controller for electric vehicle application. Table 2.1 shows cycle performance starter and deep-cycle batteries.



A The battery consists of six two-volt cells connected in series.

B Each component cell is composed of several negative and positive electrodes made of pure spongy lead and lead oxide, respectively; the electrodes, connected in parallel, are immersed in a dilute solution of sulfuric acid.

Figure 2.2: Construction of lead-acid battery (Oberhofer and Meisen, 2012)

Pros:

+ Simple and easy to produce and therefore low cost

+ It is more than 150 years mature technology with a lot of available field testing data

+ Can provide high bursts of current make it highly suitable to use as car starter; hence it has high surge-to-weight-ratio

+ Can be recyclable easily

Cons:

- Can be heavy, occupy space and bulky
- Short lifespan
- Environmental concerns: lead can be very toxic when exposure to human or animal can cause severe damage
- Acidly and chemical reaction can be corrosion

2.2.2 Lithium-Ion Batteries

Working Principle

Lithium, in theory, is the lightest metal, therefore, it has the highest potential as it has very reactive behavior in nature. This makes them a very good and suitable compound for used in batteries (Oberhofer and Meisen, 2012). Just like all other batteries, the lead-acid and majority of other batteries, the Lithium-Ion battery does also use chemical reactions to produce electricity. Although all of them are called lithium-ion batteries but they have a lot of variation due to different chemical compounds used. Their construction looks like a capacitor which has three different layers curled up to minimize the space. The first layer which is made of a lithium compound is the anode; the second one which is generally made of graphite is cathode. The third layer is the separator which made of various compounds with different characteristics, different benefits, and flaws. It separates anode and cathode but must allow lithium-ion to pass through. All these three layers are dip into organic solvent known as an electrolyte which acts as a medium for the ions to interact. The ions is moving between the anode and the cathode.

During the charging mode or charging process as shown in Figure 2.3, the lithium ions will move through the microporous separator than into spaces between the graphite (though not compounded) and accepting an electron from the external power source.

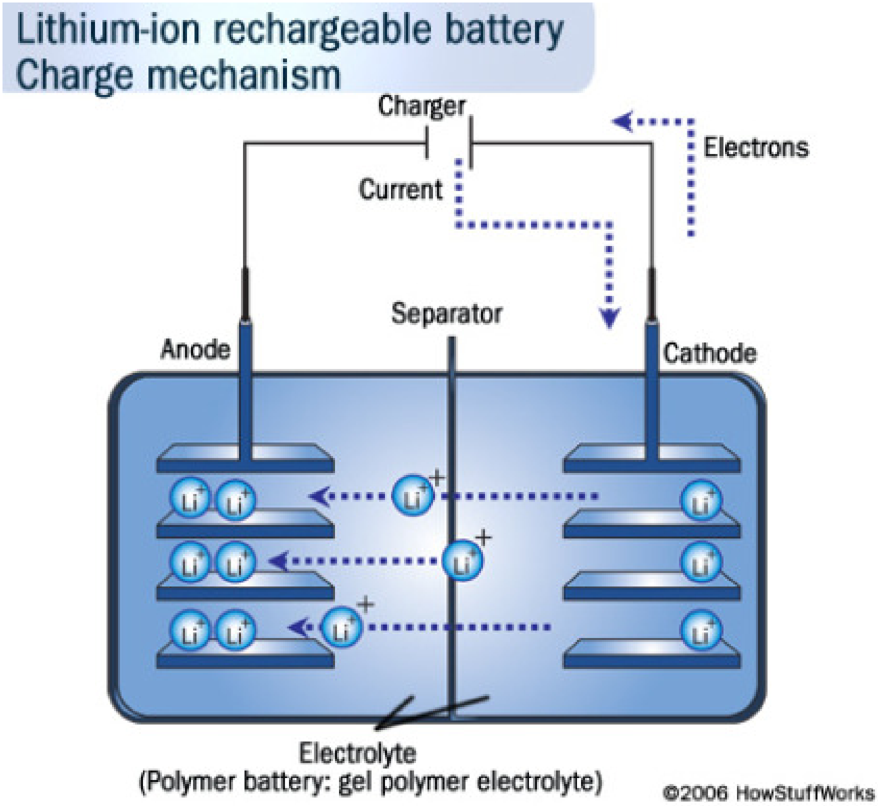


Figure 2.3: Charging of a lithium-ion battery (Brain, 2006)

During the discharging mode or discharging process as shown in Figure 2.4, the lithium atoms which located between the graphite is releasing its electrons that flow through the external circuit to the anode producing a current. The lithium ions are now moving back to the anode. This process will release electrons. Lithium is a very reactive compound which can easily catch fire. Due to this behavior, therefore, safety precautions need to take into account when designing a circuit that uses a lithium battery. The precautions include onboard control chips that could manage the temperature and to prevent the cell from a complete discharge.

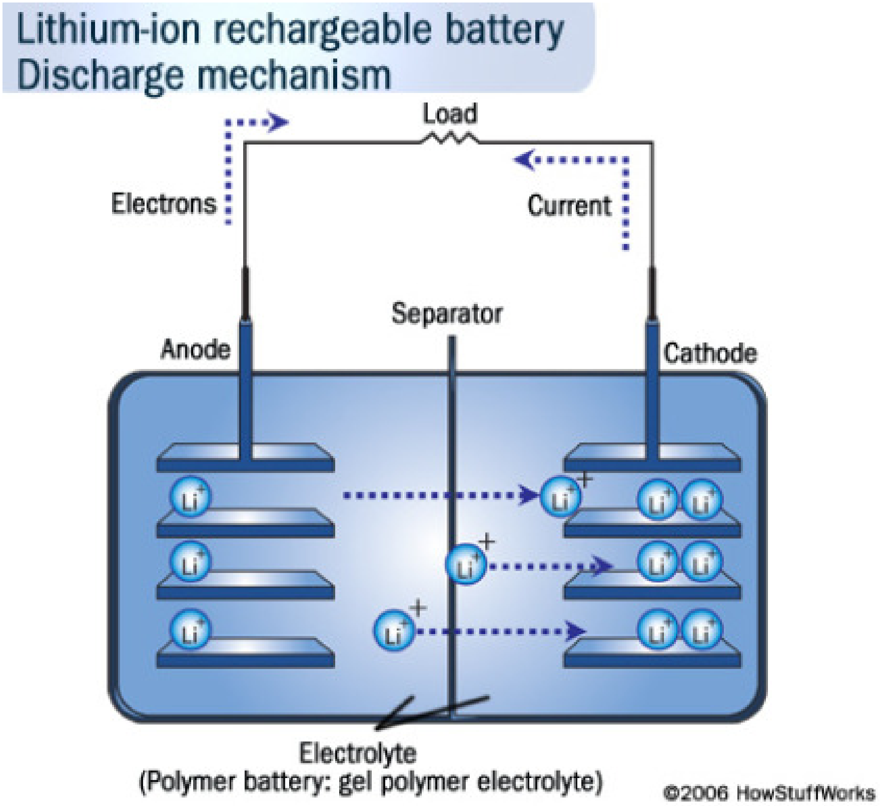


Figure 2.4: Discharging of a lithium-ion battery (Brain, 2006)

2.2.3 Other Batteries in Development

Other batteries which are in development stage:

- **Redox-Flow Battery:** A type of rechargeable flow battery that employs vanadium ions in different oxidation states to store chemical potential energy**.** This system is using the refillable fluid as electrolytes. Different types of exchangeable fluid are available. If the battery is discharged, to charge it back simply replaces the fully charged fluid.

- **Sodium Battery:** Sodium-ion batteries are a type of rechargeable metal-ion battery that uses sodium ions as charge carriers which already operational in some countries like Japan. Sodium battery required to operate at high temperatures around the range of 350° C/623° K in order to get the sodium liquid. This makes the system very expensive and difficult to operate. Liquid sodium could reacts easily with the water in the atmosphere, this also make it more dangerous to use. There is a record that at least three fires incident occurred since Nippon Tokusyu Tōgyō Kabushiki-gaisha Co. LTD (NGK) and the Tokyo Electric Power Co. LTD (TEPCO) shipped out sodium batteries in 2002, a major setback on sodium battery development (Oberhofer and Meisen, 2012).

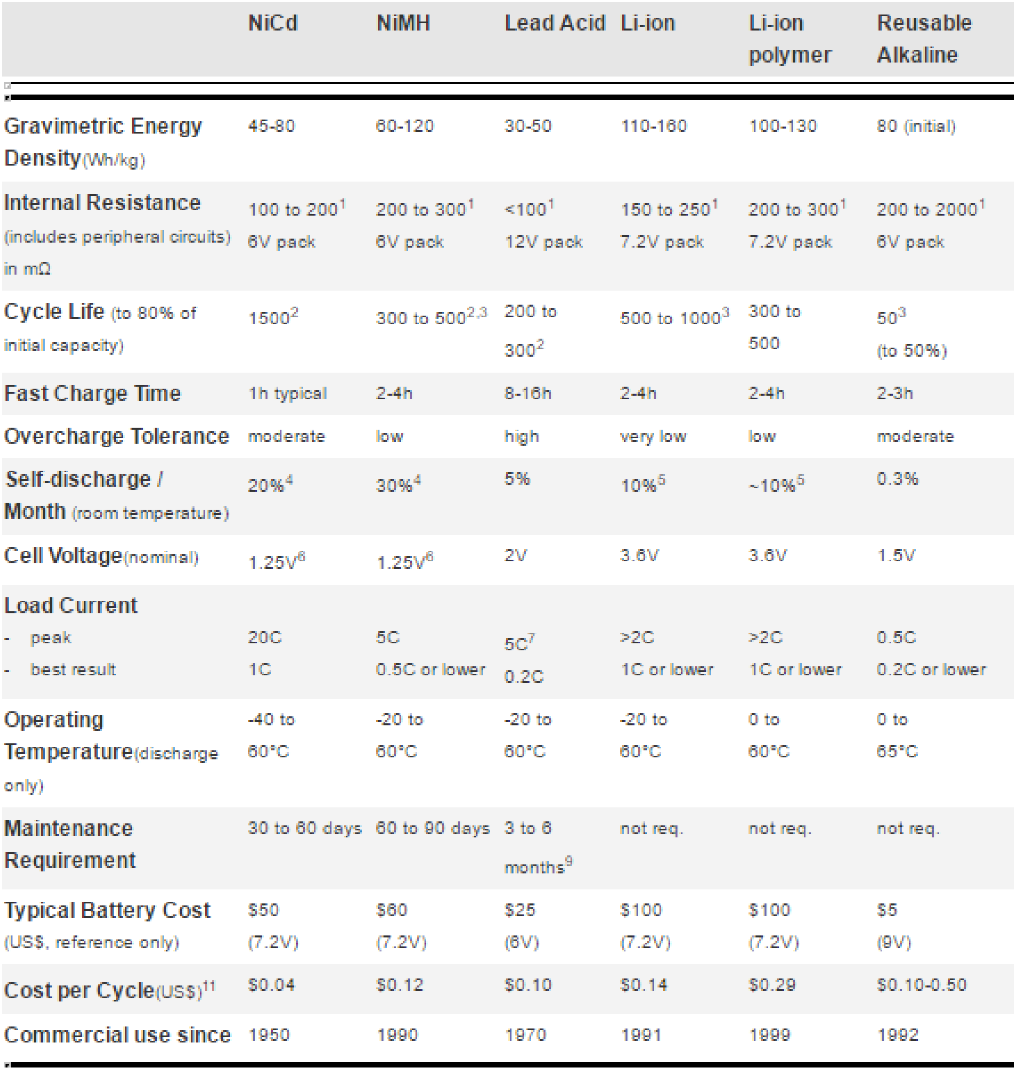
- **Zinc-air Battery:** To use the energy produced by zinc-air cells, it required atmospheric oxygen absorbed into the electrolyte via a gas-permeable, liquid-tight membrane. Presently no reliable data because no field tests have been done to support the technology, therefore, it remains as a theoretical idea with a very high potential. Therefore it is worthwhile to explore the application.

2.2.4 Battery Used For Project Experiment

Figure 2.5 provides characteristics of commonly used rechargeable batteries (Buchmann, 2010) in the market. However, the lead-acid battery is chosen for the testing and evaluation on this project/experiment as it provides the following advantages.

Advantages

- Low cost in terms of cost per watt hours and it is easily available off the shelf.
- It is a more than 150 years old technology. Therefore it is mature, reliable and well-understood technology.
- It has low self-discharged. The self-discharge rate is one of the lowest in rechargeable battery systems.
- Low maintenance requirements: no memory, no electrolyte to fill (seal type)
- Capable of providing high discharge rates.



	NiCd	NiMH	Lead Acid	Li-ion	Li-ion polymer	Reusable Alkaline
Gravimetric Energy Density (Wh/kg)	45-80	60-120	30-50	110-160	100-130	80 (initial)
Internal Resistance (includes peripheral circuits) in mΩ	100 to 200[1] 6V pack	200 to 300[1] 6V pack	<100[1] 12V pack	150 to 250[1] 7.2V pack	200 to 300[1] 7.2V pack	200 to 2000[1] 6V pack
Cycle Life (to 80% of initial capacity)	1500[2]	300 to 500[2,3]	200 to 300[2]	500 to 1000[3]	300 to 500	50[3] (to 50%)
Fast Charge Time	1h typical	2-4h	8-16h	2-4h	2-4h	2-3h
Overcharge Tolerance	moderate	low	high	very low	low	moderate
Self-discharge / Month (room temperature)	20%[4]	30%[4]	5%	10%[5]	~10%[5]	0.3%
Cell Voltage (nominal)	1.25V[6]	1.25V[6]	2V	3.6V	3.6V	1.5V
Load Current						
- peak	20C	5C	5C[7]	>2C	>2C	0.5C
- best result	1C	0.5C or lower	0.2C	1C or lower	1C or lower	0.2C or lower
Operating Temperature (discharge only)	-40 to 60°C	-20 to 60°C	-20 to 60°C	-20 to 60°C	0 to 60°C	0 to 65°C
Maintenance Requirement	30 to 60 days	60 to 90 days	3 to 6 months[9]	not req.	not req.	not req.
Typical Battery Cost (US$, reference only)	$50 (7.2V)	$60 (7.2V)	$25 (6V)	$100 (7.2V)	$100 (7.2V)	$5 (9V)
Cost per Cycle (US$)[11]	$0.04	$0.12	$0.10	$0.14	$0.29	$0.10-0.50
Commercial use since	1950	1990	1970	1991	1999	1992

Figure 2.5: Characteristics of commonly used rechargeable batteries (Buchmann, 2010)

2.2.5 State-of-Charge (SOC)

The SOC is defined as battery available capacity in term of percentage of its maximum available capacity and often is being called "fuel gauge".

$$\mathrm{SOC} = \frac{\text{available capacity (Ah)}}{\text{maximum available capacity (Ah)}} \times 100\%.$$

2.2.6. State-of-Health (SOH)

The State-of-Health (SOH) is an indication or the “measurement” of the point which the battery has been reached in the life cycle (remains before it must be replaced) of its condition compare to a new battery. It also an indication of its ability to deliver the specified performance compared with a new battery by taking into consideration on factors such as charge acceptance, internal resistance, voltage and self-discharge. Knowledge of the SOH will also help the plant engineer to anticipate problems to make fault diagnosis or to plan replacement. This is essentially a monitoring function tracking the long-term changes in the battery.

SOH for EV applications means the ability to achieve the range when called upon to do so is most important; hence the SOH is based on a comparison of current capacity with capacity when new. Battery manufacturers do not state the SOH in their product because they only supply new batteries. The SOH only applicable to battery once they are in used or after they have started their aging process either on the shelf or once they have entered service.

2.2.7 Common Battery Definitions

Voltage

Normally, batteries are printed with nominal voltage but when a measurement is taken, the open circuit voltage (OCV) on a fully charged battery is about 5 to 7 % higher than the nominal voltage. Chemical medium and the number of cells which connected in series will determine the OCV. On the other hand, the closed circuit voltage (CCV) is the operating voltage. It is advisable to always check the correct nominal voltage rating before using it.

Capacity

Capacity is the specific energy in ampere-hours (Ah). This is a health indicator of a battery. An ampere-hour is the amount of discharge current or energy that a battery can deliver with respect to time. Using a higher Ah rated than specified value, the battery will have a longer runtime while a lower Ah than specify will have a shorter runtime. Higher Ah rating will take a longer time to fully charge. Lower Ah rating will take a shorter time to fully charge the battery. The recommended practice on Ah is that not to deviate more than to exceed 25 percent from its original value. European standard typically the German DIN (Deutsches Institut für Normung) standard and IEC (International Electrochemical Commission) standard use Ah in the battery specification; Reserve Capacity (RC) is used by Society of Automotive Engineers (SAE) in North America to indicate the discharging time or runtime in minutes at a steady 25A discharge current. No precise formula to convert RC to Ah but the most common factor used is RC divided by 2 plus 16 or simply dividing RC by 1.9.

Cold Cranking Amps (CCA)

Starter batteries or SLI (starter-light-ignition) are normally printed with CCA rating at 18°C (0°F). This indicates at 18°C (0°F) how much current in ampere that the battery can provide. CCA provide measurements that assure the battery has sufficient power to crank or start the engine when is cold.

Specific Energy / Energy Density

Specific energy or gravimetric energy density specifies the battery capacity in weight (Wh/kg) (Buchmann, 2016). Energy density, or volumetric energy density, provides volume in liters (Wh/l) information (Buchmann, 2016). Products that required long runtimes at moderate load are optimized for high specific energy (Buchmann, 2016).

Specific Power

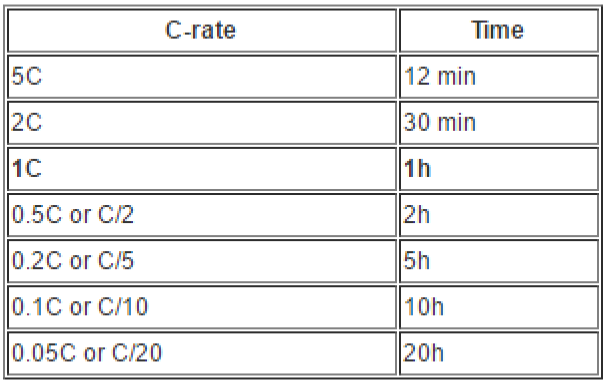
Specific power or gravimetric power density provides loading capability information. Batteries that are used for power tools are made for high specific power, they come with reduced specific energy (capacity).

C-rates

The C-rate tell us how fast is a battery is being charged or discharged. At 1C, the battery is being charged and discharged at a current that are the same with the specify Ah rating. At 0.5C, the charging or discharging current is half, therefore, the time is doubled. At 0.1C the charging and discharging current is one-tenth and therefore the time is 10-fold.

Charge and discharge rates of a battery are defined by C-rates. If the battery discharge at 1C means a fully charged battery with 1Ah rated could provide 1A current for 1 hour (also known as a one-hour discharge). The same battery discharge at 0.5C means it could provide 500mA current for 2 hours (two-hour discharge). If it is 2C means can provide 2A for 30 minutes (30-minute discharge) and so on. There is good quality and high-performance batteries can have C-rate more than 1C with moderate stress. Table 2.2 illustrates typical times at various C-rates.

Table 2.2: C-rate and service times when charging and discharging batteries (Buchmann, 2016).



C-rate	Time
5C	12 min
2C	30 min
1C	**1h**
0.5C or C/2	2h
0.2C or C/5	5h
0.1C or C/10	10h
0.05C or C/20	20h

Watts and Volt-Amps (VA)

Watt is the real power; VA is the apparent power that is due to a reactive load. For pure resistive load, Watt will be the same as VA; reactive load can cause a phase shift between the voltage and current known as power factor (PF). A purely resistive load will have power factor equal to 1. The reactive load will have power factor less than 1. An example of the reactive load will be induction motor and fluorescent lamps. Electrical wiring and circuit are rated as VA.

2.3 Cell Balancing

Cell balancing is a method of saving weaker cells by adjusting an appropriate amount of charging and discharging on the cells in each battery unit. Cell balancing is necessary for extending battery life. Common multiple battery cell pack is configured in series and parallel or their combination. This configuration provides necessary voltage and current requirement to power the load depending on the application but they may not be as efficient as they could be. The issue limits the battery pack capacity to the capacity of the weakest cell.

Battery systems that have a series connection are required to equip with cell balancing circuits to prevent individual cells from over-voltage or under-voltage, which can lead to performance degradation, shorter life, or in some cases even hazards.

2.3.1 Cause of Cell Imbalance

As discussed in the previous section, cell balancing is important to extend the battery lifetime, prevent the battery from overcharge or over discharge, obtain optimum performance, etc. The cause of cell imbalance will be discussed here. Cell imbalance comes from 2 sources namely internal and external.

Internal source:

- Manufacturing batch variation

- Variations in battery internal impedance
- Differences in self-discharge rate
- Chemical Efficiency Variations

External source:

- Poor cell capacity matching between cells in a series connection and Multi-rank pack protection ICs draining unequally from the different series ranks in the pack.
- Non-uniform thermal stress created thermal difference across the pack causing individual cell discharge at a different rate. Thermal heat cause self-discharge doubles for each 10º C rise
- Impedance variations between batteries
- Non-uniform electrical loading of pack

2.3.2 Battery Management System (BMS)

Battery management systems (BMSs) are part of the important battery control system in electric vehicles with the aim to protect the battery system from damage, to predict and increase batteries lifespan, and to maintain the battery system in an accurate and reliable operational condition (Daowd et al., 2014). The BMS performs the following tasks:

- Measuring and monitoring the system voltage, current and temperature (VIT)
- Measuring and monitoring the state-of-charge (SOC) and state-of-health (SOH) of the cell

- Predict the battery remaining useful life (RUL)
- Perform thermal management by protecting the cells from overheating
- Controlling and monitor the charge/discharge profile
- Acquired data for monitoring and storing historical data
- Cell balancing.

Cell imbalance can affect the battery life. It will cause the individual cell voltages drift apart over time. The capacity of the battery will also decrease more quickly during operation and could fail prematurely. The cell imbalance could come from internal and external factors. The internal factors will be the manufacturing batches variation in charge storage volume, variations in internal impedance and differences in self-discharge rate for an individual cell. External factors are mainly due to multi-rank pack protection integrated circuits (ICs) cause by poor cell capacity matching, which drains charge unequally from the different series ranks in the pack. On the other hand, thermal difference across the pack could also create different self-discharge rates of the cells. Figure 2.6 shows passive and active cell balancing topologies (Daowd et al., 2014).

The active cell balancing methods remove charge from higher energy cell(s) and deliver it to lower energy cell(s). This makes active cell balancing more efficient compared to the passive balancing method. Different topologies are used for different purposes according to the active element used for storing the energy such as using a capacitor, inductive component for controlling the switches or converters. Figure 2.6 give an overview of different passive and active cell balancing topologies.

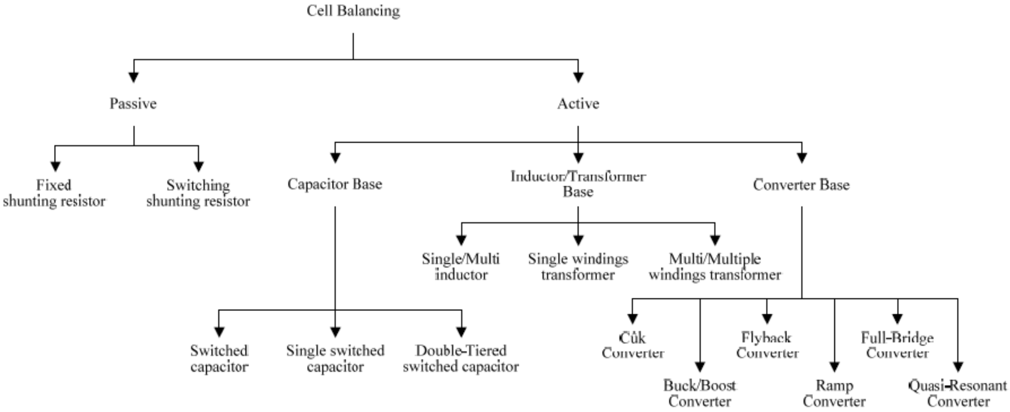


Figure 2.6: Passive and active cell balancing topologies (Daowd et al., 2014)

2.3.3 Passive Cell Balancing Circuit

Passive cell balancing methods is using shunting resistors to bypass charge current and dissipate energy for high voltage cells to achieve cell balance. The shunt resistor could be either in fixed mode as shown in Figure 2.7 (a) or in switched mode as shown in Figure 2.7 (b).

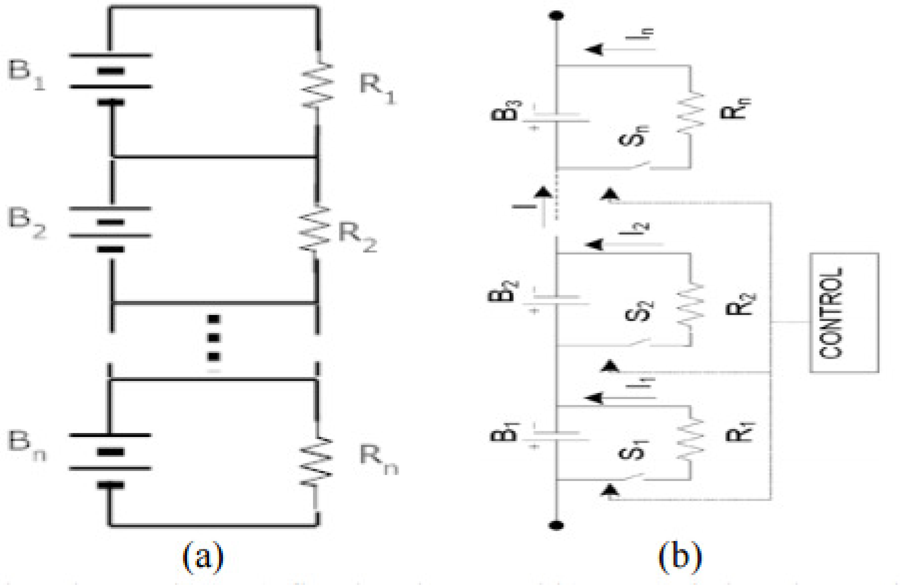


Figure 2.7: Shunting resistor a) fixed resistor and b) control shunting resistor (Daowd et al., 2011)

Passive cell balancing circuit shown in Figure 2.7 (a) supports balancing in battery charge only and achieves a balance of cell voltages by dissipating energy in the resistors for cells until the charge matches those of the lower cells in the battery pack or matches a charge reference (Lee et al., 2011). The fixed shunt resistor is bypassing the current continuously for all the cells with the cells voltage limited by the resistor. This is a simple low-cost method but it dissipates energy continuously for all cells.

Another method is the switched shunt resistor (see Figure 2.7-b). It removes the energy from the higher cell(s) by using switches/relays. It can work either in continuous mode to control all relays with a common on/off signal or in detecting mode to monitor the cell voltages. Therefore, this method is much proficient compared to fix resistor method but it needs for thermal management as more heat will be dissipated from the cell(s) which has higher energy. It will also shorten the battery run time.

2.3.4 Active Cell Balancing Circuit

Shuttling active cell balancing method utilizes external energy storage devices (normally capacitors) to shuttle the energy among cells to achieve cell balancing. There are two shuttling topologies (Cao et al., 2008); Switched Capacitor Topology and Single Switched Capacitor Topology. For Switched Capacitor, it requires n-1 capacitors to balance n cells whereas Single Switched Capacitor only needs 1 capacitor to balance n cells (Cao et al., 2008). The Single Switched Capacitor is a variation of the Switched Capacitor (Cao et al., 2008). Shuttling balancing method used external energy storage devices (usually a capacitor) to shuttle the energy between adjacent cells (Cao et al., 2008).

Switched Capacitor

Figure 2.8 shows active switched capacitors shunt balancing circuit. For this design, for n cells balancing 2n switches and n-1 capacitors will be required. The control strategies for this design is simple as they only have are two states.

For example:

In one of the state, C1 is paralleled with B1 and C1 will be charged or discharged to obtain the same voltage as B1. Then after this process, the system will turn to the other state. In this state, C1 is paralleled with B2. The same thing will happen in this state as the previous state. After repeat cycling process, B1 and B2 will be balanced. The same thing will happen to C2 and so on. So finally, all battery cells can be balanced.

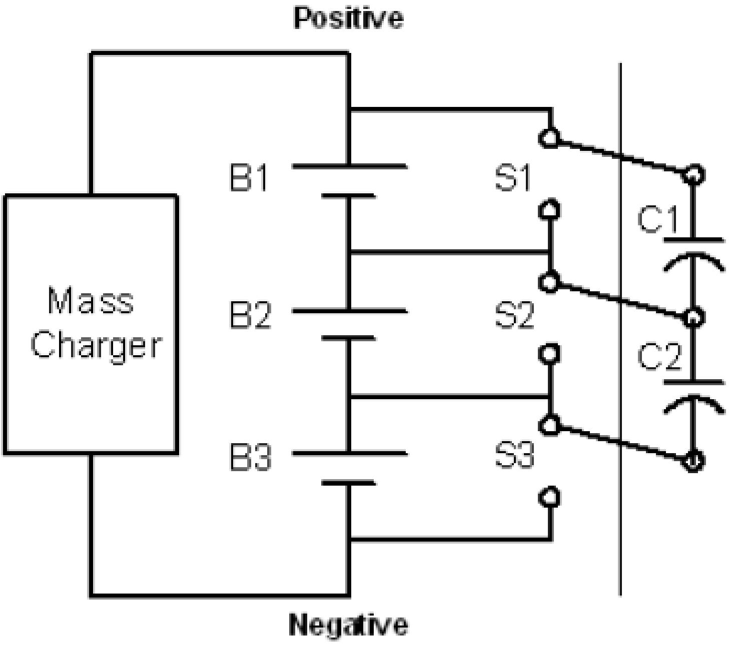


Figure 2.8: Switched Capacitors (Cao et al., 2008)

The advantage of the switched capacitor design is that it is simple which does not need intelligent control and it can work for both recharging and discharging operation.

Single Switched Capacitor

Figure 2.9 shows a Single Switched Capacitor design which is a variation of the Switched Capacitors. This method uses only one capacitor to shuttle the energy. If simple control strategy is used, that is to switch the capacitor to parallel with each cell regularly. The speed of balancing is only 1/n of regularly switched capacitor method where n is the number of cells (Cao et al., 2008). However, for this design, more advanced control strategies can be used to switch between the highest and the lowest voltage cell, which is called the cell to cell method. The balancing speed will be much higher too. For this design, n switches and one capacitor are needed to balance n cells.

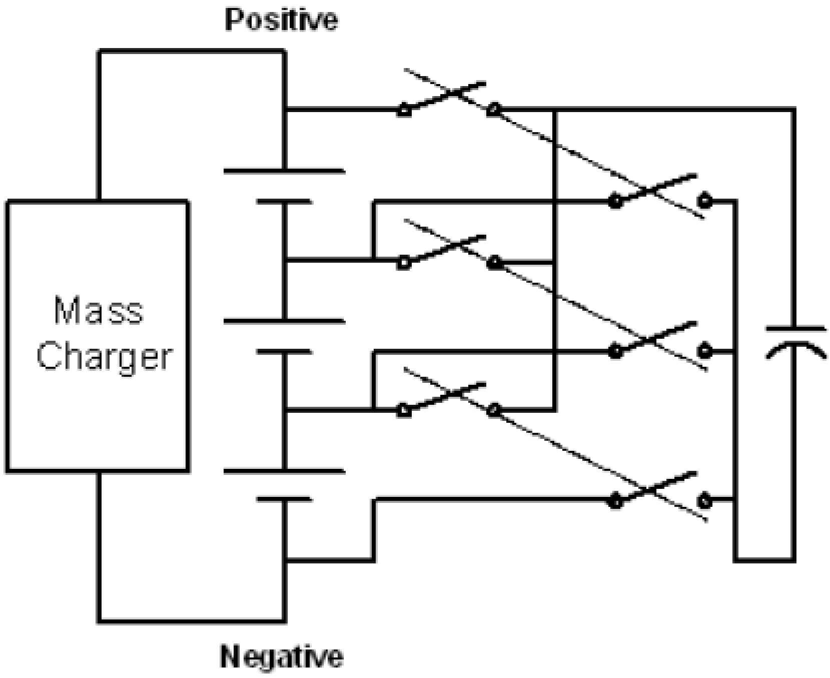


Figure 2.9: Single Switched Capacitor (Cao et al., 2008)

2.4 DC to DC Converter

An electric vehicle generally required a supply voltage in the region of 144 to 500V DC. This voltage is more than a single battery can provide. For example, if the EV motors and its control circuitry required a voltage of 144V DC to run then it will require a battery bank to operate rather than one single battery. When all the cells in the battery bank are new and fully charged it might provide more than 144V DC. As the charge is used up, the voltage will drop below 144V DC. This will significantly affect the performance of the electric vehicle. Any system powered by a battery, at some point in time, the battery will discharge to a voltage that is not sufficient to power the circuit being powered. Therefore the output voltage of a battery or battery bank needs to be conditioned for electric vehicle application.

For consistent performance, when the input voltage to the EV is above 144V DC, buck converter will be used to bring down the voltage to 144V DC. When the voltage falls below 144V DC a boost converter will be required to bring up the voltage to 144V DC.

For EV which required much higher voltage, it will not be practical by just adding more battery pack. Even if more battery bank were used, the weight and space taken up would be too large to be practical. The answer to this problem is to use fewer batteries with a buck-boost converter to bring up DC voltage to the suitable and useful level.

Buck, boost, and buck-boost converter are DC to DC converter which could be used to condition the voltage to a suitable level for EV application. Using these converters, the lifespan of the battery can be longer as well.

2.4.1 The Buck Converter

The buck converter is a DC to DC converter circuitry where its DC output voltage is lower than the DC input voltage. The DC input voltage can be taken from rectified AC source or from any DC source including battery. Figure

2.10 shows the rectified AC input source where Figure 2.11 shows DC input source.

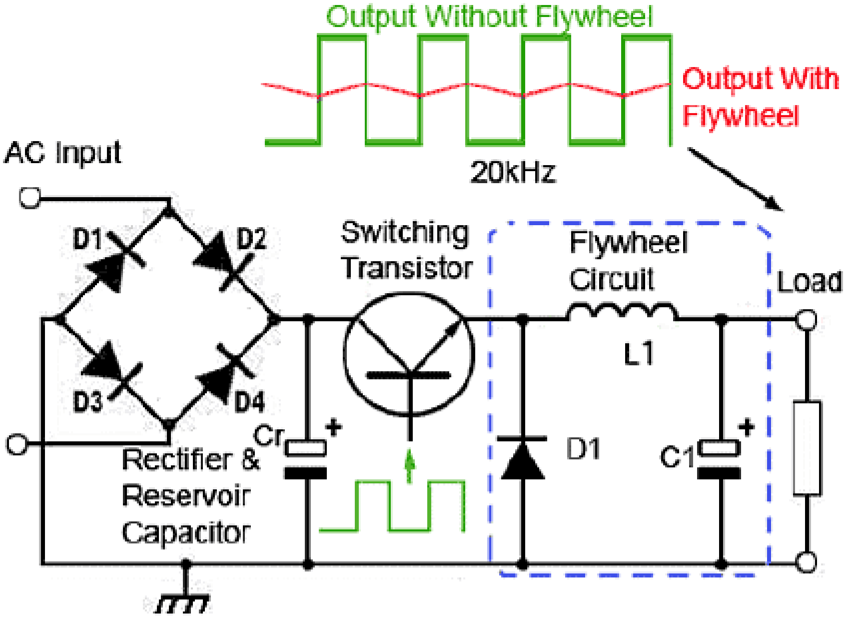


Figure 2.10: Buck converter with rectified AC input source (Switched mode power supplies, 2007)

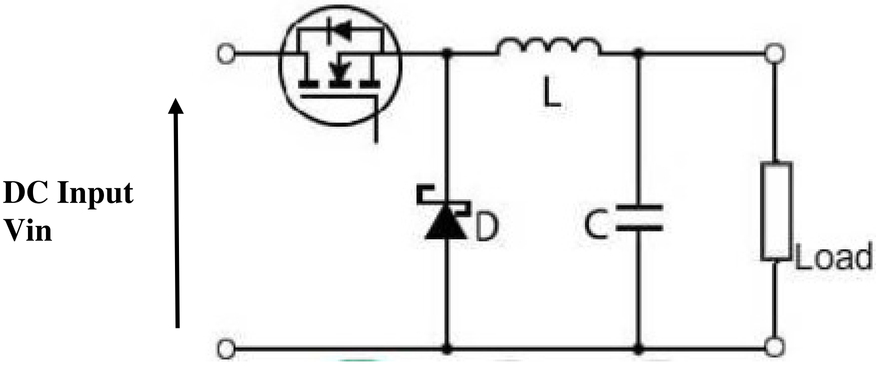


Figure 2.11: Buck converter with DC input source (Switched mode power supplies, 2007)

Generally, a buck converter will have an inductor to store energy during the switching transistor on stage and release energy when switching transistor in off stage. This will ensure continuous current flow to the load during transistor off stage. It is known as Continuous Current or Conduction Mode, CCM. The Buck Converter also has a capacitor at the output stage and it should be large enough to maintain a constant output voltage. In other words, the inductor will determine the CCM and the capacitor will determine the output voltage ripple. Ripple can be reduced by increasing switching frequency, increasing inductor size or increasing capacitor size.

The switching transistor is turning on and off between the input and output continuously at high frequency as shown in Figure 2.10 and Figure 2.11. To be in a continuous conduction mode (CCM), the circuit used the energy stored by the inductor L previously (during the on periods) to supply to the load during the off periods continuously. This type of circuit operation sometimes is also known as a Flywheel Circuit.

The switching transistor could be Bipolar Junction Transistor (BJT) or Metal–Oxide–Semiconductor Field-Effect Transistor (MOSFET). The choice of the transistor is determined by the current, voltage, switching speed and cost considerations. MOSFET will have higher efficiency and can operate at higher frequency.

2.4.1.1 AC or DC Input Source

The buck converter is a DC to DC converter where the DC input voltage source can be coming from rectified AC power or from any DC source such as a battery. For electric vehicle application, the battery will be used as the DC input source where the AC source is used to power on the charger to charge the battery.

Battery voltage applied to the buck converter is transferred to a regulated DC power supply in a much more efficient way via a chopper circuit driven by a high-frequency pulse width modulator.

2.4.1.2 Buck Converter Operation

A buck converter circuit consists of a switching transistor, diode D1, inductor L1 and capacitor C1 (known as flywheel circuit) as shown in Figure 2.10. When the switching transistor is on (refer to Figure 2.12), current is flowing through the load via the inductor L1. By the characteristic of any inductor, it will oppose sudden changes in current flow and also acts as a storage device to store energy. This will prevent the switching transistor output from increasing immediately to its peak value while charging (stored energy) ups the inductor. This stored energy will be used later on to discharge back into the circuitry as a back e.m.f. and current to the load.

Transistor Switch ‘on’ Period

In Figure 2.12, when the switching transistor is on, current will flow to the load. Initially, the current flow to the load and it will also charge up the inductor L1 and capacitor C1 gradually during the ‘on’ period. Energy will store in inductor L1 during this on period. During this on period, there will be a large positive voltage applied to the cathode of the diode D1 which the diode will be reverse biased and therefore the diode is off so no current flow through the diode.

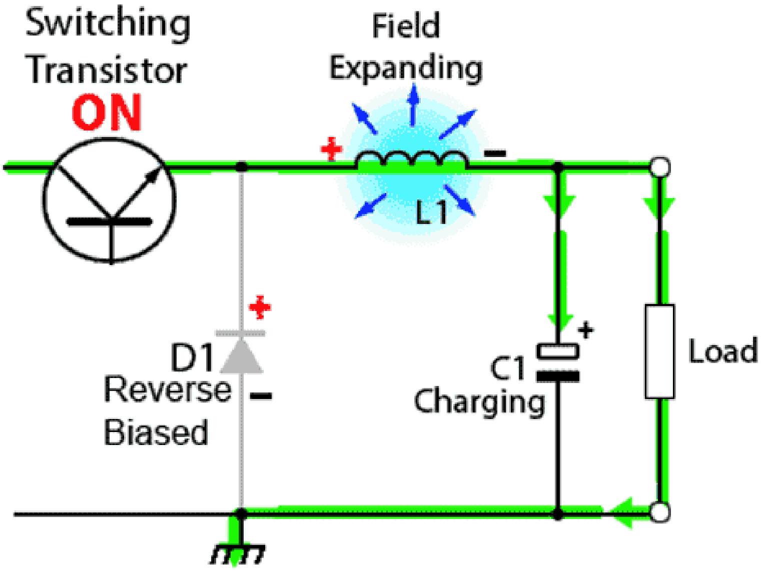


Figure 2.12: Switching transistor at on stage.

Transistor Switch ‘off’ Period

When the transistor is off as shown in Figure 2.13, the energy stored in the inductor as magnetic field around L1 is released back into the circuit. The voltage across the inductor is now in reverse polarity to the voltage across L1 during the ‘on’ period. This stored energy (come from collapsing magnetic field at the inductor) will release as current to keep current flowing (CCM) to the load.

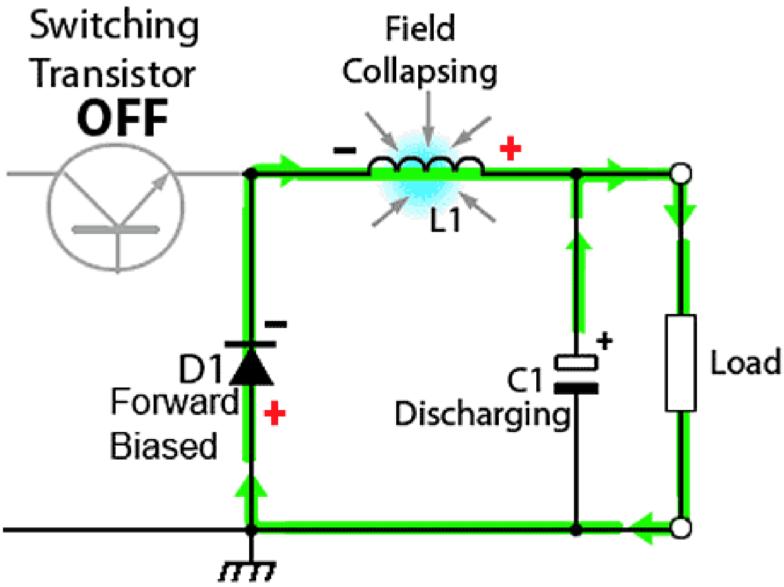


Figure 2.13: Switching transistor at off stage

The voltage (back emf) created from L1 due to the stored energy during on stage is now discharged causing the current to flow to the load via diode D1 as the diode D1 is now forward biased. Once the inductor L1 begin discharging its stored energy, the load voltage will start falling. At this point of time, the stored charge in C1 will take over as the main source, supplying the current to the load. It will keep the current flowing to the load until the next 'on' period begins. The overall effect due to the smoothing capacitor is to maintain the voltage to the load with a small ripple.

$V_{OUT} = V_{IN}$ x [On time of switching waveform (t_{ON}) / periodic time of switching waveform (T)]

or:

$\mathbf{V_{OUT} = V_{IN} \times D}$

If the circuit has a 50% duty cycle D, the output V_{OUT} from the buck Converter circuit will be V_{IN} x (0.5/1) or half of V_{IN}. However, if the duty cycle is varied, the output voltage can be any value between approximately 0V and $V_{IN.}$

2.4.1.3 Buck Converter Basics Summary (Admin, 2015):

1. The buck converter is a step-down converter ($V_{OUT} < V_{IN}$). The output voltage is controlled by adjusting the duty cycle.
2. It can operate in two modes: CCM or DCM. The minimum value of the inductor is determined by the CCM/DCM boundary, ripple voltage, or ac losses in the inductor and the filter capacitor.
3. The peak-to-peak value of the inductor ripple current i_L is independent of the dc load current for CCM (Admin, 2015).
4. The peak-to-peak values of the current through the filter capacitor i_C is relatively low and is equal to the peak-to-peak inductor ripple current i_L (Admin, 2015).
5. If the smoothing capacitor is high enough, the output ripple voltage is determined only by the Equivalent Series Resistance (ESR) of the smoothing capacitor and is independent of the capacitance of the filter capacitor (Admin, 2015).
6. The disadvantage of the buck converter is pulsating input current. This can be improved by using an LC filter placed at the converter input to get a non-pulsating input current waveform.

7. The corner frequency of the output filter, $f_O = 1/(2\pi LC)$, is independent of the load resistance (Admin, 2015).
8. The size of the inductor will determine whether it operates in Continuous conduction mode (CCM) or Discontinuous conduction mode (DCM). DCM is mostly used in low power converter circuits only.
9. Continuous conduction mode (CCM) means the current through inductor never goes to zero that is inductor is not fully discharged before the start of the switching cycle.
10. Discontinuous conduction mode (DCM) means the current through inductor must go to zero that is inductor is discharged completely at the end of switching cycle.

2.4.2 Boost Converter

A boost converter is a DC to DC converter that provides output voltage higher than the input voltage. Sometimes it is also known as a step-up converter. The boost converter is used for the purpose where the available DC supply voltage is not sufficient to drive the circuit; boost converter is used to bring up the voltage to the acceptable level. For example, if the motors for EV application require a much higher voltages (could be in the region of 144 to 500 volt DC) than could be supplied by a single battery alone or even if a battery bank were used, it will not be practical as the weight and size taken up too big space. The solution to the mentioned scenario is to use fewer batteries working together with boost converter to bring up the DC voltage to the required level. On the other hand, all batteries being big or small will discharge at a different rate which causes the output voltage varies. At some point of time, the battery output voltage will not be sufficient to power the circuitry being supplied, it will require a boost converter to bring the voltage to a suitable level. Using a boost converter for this application will also extend the lifespan of the battery.

The DC input to a boost converter can be taken from batteries, rectified AC power, solar panels, fuel cells, dynamos or DC generators but the majority of the application are for battery powered applications where they have a space limitation. Without boost converter, to achieve a higher voltage, more batteries will be required, more batteries mean more space. This is true, especially for electric vehicle application.

The boost converter is different from the buck converter. Output voltage of a boost converter is equal to, or greater than its input voltage. However, it is important to remember that, due power conservation, for a given power rating [Power (P) = Voltage (V) x Current (I)], if the output voltage is increased, the available output current must decrease.

Figure 2.14 shows the basic circuit of a boost converter. The switching transistor could be Bipolar Junction Transistor (BJT) or Metal–Oxide–Semiconductor Field-Effect Transistor (MOSFET). The choice of the transistor is determined by the current, voltage, switching speed and cost considerations. MOSFET will have higher efficiency and can operate at higher frequency. The other components will be the same as those used in the buck converter as shown in Figure 2.12 (page 34), except that their positions have been rearranged.

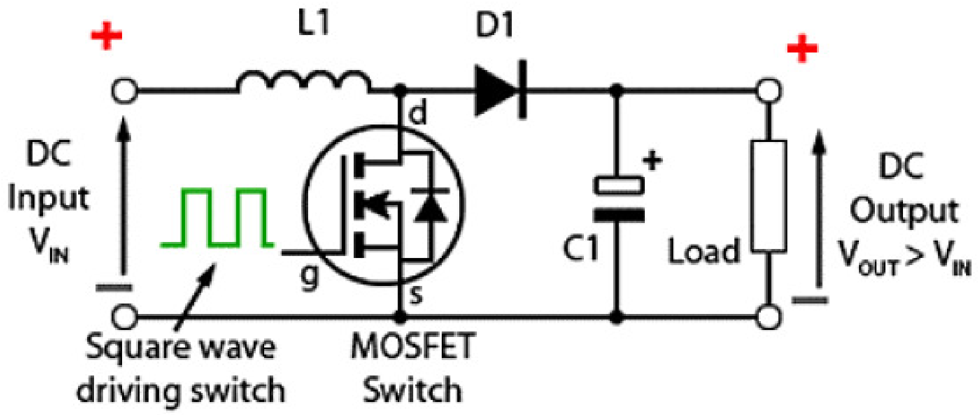


Figure 2.14: Basic Boost Converter Circuit

2.4.2.1 Boost Converter Operation

Figure 2.15 illustrates how the boost converter circuit operation. When the switching transistor is conducting, the right-hand side of inductor L1 will tie to the negative supply terminals. A current will flows through inductor L1. This current will charge up the inductor, which stores energy in its magnetic field. There is no current flowing in the remainder of the circuit as the combination of diode D1, capacitor C1 and the load represent much higher impedance than the path directly through the heavily conducting MOSFET.

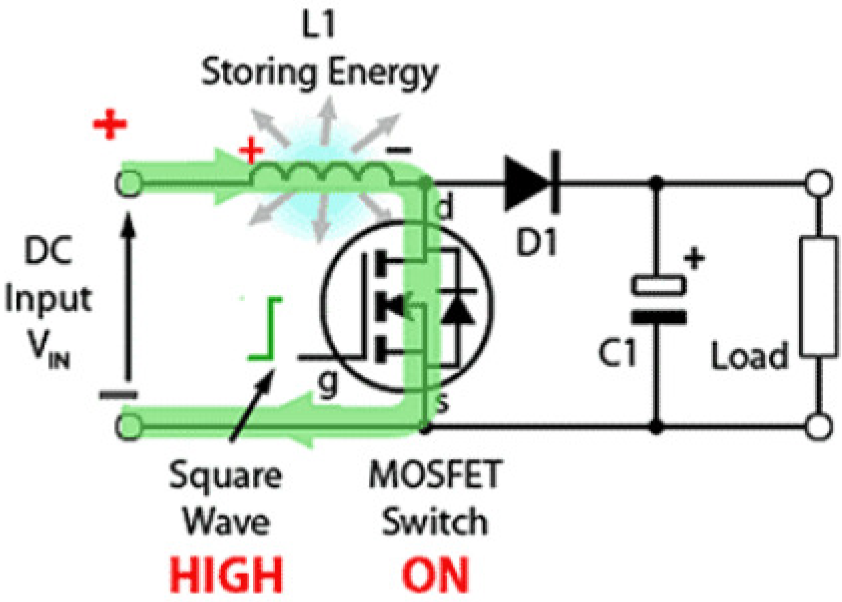


Figure 2.15: Boost Converter Operation when switching transistor at ON stage

Figure 2.16 shows the current path when the switching transistor is off. When the MOSFET is off, the inductor L1 trying to maintain the current by releasing its energy which produces a voltage (back e.m.f.). Take note that the polarity is now opposite to the voltage across L1 during previous on period. As a resultant, the two voltages will be added up namely the supply voltage V_{IN} and the back e.m.f. (V_L) across L1 because they are in series with each other. Series means the voltage across the load will be the addition of these two voltages.

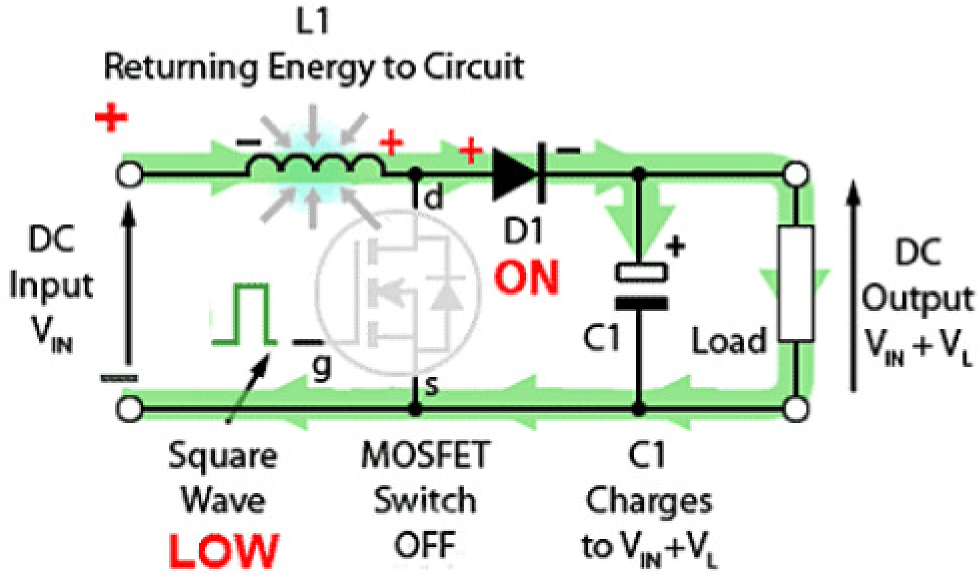


Figure 2.16: Current path with switching transistor at OFF stage

This higher voltage (V_{IN} +V_L) with diode D1 is forward bias is applied to the load (no current path through the MOSFET as it is off). The resulting current through diode D1 charges up C1 to V_{IN} +V_L minus the small forward voltage drop across D1. This is also the voltage supply to the load.

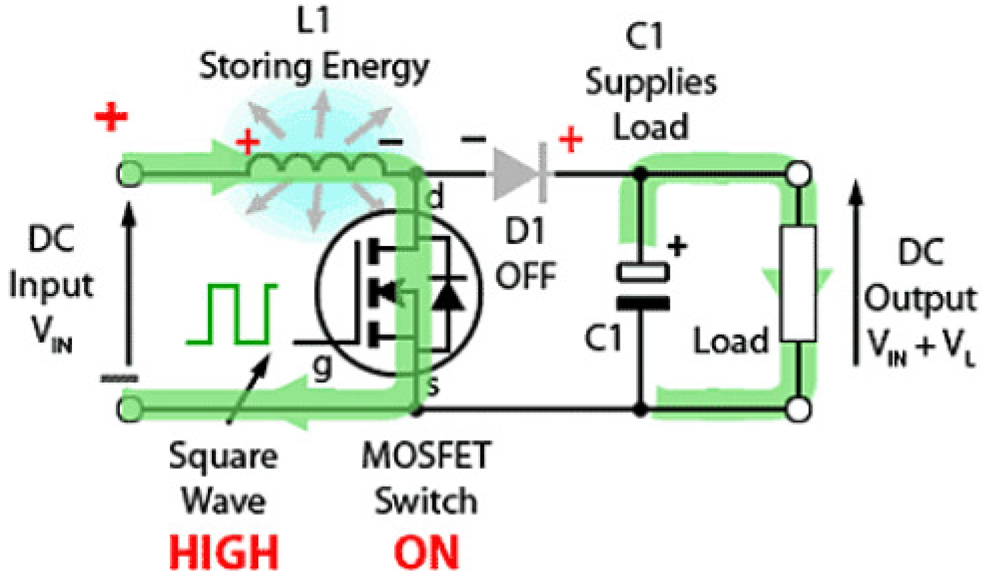


Figure 2.17: Current path with switching transistor at ON stage

Figure 2.17 shows the circuit operation when the switching transistor is turning on. Whenever the transistor conducts, diode D1 is in revise bias mode, due to the charge on capacitor C1 (more positive). Hence, Diode D1 is turned off so the output of the circuit is isolated from the input; at this point of time, the load is supported by capacitor C1. Capacitor C1 continuously supplied with V_{IN} +V_L from its stored energy. Part of the stored energy or charge at capacitor C1 will be discharged through the load during this period but it will be recharged each time the switching transistor is switched off. This will maintain a constant output voltage across the load.

The DC output voltage V_{OUT} can be obtained by using the formula:

$$\mathbf{V_{OUT} = V_{IN} / (1-D)}$$

$$\mathbf{D = t_{ON} / (t_{ON} + t_{OFF})}$$

Example:

Switching period = 5μs

Input voltage = 10V

Duty Cycle D = 50%

V_{OUT} = 10 / (1- 0.5) = 10/0.5 = 20V (minus output diode voltage drop)

By controlling the duty cycle the output voltage will change. In order words, if the duty cycle D adjusted from 0.5 to 0.99 than the output voltage will be:

V_{OUT} = 10 / (1- 0.99) = 10/0.01 = 1,000V

2.4.2.2 Boost Converter IC - 2014 Market Analysis and Overview (Friebe, 2016)

The boost converter is a very popular application for the industry, therefore, ready IC is easily available in the market. The comprehensive market survey was carried out by DCDCselector.com. Their market analysis is presented in Figure 2.18 to Figure 2.20.

Figure 2.18 shows the manufacturer name (Y- axis) and the number of boost converter product (X – axis). Figure 2.19 shows market overview on DC to DC boost converter IC on the number of available products per maximum output voltage and Figure 2.20 shows the number of available products per output current segment.

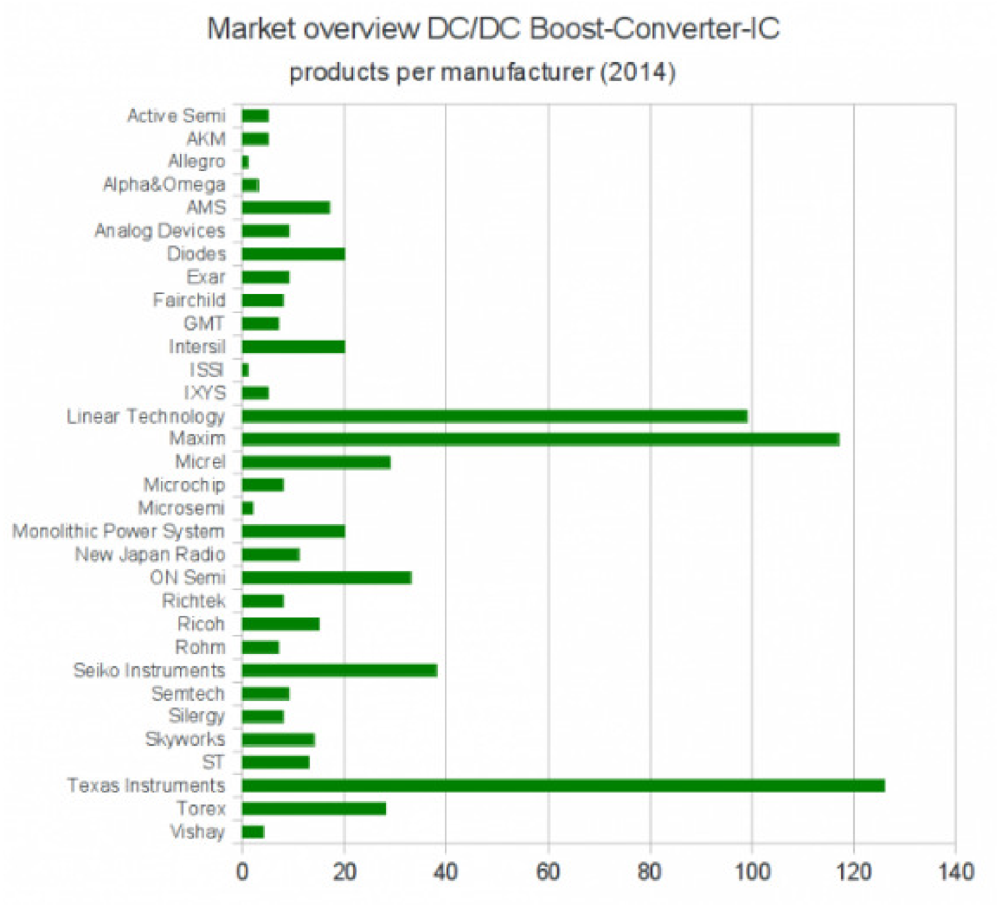


Figure 2.18: Market overview on DC to DC boost converter IC products per manufacturer (2014) (Friebe, 2016).

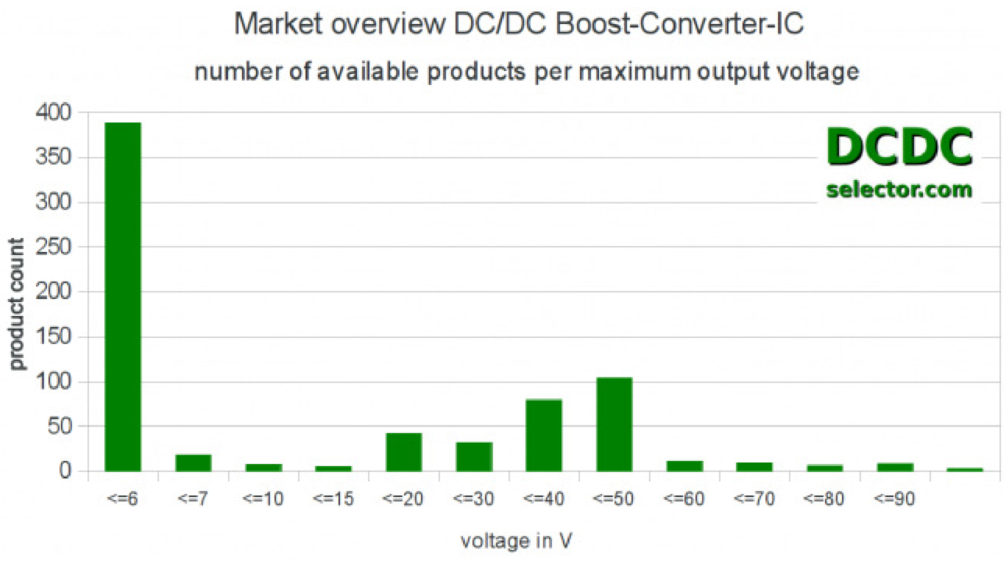


Figure 2.19: Market overview on DC to DC boost converter IC - Number of available products per maximum output voltage (Friebe, 2016).

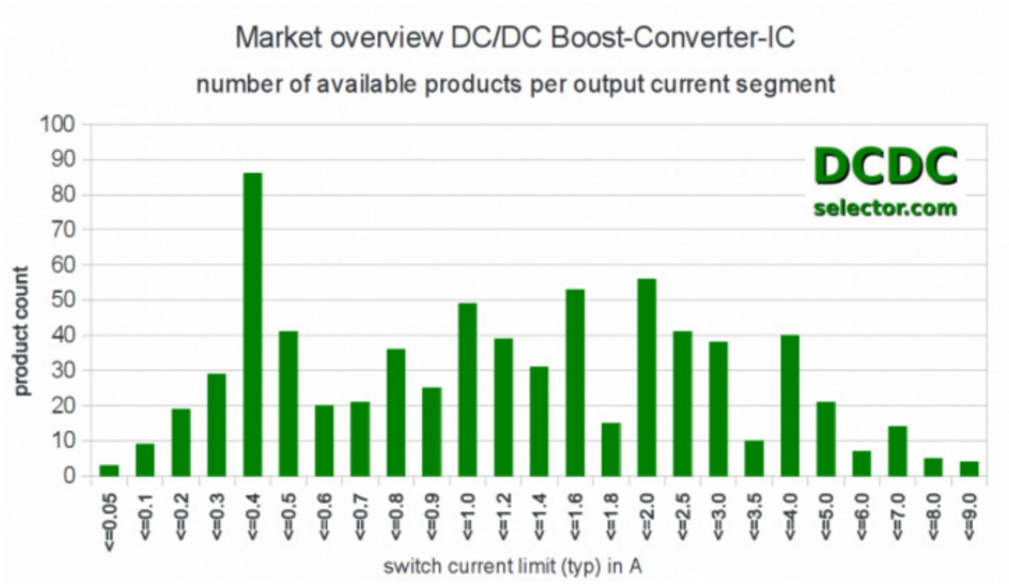


Figure 2.20: Number of available products per output current segment

From the survey, it is observed that there are many IC manufacturers producing boost converter IC. This also implies that there are many industrial applications which need the boost converter IC. However, very few manufacturers produce the converter with output voltage above 90V and above 9A output current. Hence they are not suitable for EV application. Most of the EV needs at least 144V output.

2.4.3 Buck-Boost Converters

A Buck-Boost converter is a DC to DC converter that combines the principles of the buck converter and the boost converter in a single circuit to provide a regulated DC output from either an AC or a DC input. There are many applications on buck-boost converter, especially battery-powered circuitry. Battery powered circuitry will have high voltage fluctuation. A 12V battery when is fully charged the terminal voltage can be as high as 13.5V. In this case, a buck converter will bring down and regulate the voltage is required. However, as the charge diminishes the input voltage falls below the level required by the circuit. In this case, a boost converter to bring up and regulate the voltage level is required. By combining these two converters it becomes buck-boost converter which can cope with a wide range of input voltages both higher and lower and yet still able to maintain and regulate at fix voltage required by the circuit.

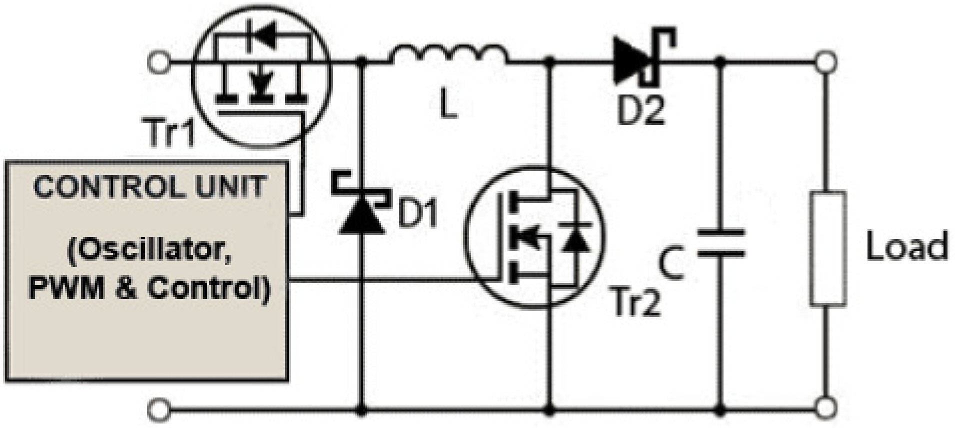


Figure 2.21: Buck and Boost Converters Combined

Beside the common components used in the buck-boost converter circuits, a control unit are added to the converter to sense the input voltages to determine whether the converter should operate as a buck or boost converter (see Figure 2.21). The operation of the buck-boost converter can be explained using Figure 2.22 to 2.25.

2.4.3.1 Operate as a Buck Converter

- To operate as a buck converter: Transistor Tr2 is off. The output voltage is control by switching transistor Tr1. Transistor Tr1 is switching on and off at a high-frequency. The switching is controlled by the PWM control unit.

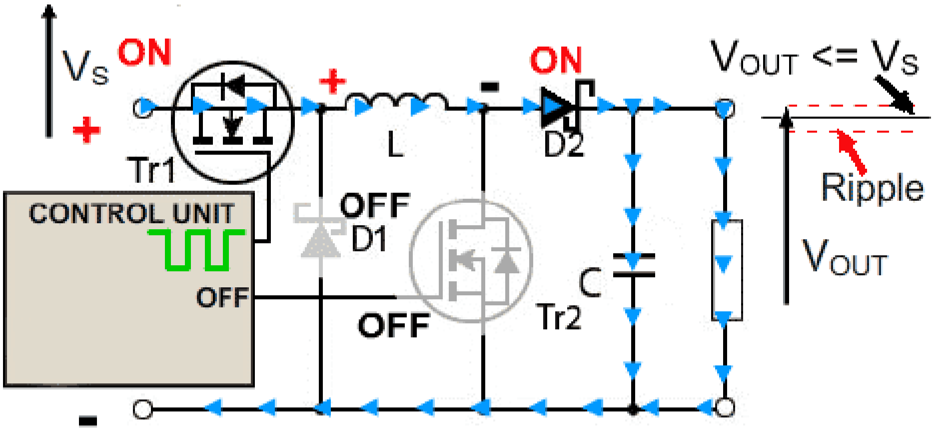


Figure 2.22: Operate as a Buck Converter during Tr1 'on' Period

Figure 2.22: shows that the circuit operates as Buck Converter. When it operate as buck converter transistor Tr2 is off. Now the switching transistor Tr1 is turning on and off at a high-frequency wave driven by the PWM control unit. When the transistor of Tr1 is turn on, diode D2 is turned on as it is forward biased causing current flows to the load at the same time charging up the capacitor C via inductor L. Inductor L will store its energy as a magnetic field.

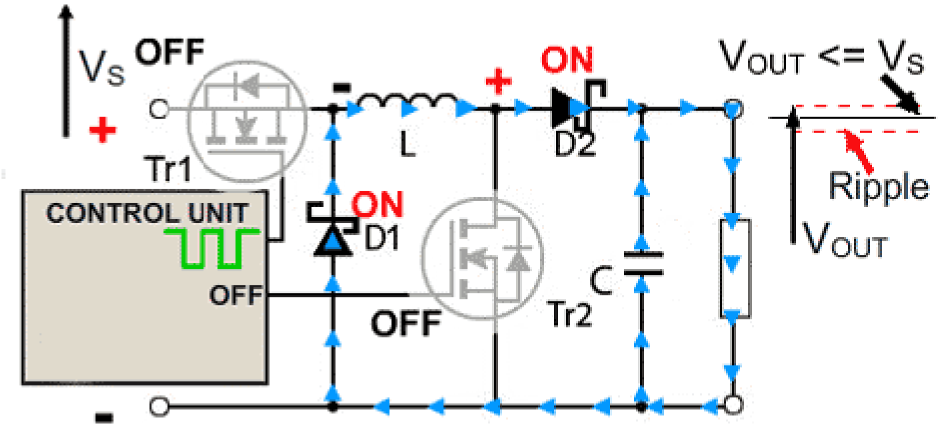


Figure 2.23: Operate as a Buck Converter during Tr1 ‘off’ Period

Figure 2.23 shows the direction of current flow when the circuits operate as a buck converter and when transistor Tr1 is off. Inductor L1 will provide the current to the load as its magnetic field is collapsing generating the back e.m.f. The collapsed magnetic field reverses the polarity of the voltage across L causing diode D1 and D2 to turn on. As it is forward bias and complete circuit path current flows through D2 to the load and return to inductor L1 via D1.

Discharge from inductor L will cause the current to decrease but the charges accumulated in capacitor C during the on period of Tr1 will also add up to support the load. This action will maintain the output voltage Vout constant with a small ripple.

2.4.3.2 Operate as a Boost Converter

- To operate as boost converter: Transistor Tr1 is on. The output voltage now is controlled by the switching transistor Tr2. Tr2 is turning on and off by the high-frequency square wave controlled by the control unit as shown in Figure 2.24.

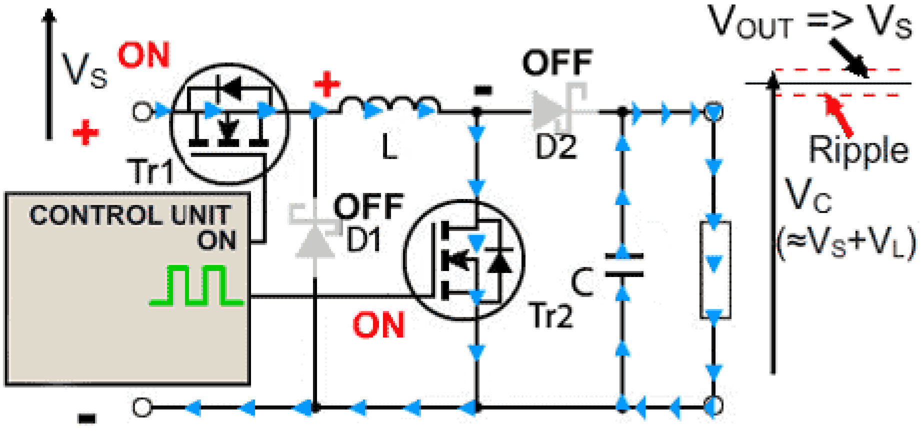


Figure 2.24: Operate as a Boost Converter during Tr2 ‘on’ Period

In Boost Converter mode, transistor Tr1 is continuously turned on. The high-frequency pulse width modulated square wave is applied to the Tr2 gate to control the output voltage. When transistor Tr2 is turned on or conducting, the input current flows via the inductor L and Tr2 than back to the supply negative terminal charging up the magnetic field of inductor L. Under this is situation, diode D2 cannot conduct due to its anode is being held at ground potential by the heavily conducting Tr2.

For the duration of the on cycle, the external load is being powered totally by the charge stored on the capacitor C, built up from previous cycles. The gradual discharge of C during the on period (and its subsequent recharging) contributed for the amount of high-frequency ripple on the output voltage. The output voltage at this stage is approximately $V_S + V_L$.

Transistor Tr2 Off Stage

At the beginning of the off period of Tr2, inductor L is charged and energy is stored. The capacitor C is partially discharged. The inductor L now produces a voltage (back e.m.f.) where its value depends on the rate of change of current as Tr2 switches off and on and the value of inductance of the coil possesses; hence the back e.m.f depending on the design of the circuit can be vary over a wide range of voltage as shown in Figure 2.25.

Take note that at this moment the polarity of the voltage across inductor L is reversed. Therefore this voltage (V_L) is added to the input voltage V_S giving an output voltage that is at least equal or greater than the input voltage. Diode D2 at this moment is forward biased so that the circuit current could supplies to the load, and at the same time recharging the capacitor to $V_S + V_L$ ready for the next on period of Tr2.

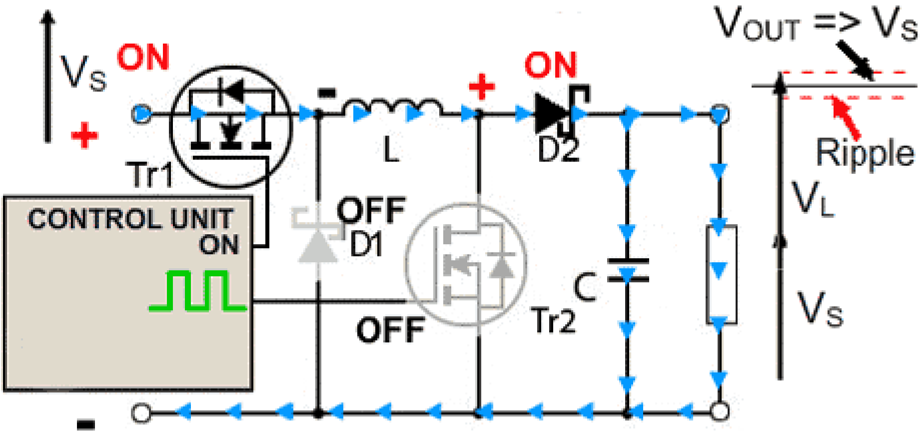


Figure 2.25: Operate as a Boost Converter during Tr2 ‘off’ Period

Therefore, for buck-boost converter the output voltage could be higher than the input voltage.

2.4.3.3 Buck-Boost Converter IC - 2014 market analysis and overview (Friebe, 2016)

DCDCselector.com has conducted a comprehensive market survey on Buck-Boost Converter IC for 2014. Here are some of the findings:

- Out of 97 buck-boost converter IC surveyed all feature internal switch with MOSFET technology and have a dedicated buck-boost topology.

- North America region is using the term as a buck-boost regulator (or step-up-down regulator) where another region is using it as converter.

- Looking into the Google index, the term buck-boost converter is about 10 times more searched than a buck-boost regulator.

DCDCselector.com also found that the DC/DC buck-boost converter segment is the smallest from all available Selectors at their parametric search. The majority of converters are optimized for single Li-Ion battery applications. Internal high-side and low-side switch, low external component count, internal diode and single inductor operation result in a compact circuit and very small total solution size. Figure 2.26 to 2.28 provide some marketing overview on the survey.

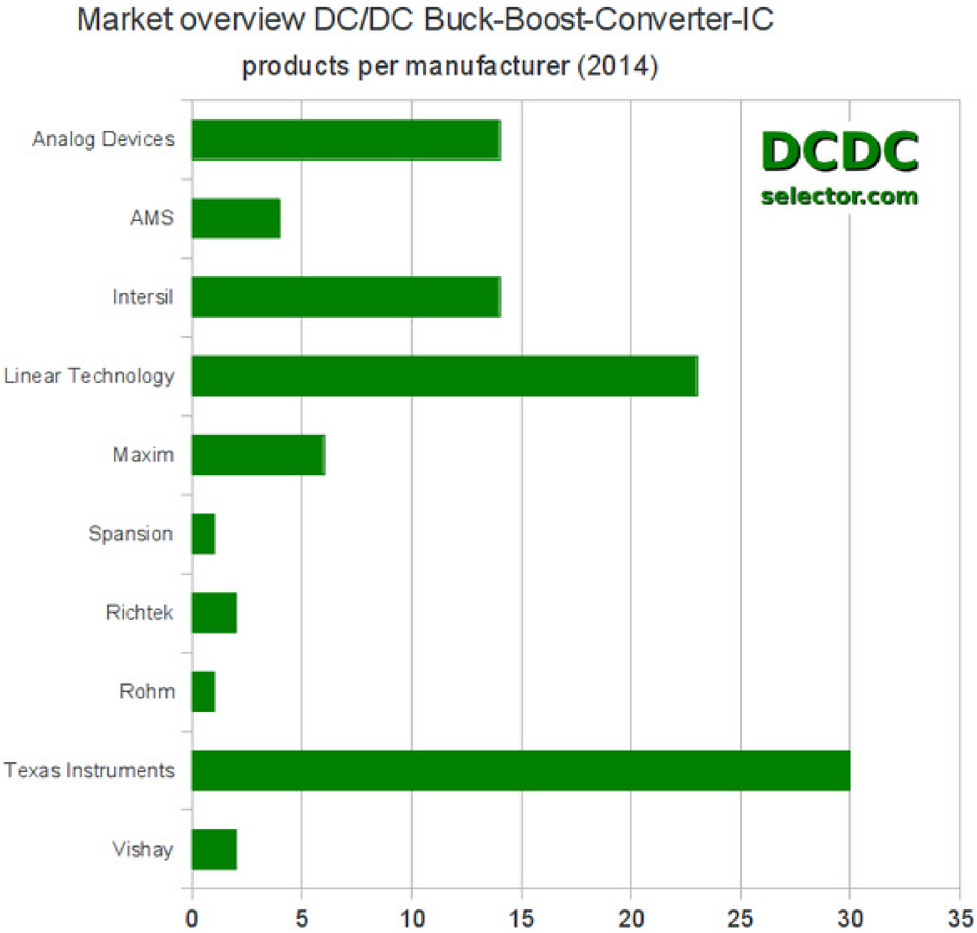


Figure 2.26: Market overview DC/DC Buck-Boost-Converter-IC on products per manufacturer

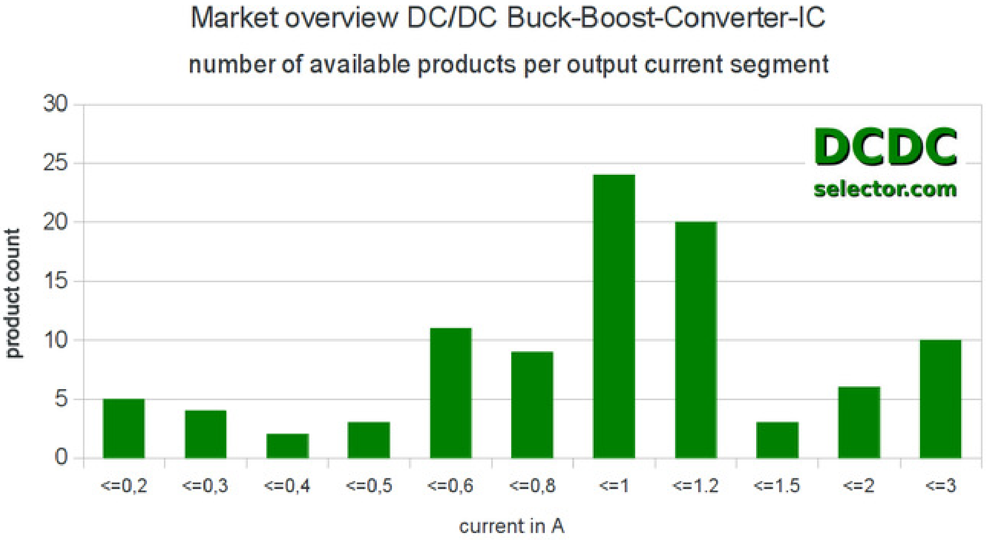


Figure 2.27: Market overview DC/DC Buck-Boost-Converter-IC on number of available products per output current

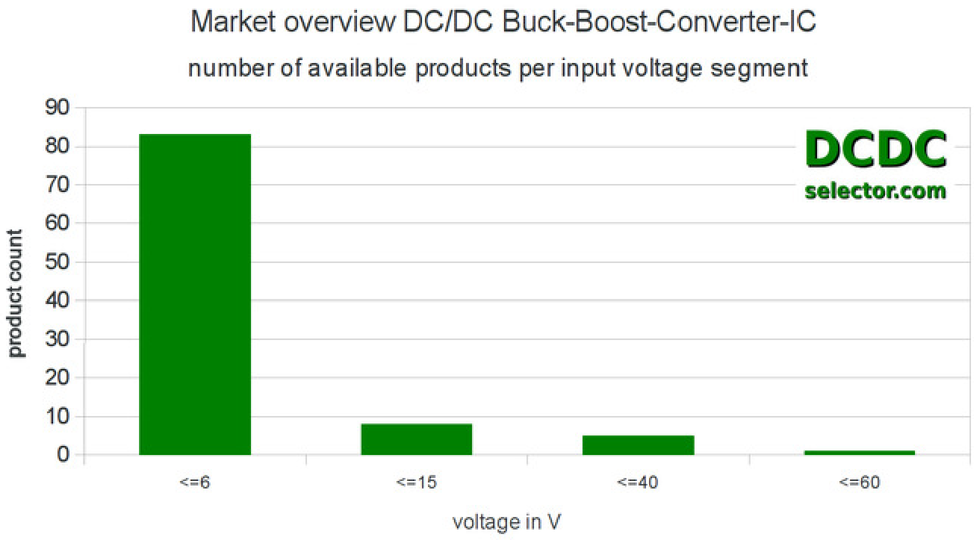


Figure 2.28: Market overview DC/DC Buck-Boost-Converter-IC on number of available products per input voltage segment

From the finding, for EV application it will be difficult to use a standard IC to design buck-boost converter as EV required higher voltage and current than the standard IC can handle.

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CHAPTER 3

LEAD-ACID BATTERY MODELLING AND SIMULATION

3.1 Why battery simulation is important?

Battery modeling and simulation included in this report is to provide the basic understanding of modeling and simulation of a battery. Modeling and simulation are an important part of the EV control design cycle. Since the selected battery for this project is the lead-acid type, therefore, the discussion is focus on the lead-acid type of battery.

EV circuitry is all about battery selection and how to condition the battery to achieve longer lifespan through cell balancing, detecting of battery failure than bypass it so that the EV can still continue functioning, maintaining and regulating the output voltage to the motor for optimum performance under voltage fluctuation from battery cells and so on. All the factors are involved in the understanding on the characteristic battery. To design a good EV control system, the designer will require understanding the behavior of the battery intended to use. Moreover, all design before putting into production will require extensive testing under various field conditions. To speed up the process battery modeling and simulation will play its part.

3.2 Evaluation on Lead Acid Battery Modelling and Simulation using Simscape.

Charging and discharging a battery is taking a long time and it is very time-consuming to set up the test. In many cases, the designer cannot afford to spend this time. To speed up the test on the design of a battery powered system and to study the behavior of that system before it being built, modeled battery will be used. The available simulation method by Simscape (Simscape is building on Matlab platform) could provide drive cycle simulation accuracy of battery voltage within 3.2%, and simulation speed of up to10,000 times real-time on a typical PC (Jackey, 2007). This section will be the review on battery model and simulation based on the standard library provided by Simscape and the validation done by Robyn A. Jackey, The MathWorks, Inc. (A Simple, Effective Lead-Acid Battery Modeling Process for Electrical System Component Selection, Robyn A. Jackey, The MathWorks, Inc.).

Battery simulation and controls are an important component for Electric Vehicle. Battery modeling has become an indispensable tool for the design of battery-powered systems. Their usage includes battery characterization, state-of-charge (SOC) and state-of-health (SOH) estimation, algorithm development, system-level optimization, and real-time simulation for battery management system design.

Battery models based on equivalent circuits are preferred for system-level development and controls applications due to their relative simplicity. The simplest electric model consists of an ideal voltage source in series with an internal resistance and parallel RC circuits as shown in Figure 3.1.

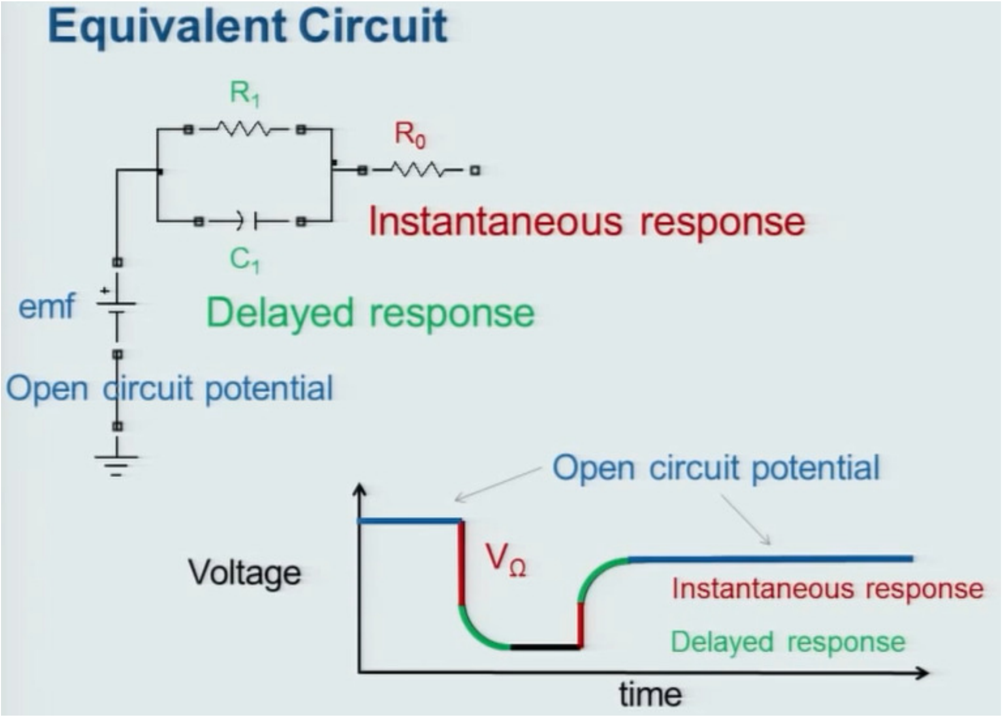


Figure 3.1: Simple Battery Equivalent Circuit

A more detail battery equivalent circuit is shown in Figure 3.2. The structure of the battery circuitry is a simple nonlinear equivalent circuit, which don’t really model directly how the lead-acid internal chemistry work; the equivalent circuitry empirically approximated the behavior looking at the battery terminals (Jackey, 2007). Their structure consisted of two main parts: the main branch which approximated the battery dynamics under most conditions, and a parasitic branch which accounted for the battery behavior at the end of a charge (Jackey, 2007).

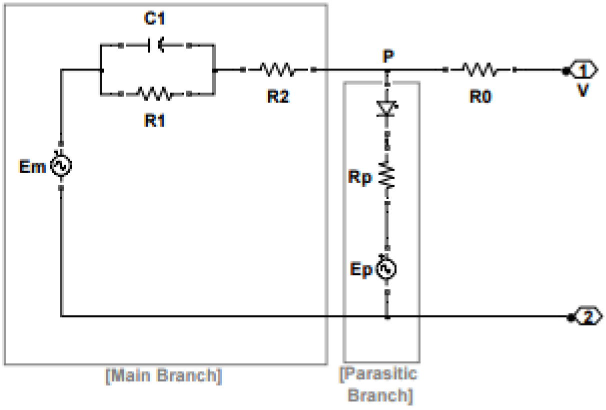


Figure 3.2: More Detail Battery Equivalent Circuit (Jackey, 2007)

According to Robyn A. Jackey (2007), the MathWorks, Inc., the lead-acid battery can be modeled as per Figure 3.2 with the equations described by equation (1) to (11). This simulation method could provide drive cycle simulation accuracy of battery voltage within 3.2%, and simulation speed of up to10,000 times real-time on a typical PC (Jackey, 2007). The modeling and simulation are already available in the library of Simscape under the Matlab platform. Explanation in this section is the summary on the battery simulation by Simscape under Matlab platform.

3.2.1 Main Branch Voltage

An internal voltage source also known as emf, or an open-circuit voltage of one cell is given by the equation (1). The value, when the battery is fully charged it is assumed to be constant but the value will vary with temperature and its state-of-charge (SOC).

$$E_m = E_{m0} - K_E(273+\theta)(1-SOC) \quad (1)$$

where:

E_m was the open-circuit voltage (EMF) in volts
E_{m0} was the open-circuit voltage at full charge in volts
K_E was a constant in volts / °C
θ was electrolyte temperature in °C
SOC was battery state of charge

R_0 is a resistance seen at the battery terminals, and it is assumed constant at all temperatures, and varied with the State-of-Charge.

$$R_0 = R_{00}\left[1 + A_0(1-SOC)\right] \quad (2)$$

where:

R_0 was a resistance in Ohms
R_{00} was the value of R_0 at SOC=1 in Ohms
A_0 was a constant
SOC was battery state of charge

R_1 is a resistance in the main branch of the battery. Its resistance varied with the depth of charge, a measure of the battery's charge adjusted for the discharge current. The resistance increased exponentially as the battery became exhausted during a discharge.

$$R_1 = -R_{10}\ln(DOC) \quad (3)$$

where:

R_1 was a main branch resistance in Ohms
R_{10} was a constant in Ohms
DOC was battery depth of charge

C_1 is a capacitance (time delay) in the main branch. The time constant modeled a voltage delay when battery current changed.

$$C_1 = \tau_1 / R_1 \qquad (4)$$

where:

C_1 was a main branch capacitance in Farads
τ_1 was a main branch time constant in seconds
R_1 was a main branch resistance in Ohms

R_2 is the main branch resistance where the resistance increased exponentially as the battery state-of-charge increased. The resistance also varied with the current flowing through the main branch. The resistance primarily affected the battery during charging. The resistance became relatively insignificant for discharge currents.

$$R_2 = R_{20} \frac{\exp[A_{21}(1 - SOC)]}{1 + \exp(A_{22}\, I_m / I *)} \qquad (5)$$

where:

R_2 was a main branch resistance in Ohms
R_{20} was a constant in Ohms
A_{21} was a constant
A_{22} was a constant
E_m was the open-circuit voltage (EMF) in volts
SOC was battery state of charge
I_m was the main branch current in Amps
I^* was the a nominal battery current in Amps

3.2.2 Parasitic Branch Current

I_P is a parasitic loss current which occurred when the battery was being charged. It is dependent on the temperature of the electrolyte and its voltage at the parasitic branch. This current was very small under most of the conditions, except during charging at high SOC. The unit of the constant Gpo is seconds where its magnitude is in the order of 10^{-12} seconds. This value is very small.

$$I_p = V_{PN} G_{p0} \exp\left(\frac{V_{PN}/(\tau_p s + 1)}{V_{P0}} + A_p\left(1 - \frac{\theta}{\theta_f}\right)\right) \qquad (6)$$

where:

I_p *was the current loss in the parasitic branch*
V_{PN} *was the voltage at the parasitic branch*
G_{p0} *was a constant in seconds*
τ_p *was a parasitic branch time constant in seconds*
V_{P0} *was a constant in volts*
A_p *was a constant*
θ *was electrolyte temperature in °C*
θ_f *was electrolyte freezing temperature in °C*

3.2.3 Extracted Charge

Q_e tracked the amount of charge extracted from the battery. The charge extracted from the battery was a simple integration of the current flowing into or out of the main branch. The initial value of extracted charge was necessary for simulation purposes.

$$Q_e(t) = Q_{e\_init} + \int_0^t -I_m(\tau)d\tau \qquad (7)$$

where:

Q_e *was the extracted charge in Amp-seconds*
Q_{e_int} *was the initial extracted charge in Amp-seconds*
I_m *was the main branch current in Amps*
τ *was an integration time variable*
t *was the simulation time in seconds*

3.2.4 Total Capacity

C(I,θ) is the measurement of the capacity of the battery based on discharging current and the temperature of the electrolyte. The capacity only depends on the current for discharge. During charging, the discharge current is assumed to be zero for the total capacity calculation purposes. Vehicle batteries are tested with a wide ambient temperature range. Test data from the laboratory shows that the battery capacity starts to diminish at temperatures above 60°C across the entire test current ranges. Parameter K_t from the look-up table (LUT) is empirically used to model the effect of temperature dependence of battery capacity.

$$C(I,\theta)=\frac{K_c C_{o*} K_t}{1+(K_c-1)(I/I*)^{\delta}}, K_t = LUT(\theta) \qquad (8)$$

where:

K_c was a constant
C_0 was the no-load capacity at 0°C in Amp-seconds*
K_t was a temperature dependent look-up table
θ was electrolyte temperature in °C
I was the discharge current in Amps
I was the a nominal battery current in Amps*
δ was a constant

3.2.5 State-of-Charge and Depth of Charge

State-of-Charge (SOC) and Depth of Charge (DOC) are calculated as a ratio of available charge to the battery’s total capacity. SOC is a measurement of the ratio of charge remaining in the battery where the depth of charge is a measurement of the ratio of usable charge remaining, given the average discharge current. Larger discharge currents will cause the battery’s charge to expire more prematurely, therefore DOC was always less than or equal to SOC.

$$SOC = 1 - \frac{Q_e}{C(0,\theta)} \quad , \quad DOC = 1 - \frac{Q_e}{C(I_{avg},\theta)} \qquad (9)$$

where:

SOC was battery state of charge
DOC was battery depth of charge
Q_e was the battery's charge in Amp-seconds
C was the battery's capacity in Amp-seconds
θ was electrolyte temperature in °C
I_{avg} was the mean discharge current in Amps

3.2.6 Estimate of Average Current

The battery average current I_{avg} can be estimated to be as follows:

$$I_{avg} = \frac{I_m}{(\tau_1 s + 1)} \qquad (10)$$

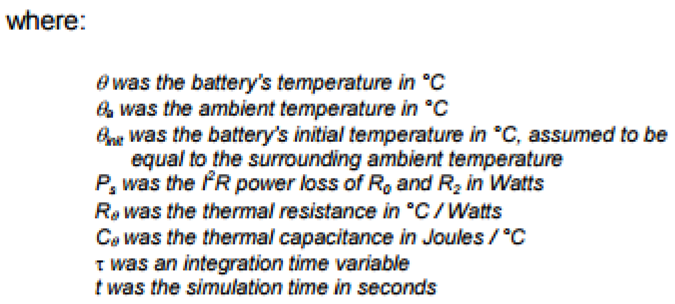
where:

I_{avg} was the mean discharge current in Amps
I_m was the main branch current in Amps
τ_1 was a main branch time constant in seconds

3.2.7 Electrolyte Temperature

The “Thermal Model” modeling block is used to track the battery’s electrolyte temperature. Equation (11) is used to model the estimated change in electrolyte temperature which can cause by internal resistance losses or ambient temperature. The thermal model is usually a first order differential equation, with parameters for both thermal resistance and capacitance.

$$\theta(t) = \theta_{init} + \int_0^t \frac{\left(P_s - \frac{(\theta - \theta_a)}{R_\theta}\right)}{C_\theta} d\tau \qquad (11)$$



where:

θ was the battery's temperature in °C
θ_a was the ambient temperature in °C
θ_{init} was the battery's initial temperature in °C, assumed to be
equal to the surrounding ambient temperature
P_s was the I^2R power loss of R_0 and R_2 in Watts
R_θ was the thermal resistance in °C / Watts
C_θ was the thermal capacitance in Joules / °C
τ was an integration time variable
t was the simulation time in seconds

Figure 3.3 shows an example on how the lead-acid battery being modeled using Simscape standard library. This example simulates the battery initially is discharged at a constant current of 10A. The battery is then recharged at a constant 10A back to the initial state-of-charge. A simple thermal model is used to model battery temperature. It is assumed that cooling is primarily via convection and that heating is primarily from battery internal resistance, R2. A standard 12V lead-acid battery can be modeled by connecting six copies of the 2V battery cell block in series. The result of the simulation is shown in Figure 3.4.

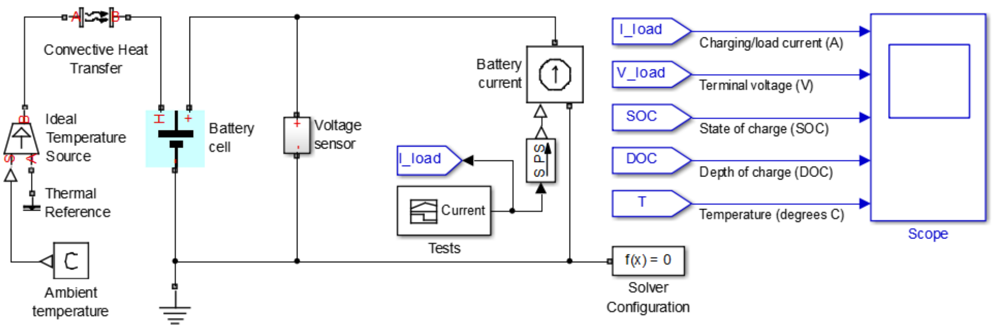


Figure 3.3: Lead-Acid Battery modeling using Simscape

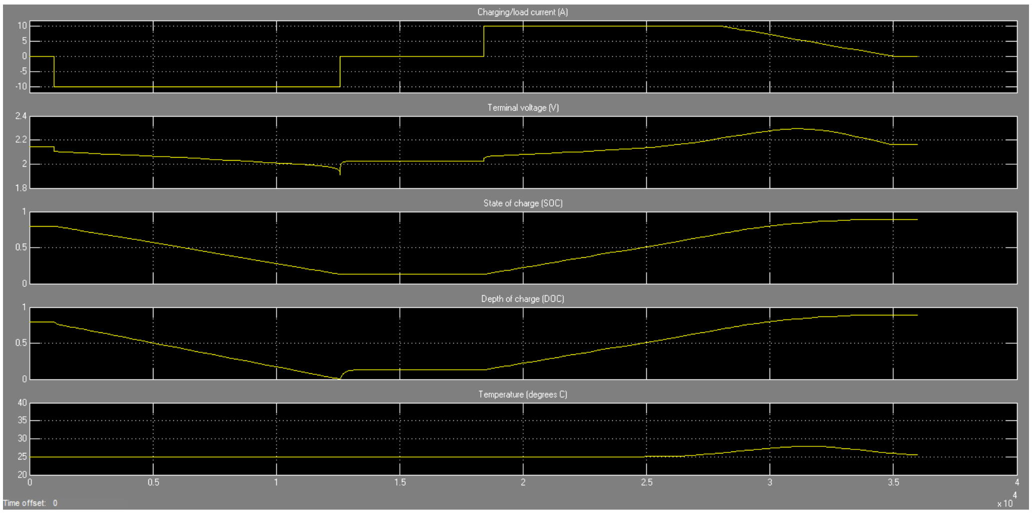


Figure 3.4: Results of the simulated lead-acid charging and discharging (adopted from library of Simscape, part of Matlab)

3.2.8 Summary of the Evaluation

Using Simscape lead-acid battery modeling and simulation with parameterizing tools can achieve accuracy within 3.2% compared to measurement in vehicle drive cycle. The simulation speed is at approximately 10,000 times real-time.

Battery simulations can optimize the electrical system design of EV on their components used and their selection. For example, the electric drives, the battery charger etc. under completely new operating conditions.

CHAPTER 4

METHODOLOGY

4.1 Conceptual System Design Overview and Functional Block Description

The EV is an automobile run by an electric motor where the motor gets its energy from the rechargeable batteries which control by the IPC controller. The IPC controller regulates the amount of power (both motor load current and output voltage to the motor) from the energy stored in the rechargeable batteries based on the driver's desire. The rechargeable batteries could be recharged by regular household AC inlet via an AC to DC converter which also known as battery charger.

Figure 4.1 shows a conceptual system design overview and functional block description of an electric vehicle. It also lists down provisional specification on the various blocks. The specification will require to fine tune with the experimental results.

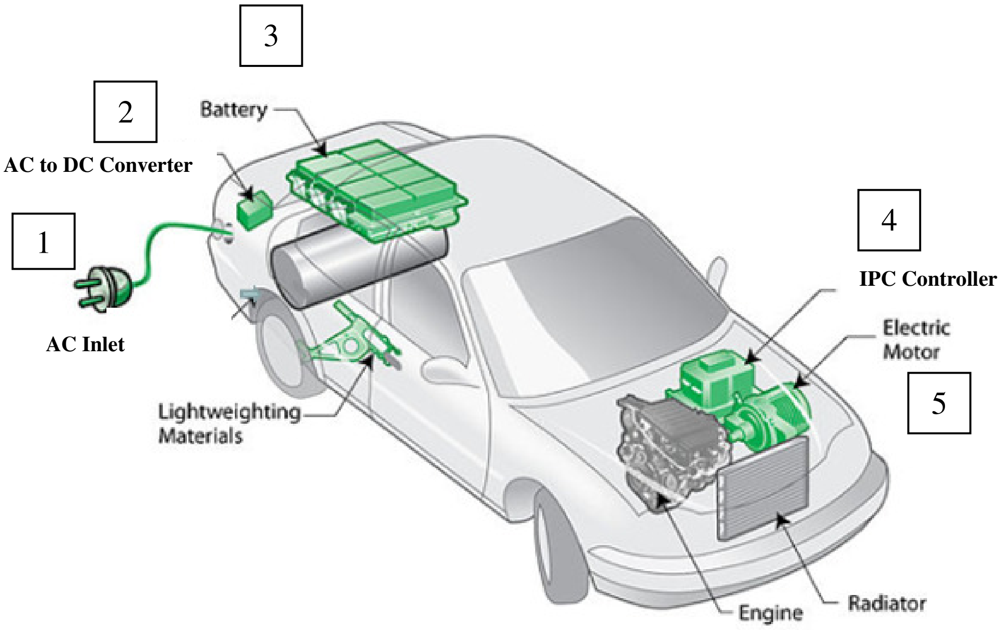


Figure 4.1: Conceptual System Design Overview and Functional Block Description

4.2 Specification and Functional Block Description

4.2.1 AC inlet

There is available IEC standard on charging Electric Vehicle (EV). Please refer to appendix 3 for detail.

The following data is adopted from appendix 3.

Level 1: Home charging, max. 2.4 KW. For 23kWh EV example Ford Focus vehicles, this means 10 hours charging from empty to full

Level 2: Fast AC charging, either 7KW (32A single phase) or 21 KW (three phase). If 7 KW is used it takes 3 hours charging from empty to full

Level 3: Fast DC charging, up to 50 KW, which means 20min. charging from empty to 80% full (for DC charging, the last 20% take a very long time, so DC charging is usually measured up to 80%).

For this project only AC inlet will be discussed as an AC to DC Converter has been included in the design concept. See also the input current requirement calculation for AC inlet to the AC to DC converter portion.

4.2.2 AC to DC Converter

This is basically a DC power supply with AC input as shown in Figure 4.2.

Figure 4.2: AC to DC converter (DC Power supply)

Based on the 20A load:

Figure 4.3 provide the understanding of the input current requirement for the IPC.

Current required by the Intelligent Power Controller (IPC):

Maximum input current = Maximum load (20A) + Maximum internal current consumption (Maximum charging current + Maximum operating current = 4.3A)

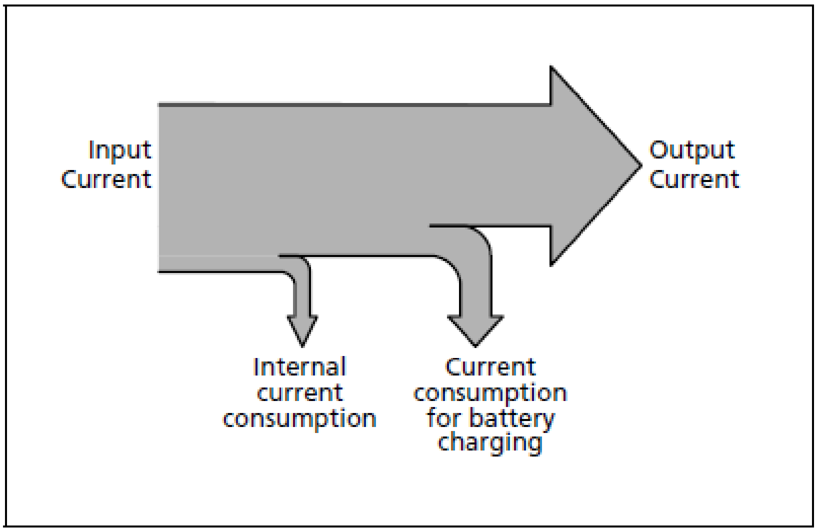


Figure 4.3: Input Current to the IPC

AC to DC Converter Rating Calculation:

Minimum rated output current required to provide by the AC to DC converter = Load Current (20A) + Maximum Internal current consumption of the IPC (4.3A) x 6 (for output of 144Vdc, 6 unit of IPC is required) = 45.8A

Take the minimum rate current as 50A (with some safety factor)

Output power = 24V x 50A = 1,200.00 W

If the efficiency of the AC to DC Converter is 94% and with 30% safety margin then the input current = $\frac{1200}{0.94} \times \frac{1}{240} \times 1.3 = 6.91$ A

Hence, a home 3 pins plug power supply with 240Vac 13A is good enough for AC inlet

4.2.3 Battery

89 Ah for 20 hours rated battery as shown in Figure 4.4 is used. Detail specification please refer to appendix 2

Figure 4.4: Lead-Acid Battery cell

4.2.4 Intelligent Power Controller, IPC

The application of Intelligent Power Controller (IPC) as shown in Figure 4.5 is to maintain or regulated the output voltage when it is in Battery Mode. Battery voltage fluctuations during discharge within the specify range (Minimum 9V is required) will not affect the output voltage (below 9V will trigger the deep-discharge protection).

Figure 4.5: Intelligent Power Controller

The output voltage when in battery mode can be set to four different output values namely 22.5V, 24V, 25V or 26V. With a center tap installed, two 12V-batteries connected in series will be charged by two independent battery chargers. The battery is charged and monitor individually. This feature makes matching batteries unnecessary and allows for precise battery charging, testing and optimized usage of the battery capacity to achieve the longest battery service life.

The IPC come with various batteries diagnostic functions that make sure it operates reliability. A temperature controlled charging with PT1000 temperature sensor is included to extend the life of the batteries. A “replace battery contact” is provided when the battery fails the test battery signal. For safety and maintenance purpose, an inhibit input signal is included which prevents the battery to power the load. Table 4.1 provides data on the performance of the IPC. To charge the battery, the IPC required to power by a 24Vdc power supply.

Table 4.1: Performance on Intelligent Power Controller, IPC			
Efficiency	Typically	99%	Battery is fully charged. Full external load is connected (20A) / load is drawing 20A. External 24Vd 69 er supply with minimum 20A capacity is connected. Output is maintained at 24Vdc.
Power losses	Typically	1.9W	Battery is fully charged. No external load is connected. External 24Vdc power supply with minimum 20A capacity is connected. Output is maintained at 24Vdc.
	Typically	4.8W	External 24Vdc Power supply with minimum 20A capacity is connected. No external load is connected. The intelligence converter is charging up the battery where the battery is rated < 10Ah. Output is maintained at 24Vdc.
	Typically	6.8W	External 24Vdc Power supply with minimum 20A capacity is connected. No external load is connected. The intelligence converter is charging up the battery where the battery is rated > 10Ah. Output is maintained at 24Vdc.
	Typically	4.6W	Battery is fully charged. Full external load is connected (20A) / load is drawing 20A. External 24Vdc power supply with minimum 20A capacity is connected. Output is maintained at 24Vdc.
	Typically	4.2W	External 24Vdc Power Supply is not connected. No external load is connected. Output is maintained 24Vdc.
	Typically	7.6W	External 24Vdc Power Supply is not connected. External load is drawing 10A. The load is powered by battery where the output is maintained 24Vdc by the intelligence converter
	Typically	21.3W	External 24Vdc Power Supply is not connected. External load is drawing 20A. The load is powered by battery where the output is maintained 24Vdc by the intelligence converter

SOC is determined simply by voltage measurement with PT1000 temperature sensor providing the temperature data. In the absent of PT1000, a battery temperature of 40°C is assumed.

Functional Description on Intelligent Power Controller (IPC)

Figure 4.6 shows the functional block of IPC.

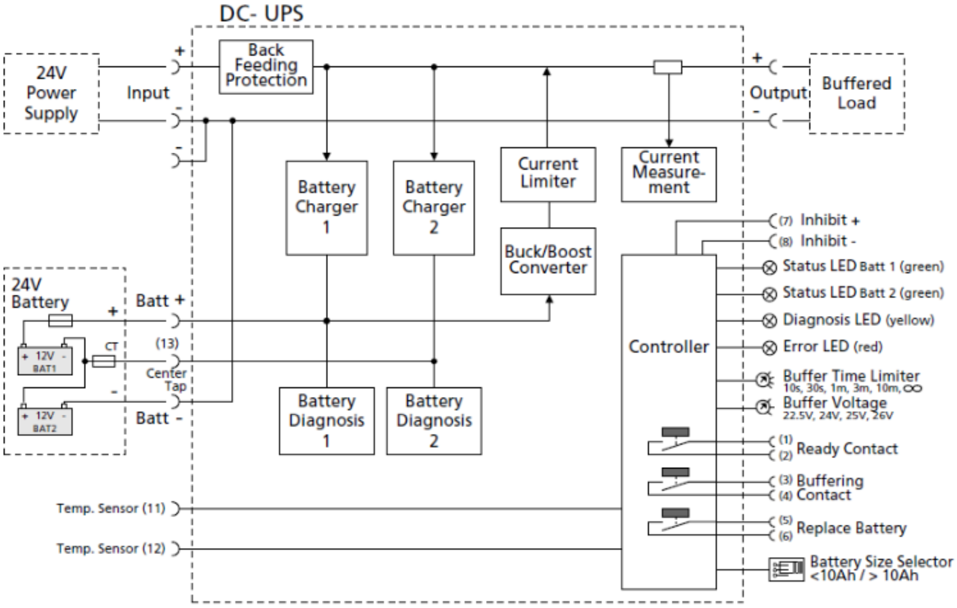


Figure 4.6: Functional block of IPC

Power Supply

240V AC inlet is required to power the AC to DC (DC power supply) converter as shown is Figure 4.7. Please refer to section 4.2 on DC power supply rating calculation.

Figure 4.7: AC to DC converter (DC Power supply)

Back Feeding Protection

The output of IPC1 (refer to Figure 4.16 page 80) is connected to the input of IPC2 (refer to Figure 4.16 page 80) via a back-fed protection (MOSFET) as shown in Figure 4.9. In the battery charging mode, the output voltage follows the input voltage minus a small voltage loss across the MOSFET. In battery operation mode, the output voltage is maintained at a constant voltage, which can be selected from one of four voltages namely 22.5V, 24V, 25V, and 26V.

Figure 4.8 is providing the relationship between input and output voltage and Figure 4.9 shows how the input-output voltage being measured and back fed protection by MOSFET

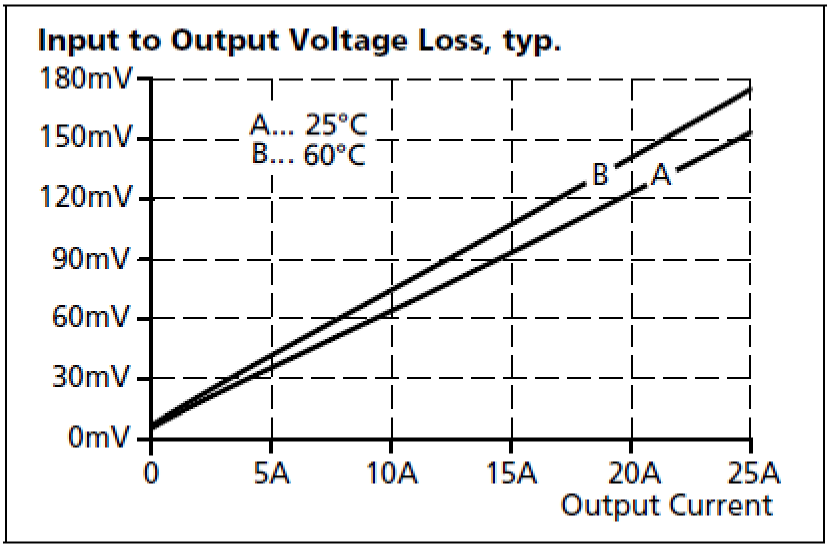


Figure 4.8: Relationship between input and output voltage

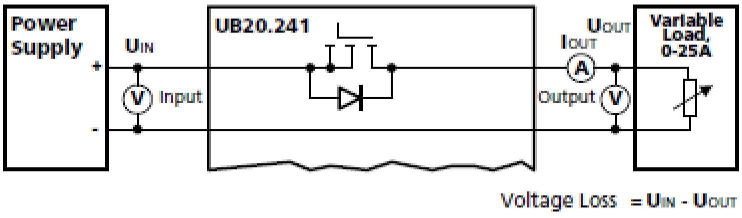


Figure 4.9: Input to output voltage loss measurement setup and back fed protection by MOSFET

Battery Charging Block

The IPC is using a constant current / constant voltage (CC-CV) charging method. There are two built in individual battery charger. For individual battery charging by individual charge center-tap connection need to be installed. When the center tap is not wired, both batteries will be charged with one common charging voltage. The center tap connection is detected automatically by the IPC. When the charging reaches 85%, respective green “Ready” LED flashing and it is will be permanently on. At charging, the IPC will consume additional current from the input (maximum = 4.3A) as the description in section 4.2.2.

Temperature Sensor

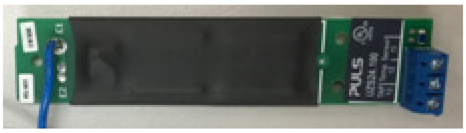
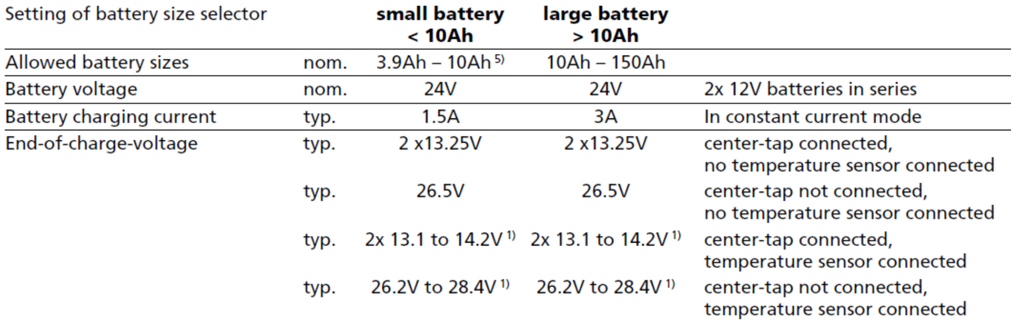


Figure 4.10: PT1000 temperature sensor

When the PT1000 temperature sensor (Figure 4.10) is installed, the IPC will automatically detect the present of the sensor and the end-of-charge-voltage compensation is activated. If the PT1000 temperature sensor is not present, the end-of-charge-voltage will be fixed to a value by assuming the battery temperature of 40°C.

Battery Size

Battery size can be select. Figure 4.11 shows the selection specification



Setting of battery size selector		**small battery < 10Ah**	**large battery > 10Ah**	
Allowed battery sizes	nom.	3.9Ah – 10Ah[5]	10Ah – 150Ah	
Battery voltage	nom.	24V	24V	2x 12V batteries in series
Battery charging current	typ.	1.5A	3A	In constant current mode
End-of-charge-voltage	typ.	2 x13.25V	2 x13.25V	center-tap connected, no temperature sensor connected
	typ.	26.5V	26.5V	center-tap not connected, no temperature sensor connected
	typ.	2x 13.1 to 14.2V[1]	2x 13.1 to 14.2V[1]	center-tap connected, temperature sensor connected
	typ.	26.2V to 28.4V[1]	26.2V to 28.4V[1]	center-tap not connected, temperature sensor connected

Figure 4.11: Battery size selection specification

Battery Diagnostic and Heath Status

The IPC is equipped with various diagnostic and health status with contact output for controlling and remote monitoring purposes.

Ready Contact

This contact is normally opened contact, will turn on if both batteries are charged above 85% and the input voltage is sufficient, no wiring failure is detected, plus the inhibit contact is not active.

On-Load Contact

This contact is closed (normally open contact) when the IPC is powered by a battery and no inlet source**.**

Replace Battery Relay Contact

This contact (normally opened contact) is activated when the individual battery failed the quality tests. It can be reset by turning on and off of the inlet source. When the battery failed, battery status green LED is off. In this situation, it is advisable to replace the battery as soon as possible.

Battery Inhibit Input

The inhibit input (refer to Figure 4.12) disables the current supply to the load. When AC inlet is connected and turns on, a permanent signal is required but if it is in battery mode a minimum 250ms pulse width is required to stop the current supply to the load.

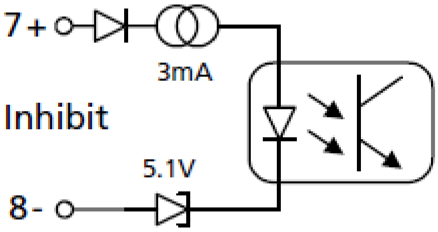


Figure 4.12: Inhibit input

4.2.5 Electric Motor

Sample Specification on DC Electric Motor supply by Advance D.C. Motors, Inc (Model: FB1-4001; Voltage range: 144Vdc) is provided by Figure 4.14. For wiring diagram please refer to appendix 4.

For the experiment, heater will be used as the load to replace electric motor. This heater (Figure 4.13) will be connected in series, parallel or combination to have different load current. The heater is used to simulate the motor (load).

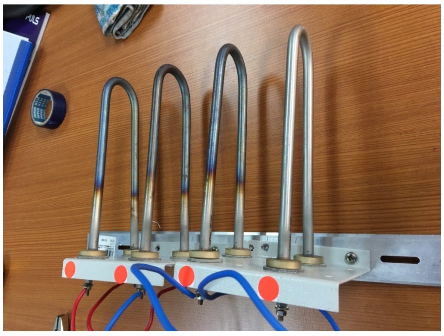


Figure 4.13: Heater is used to simulate the load

Every piece of heater is 10 Ohms. By connecting the heater in parallel and series, we can get 2.5A load, 5A load, 7.5A, 10A …20A and so on.

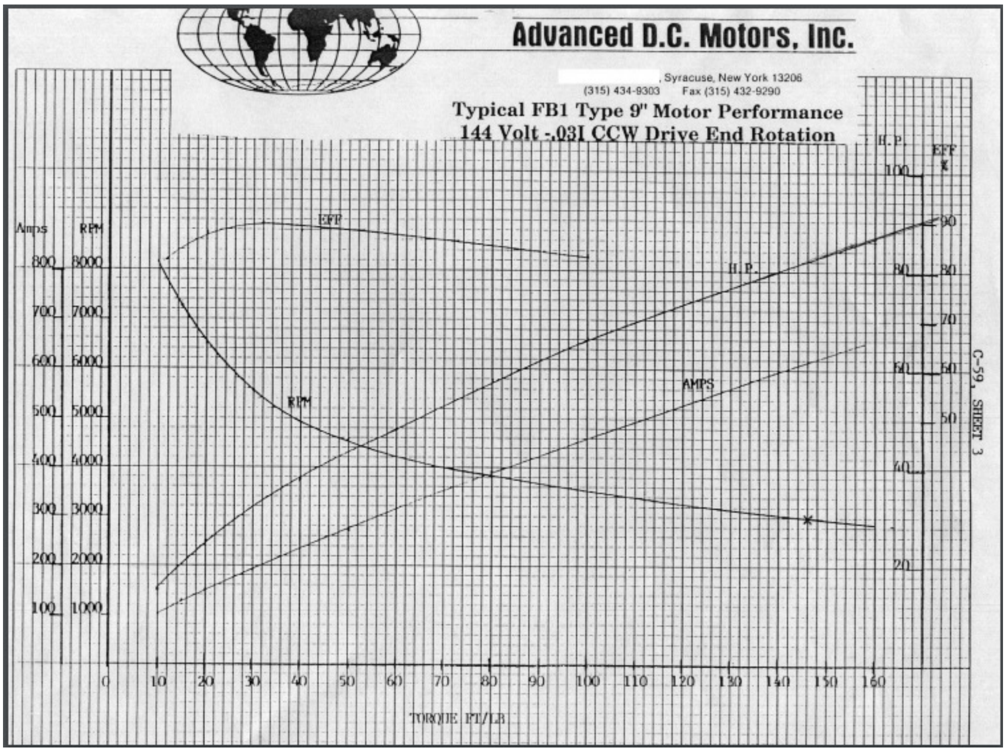


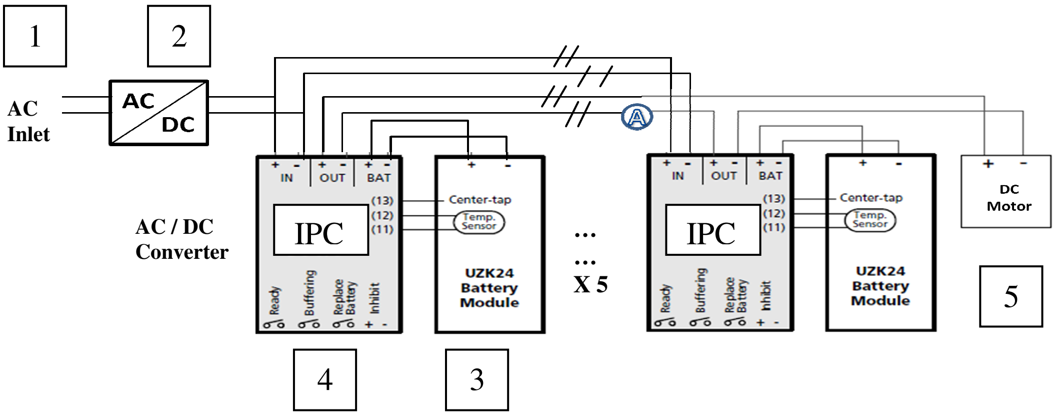
Figure 4.14: Typical FBI Type 9” Motor Performance

Further technical information can be obtained from:

http://www.evmotors.com.au/products/download/index.html

4.3 Conceptual Hardware Design

The conceptual system design hardware is shown in Figure 4.15.



Legend

Ⓐ = Ammeter

1: AC inlet
2: AC to DC converter
3: Battery
4: IPC
5: DC Motor

Figure 4.15: Conceptual hardware design of the EV

4.4 Downscale Experiment and Test Bench

The conceptual system design is downscale for testing and evaluation purposes. The downscales design is shown in Figure 4.16 and the test bench setup are shown from Figure 4.17 to 4.19

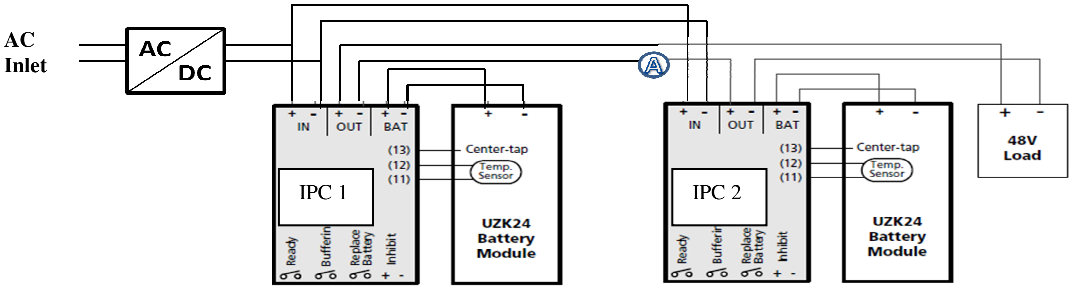


Figure 4.16: Downscale design

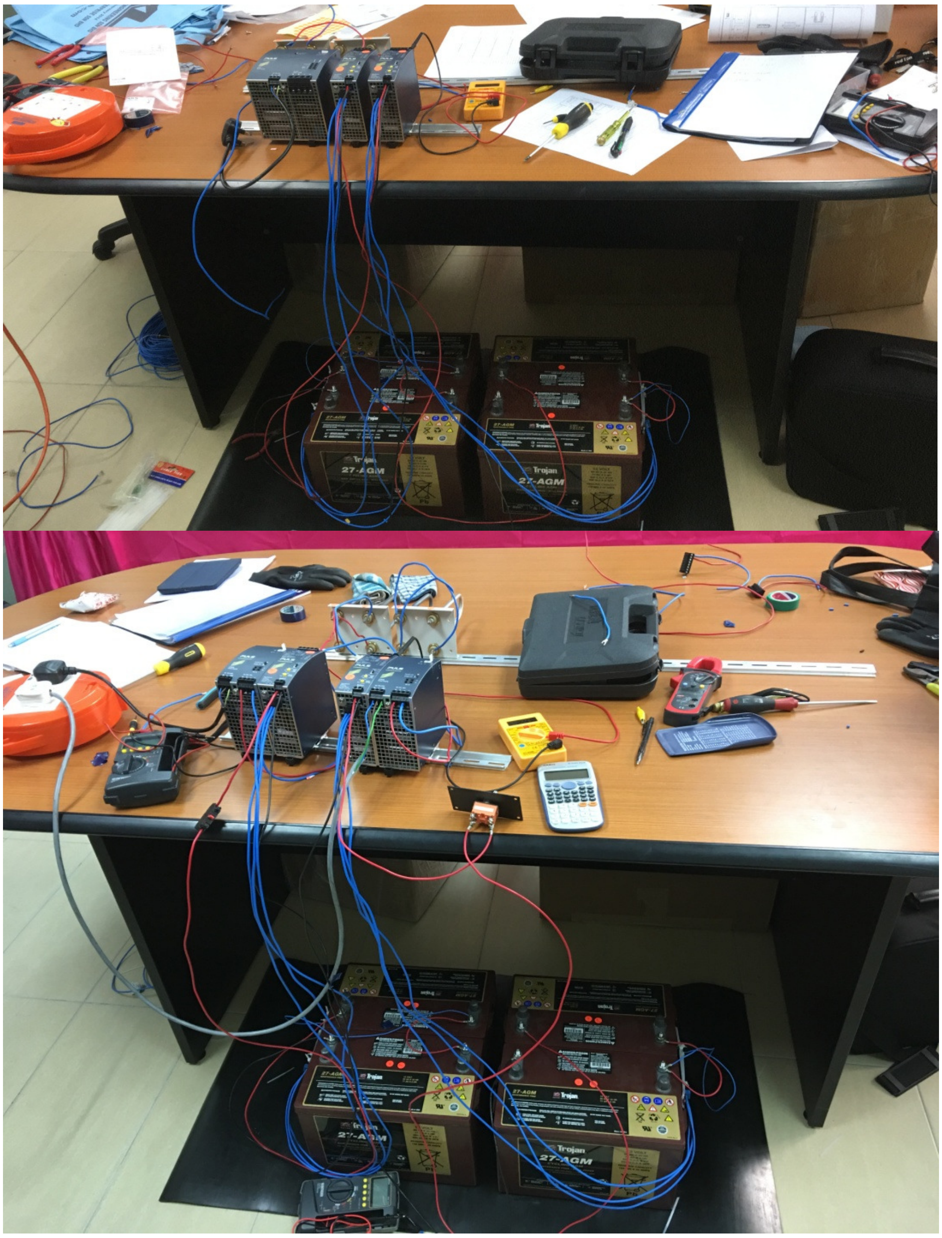


Figure 4.17: Experimental test bench (Top: Without battery disconnect switch; Bottom: With battery disconnect switch)

Figure 4.18: Zoom in view on the test setup (Top: IPC Controller; Bottom: Battery)

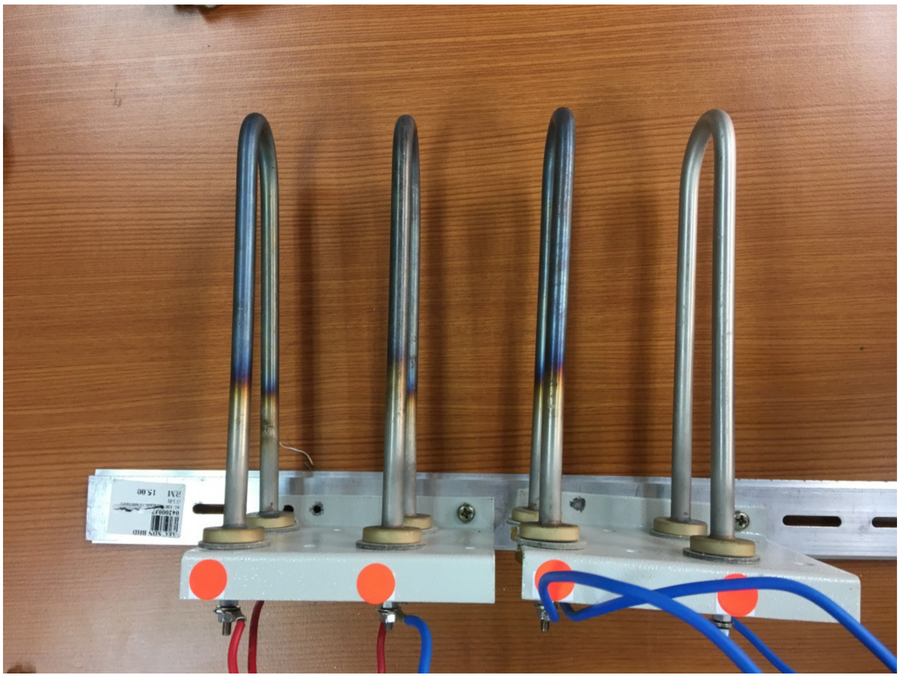


Figure 4.19: Zoom in view on the load used

4.5 Experiments

4.5.1 Experiment #1: Validate downscale design on the changes of inlet input voltage against output voltage (voltage to the load)

Objective: To evaluate the output voltage with respect to inlet voltage changes

The experiment is set up as per Figure 4.20. Detail wiring connection can refer to Figure 4.6 on page 72 and Figure 4.20.

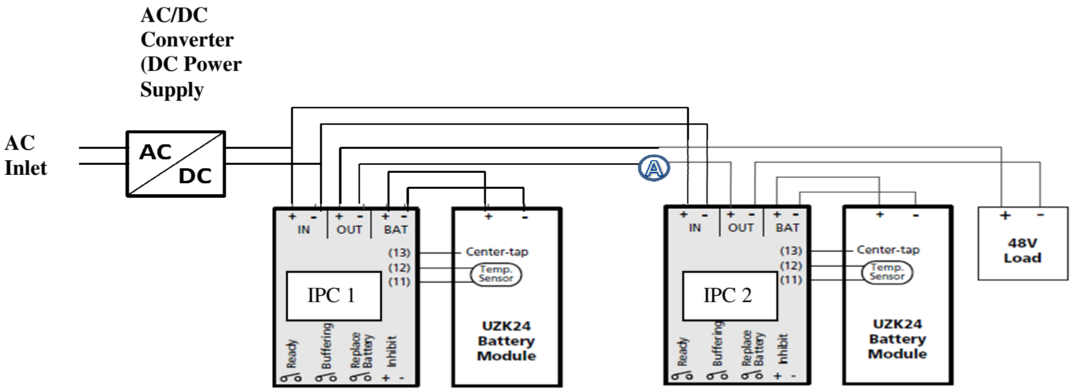


Figure 4.20: Experiment hook up diagram

Procedures:

a. AC inlet is 240V AC. AC to DC converter is a 24V DC 20A DC power supply.
b. Two units of IPC labeled as IPC 1 and IPC 2 is required
c. Each IPC required 2 twelve volt DC batteries. Total 4 units of batteries

d. Each IPC required 1 sensor board come with PT1000 sensor
e. Center tap connection on IPC is required.
f. Use heater as a load. Start with the load current of 2.5A.
g. Increase the DC power supply voltage from 25.5V to 28V DC in steps of 0.5V
h. Take the following voltage measurement Vin, V1, V2, Vb11, Vb12, Vb21 and Vb22 with respect to the load current. Record the measurement. Evaluate and comment their behavior. Plot the curve and evaluate their relationship.

   Vin: Output voltage from the DC power supply also is the (input voltage to the IPC). Refer to Figure 4.20

   V1 and V2: Output voltage from the IPC. V1 is measurement taken from IPC1 and V2 is from IPC2. Refer to Figure 4.20

   Vb11, Vb12, Vb21 and Vb22: Terminal voltage from the battery. Vb11 is from IPC1 battery 1; Vb12 is from IPC1 battery 2; Vb21 is from IPC2 battery 1; Vb22 is from IPC2 battery 2; refer to Figure 4.20 and 4.21

i. Increase the load current to 5A than repeat (g) to (h). Next, increase the load current to 7.5A and 10A
j. Load current is measured by ammeter as shown in Figure 4.20.

Heaters shown in Figure 4.21 will be used as a load. They are connected in series, parallel or combination in order to fulfill the load current required for the experiment.

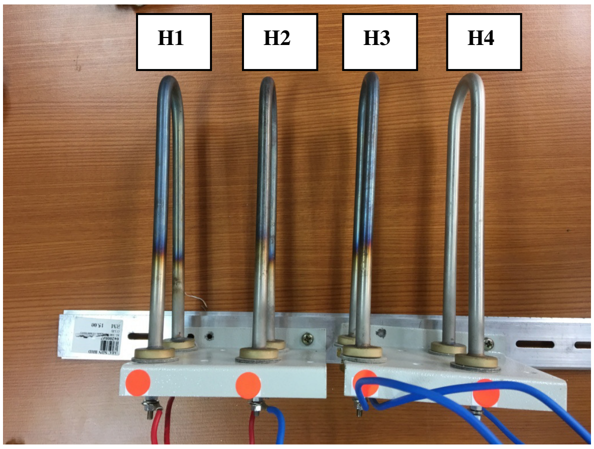


Figure 4.21: Heaters used as load

Heater used as load.

Measured Value:

H1 = 10.00 Ω

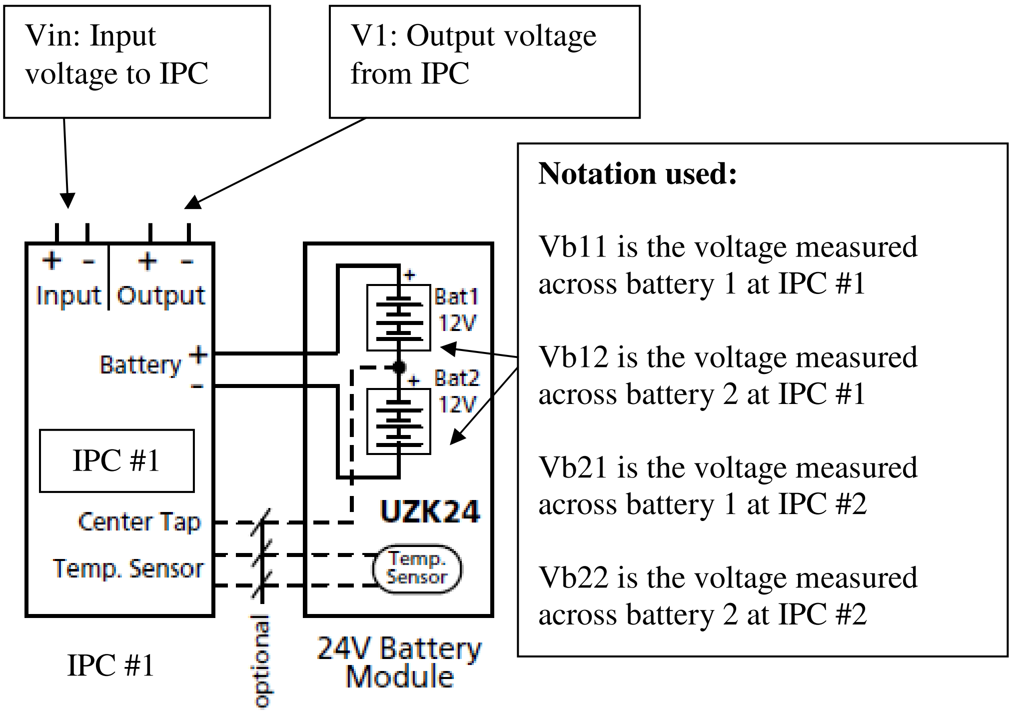
H2 = 9.90 Ω

H3 = 9.90Ω

H4 = 10.20 Ω

a. For 2.5A load: Connection H1 and H2 in series. Load = H1 + H2 = 19.90 Ω
b. For 5A load: Use only H1. Load = 10.00Ω
c. For 7.5A load: Use H1, H2 and H3. H1 and H2 connected in series than parallel with H3 [(H1 + H2) // H3]. Total load = 6.62 Ω
d. For 10A load: Use H1 parallel with H2 (H1 // H2). Total load = 4.98Ω

Detail connection on IPC and battery and their measurement points is shown in Figure 4.6 on page 72 and Figure 4.20 on page 83.



Notation used:

Vb11 is the voltage measured across battery 1 at IPC #1

Vb12 is the voltage measured across battery 2 at IPC #1

Vb21 is the voltage measured across battery 1 at IPC #2

Vb22 is the voltage measured across battery 2 at IPC #2

Figure 4.22: IPC connection diagram and measurement points

Figure 4.23: Measurement points on batteries

4.5.2 Experiment #2: Validate downscale design on the changes of battery input voltage against output voltage (voltage to the load) with no inlet supply.

Objective: To evaluate the output voltage with respect to battery terminal voltage changes

Procedures:

a. Repeat all procedures in experiment #1 except there is no inlet power supply required. No supply from the AC to DC converter. The load is now powered by a battery pack.
b. Take the reading every 10 minutes, that is from 0 minutes to 30 minutes for load current 2.5A, 5A, 7.5A, and 10A.
c. Take the same reading as described by (h) in experiment #1
d. Plot the curve, evaluate and comment the results.

4.5.3 Experiment #3: Fault simulation

Objective: To evaluate the diagnostic system of the design

Procedures:

a. **Short Circuit Test with inlet input**
   i. Use the set up for experiment #1. Make sure all power supply is turn off.
   ii. Short the two terminal of the load (heater) with a short jumper cable
   iii. Turn on the inlet power supply. Take the measurement of the load current. Observe the diagnostic LED and comment.
   iv. Remove the jumper cable and see what happen.
   v. Comment the observation

b. **Short Circuit Test without inlet input but powered by battery**
   vi. Use the set up for experiment #1. Disconnect the inlet supply permanently throughout this test and make sure that all batteries are also not connected.
   vii. Short the two terminal of the load (heater) with a short jumper cable
   viii. Connect (turn on) all 4 batteries so that the load is powered by the battery. Take the measurement of the load current. Observe the diagnostic LED and comment.

ix. Remove the jumper cable and see what happen.

x. Comment the observation

c. Battery failure test

i. Use the set up for experiment #1. Disconnect the inlet supply permanently throughout this test and make sure that all batteries are also not connected

ii. Replace of the good battery with a failed battery

iii. Connect (turn on) all 4 batteries (3 good batteries; 1 failed battery) so that the load is powered by the battery. Take the measurement of the load current. Observe the diagnostic LED, "replaced battery contact" and comment

d. Inhibit input test

i. Use the set up for experiment #1. Disconnect the inlet supply permanently throughout this test. Let the load only powered by the battery.

ii. Apply 24Vdc signal to pin 7 and 8 of the IPC. Pin 7 to +24V dc and pin 8 to 0V. Pin assignment is given by Figure 4.24

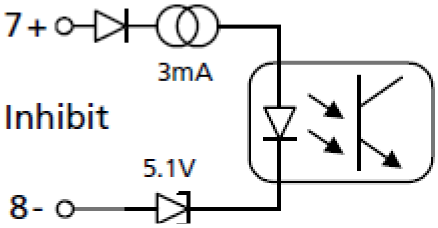


Figure 4.24: Inhibit signal pin assignment

iii. Record the load current before and after the inhibit input is activated. Observe the diagnostic LED. Comment the result and observation.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Results from experiment #1

This experiment is carried out with inlet voltage turn on and all 4 batteries are connected and online. Table 5.1, Table 5.2 and Figure 5.1 shows the result of experiment #1.

5.1.1 Observation and discussion

5.1.1.1 Load current

From the Table 5.1, it is observed that the calculated load current is always lower than the measured current. For example:

At the load = 19.9Ω

I = V / R

Calculated load current = 2.55A (50.74V / 19.9Ω)

Measured load current = 2.62A

The load used is a heater. Once is heated up the resistance will drop, therefore, higher current flow. When it is at room temperature the resistance reading is 19.9 Ω but when is heated up the reading is about 19.4 Ω. This reading is changing as it is depending on its temperature when the measurement is taken.

As the input voltage increase (the inlet voltage V1 increase), the load current is also increased. The increase is linear as observed by the curve shown in Figure 5.1. This is normal as it followed Ohm's law.

Table 5.1: IPC's performance when is powered by inlet supply

Performance when load powered by inlet supply (AC converter to DC inlet)											
Load Current (A)			Measurement in Volt (V)								
Calculated	Measured	Load / Ω	Vin	Vout	V1	V2	V1+V2	Vb11	Vb12	Vb21	Vb22
2.55	2.62	19.90	25.50	50.10	25.36	25.38	50.74	12.53	11.97	11.83	12.00
2.60	2.67	19.90	26.00	51.00	25.86	25.88	51.74	12.51	11.96	11.82	11.98
2.66	2.72	19.90	26.50	52.10	26.36	26.38	52.74	12.49	11.95	11.80	11.97
2.71	2.78	19.90	27.00	53.00	26.86	26.88	53.74	12.48	11.93	11.79	11.95
2.76	2.83	19.90	27.50	54.00	27.37	27.38	54.75	12.45	11.90	11.76	11.93
2.81	2.87	19.90	28.00	55.00	27.86	27.87	55.73	12.42	11.87	11.74	11.90
5.07	5.19	10.00	25.50	49.40	25.29	25.32	50.61	12.52	11.96	11.83	11.99
5.17	5.29	10.00	26.00	50.30	25.80	25.83	51.63	12.54	11.98	11.84	12.01
5.26	5.38	10.00	26.50	51.30	26.29	26.31	52.60	12.55	11.99	11.85	12.02
5.37	5.49	10.00	27.00	52.20	26.8	26.82	53.62	12.56	12.00	11.85	12.02
5.45	5.59	10.00	27.50	53.20	27.29	27.2	54.49	12.57	12.01	11.86	12.03
5.57	5.69	10.00	28.00	54.20	27.80	27.82	55.62	12.58	12.02	11.87	12.04
7.63	7.69	6.62	25.50	48.60	25.24	25.27	50.51	12.61	12.04	11.90	12.06
7.78	7.84	6.62	26.00	49.50	25.73	25.76	51.49	12.60	12.04	11.89	12.06
7.94	7.99	6.62	26.50	50.40	26.23	26.27	52.50	12.60	12.03	11.89	12.05
8.09	8.14	6.62	27.00	51.40	26.73	26.76	53.49	12.59	12.02	11.88	12.04
8.24	8.29	6.62	27.50	52.30	27.23	27.27	54.50	12.57	12.00	11.87	12.03
8.38	8.44	6.62	28.00	53.30	27.72	27.75	55.47	12.53	11.98	11.84	12.00
10.13	10.01	4.98	25.50	47.70	25.18	25.22	50.40	12.59	12.02	11.88	12.05
10.33	10.17	4.98	26.00	48.60	25.68	25.72	51.40	12.61	12.04	11.90	12.06
10.53	10.36	4.98	26.50	49.60	26.17	26.22	52.39	12.62	12.05	11.91	12.07
10.72	10.56	4.98	27.00	50.50	26.66	26.71	53.37	12.62	12.06	11.91	12.08
10.92	10.75	4.98	27.50	51.40	27.16	27.22	54.38	12.63	12.07	11.92	12.09
11.12	10.95	4.98	28.00	52.30	27.66	27.70	55.36	12.64	12.07	11.93	12.09

Legend:

Vin: Input Voltage Vout: Voltage at the load
V1, V2: Output voltage of the IPC
V1 + V2: Output voltage of the IPC1 + Output voltage of the IPC 2
Vb11, Vb12, Vb21, Vb22: Battery terminal voltageVoltage

5.1.1.2 Battery terminal voltage

It is observed that with inlet supply on, all 4 batteries are being charged up. This is recorded in Table 5.1 column labeled as Vb11, Vb12, Vb21, and Vb22. For example:

i. For load = 19.9Ω, the battery 1 at IPC1 (Vb11) is being charged from 12.42V (when Vin = 28V) to 12.53V (when Vin = 25.5V). Take note that the experiment for the 19.9Ω load is started with 28V inlet voltage reduces in steps of 0.5V until 25.5V.

ii. For load = 10.00Ω, battery Vb11 is being charged from 12.59V (when Vin = 25.5V) to 12.64V (when Vin = 28V). The experiment for 10.00Ω load started with inlet 25.5V inlet voltage increase in steps of 0.5V until 28V.

Since all 4 batteries can be charged up within a short of time (see Table 5.1), using the examples (i) and (ii), it has charged up by 0.11V and 0.06V respectively. We also can conclude that all 4 batteries are healthy.

Figure 5.1 shows the relationship on Vin versus load current; relationship on Vin versus V1+V2; and relationship on Vin versus Vout

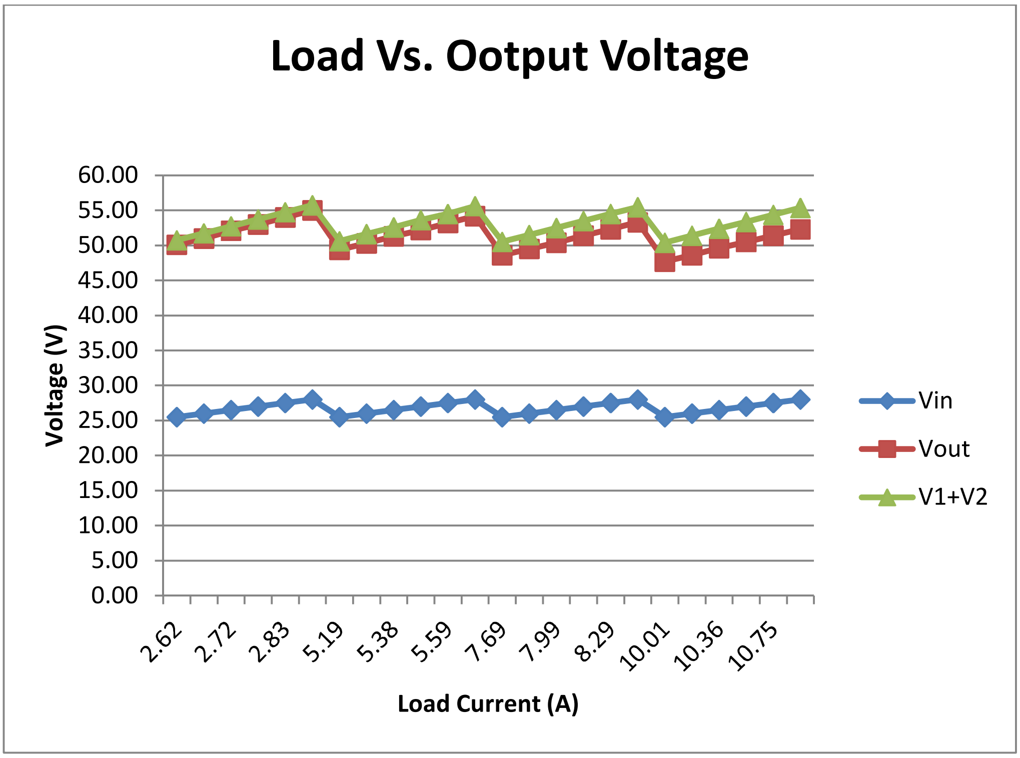


Figure 5.1: Relationship between input and output voltages against load current

5.1.1.3 Relationship on the Vout and V1+V2

From the Table 5.2, labeled as “(V1+V2)-Vout”, it is observed that there is a significant voltage drop across the cable. With 2.62A load, the voltage drop is 0.64V. When the load is increased to 10.95A, the voltage drop is 3.06V. In other words, as the load current increase, the voltage drop across the cable also increases. This could be explained by Ohm’s law. The different between Vout and (V1+V2) is the voltage drop across the interconnection cable

The cable resistance is 0.26Ω (taking average) which is consider high for a short cable. This is a valid reading as resistance does not change a lot with different load current (range from 2.62A to 10.95A) as presented in the last column of Table 5.2.

The cable resistance is further validated by using the length 10 times the original length. The voltage drop for 2.6A load is about 6V. This confirmed that the voltage drop comes from the cable resistance.

It is also observed that the cable is heated up a little bit (just feel warm). This experiment also shows that for EV application, a good quality with a bigger core and low resistance cable should be used as the current for the EV is much higher than this experiment.

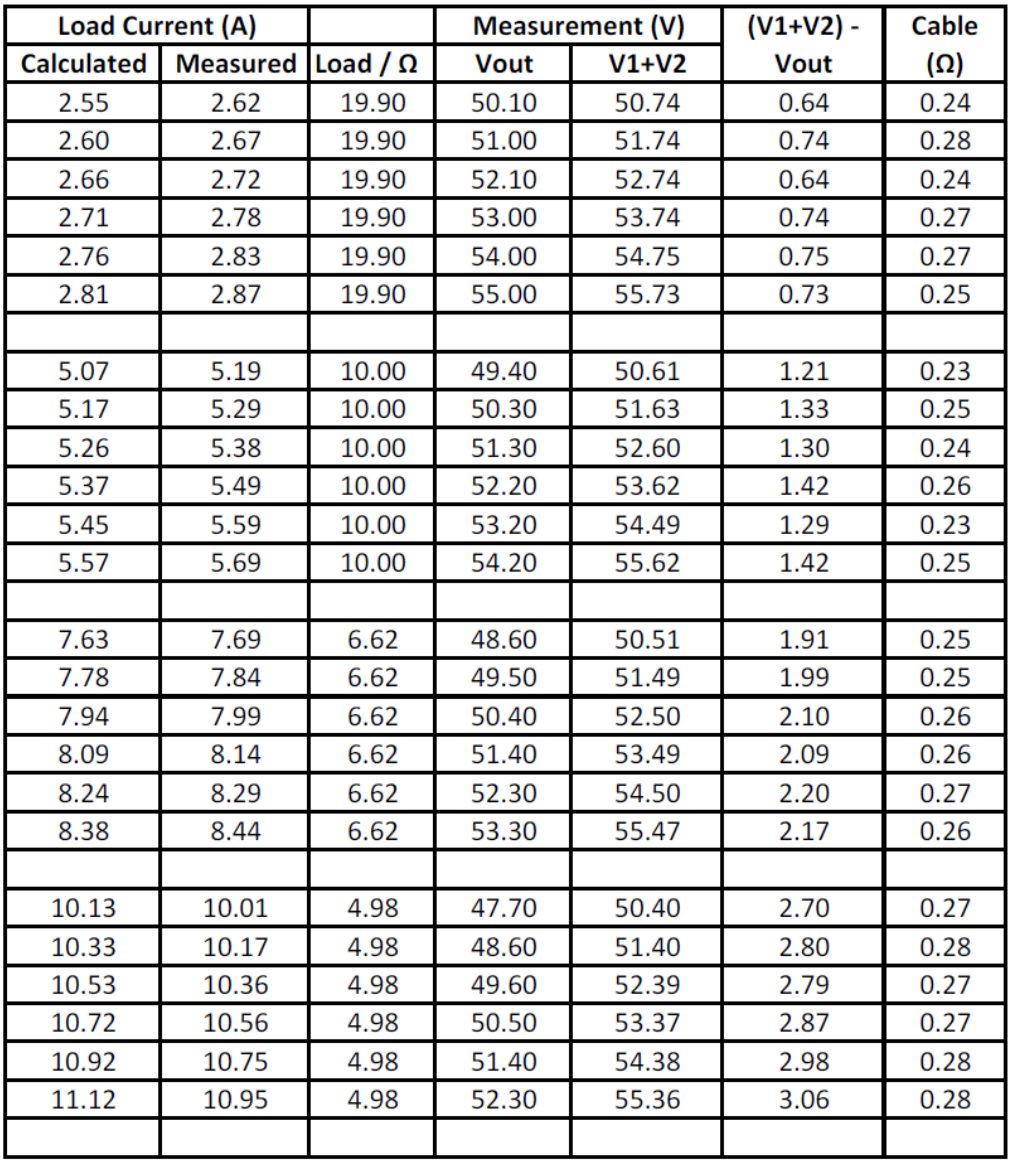
5.1.1.4 Output voltage regulation

From the Table 5.1 and Figure 5.1, it is observed when Vin increase; (V1 + V2) also increase.

The lowest value of V1 + V2 (Min) = 50.40V
The higher value of V1 + V2 (Max) = 55.73V
Different V1+V2 (Max-Min) = 5.33V

That means, with inlet supply (not powered by battery) the voltage regulation is depending on the AC to DC converter, not the IPC. IPC do not provide voltage regulation when the IPC controller is powered by inlet supply and in charging mode. That means for better control on output voltage regulation, an additional buck-boost converter is needed for overall voltage regulation.

Table 5.2: Voltage drop across the interconnection cables.



Load Current (A)			Measurement (V)		(V1+V2) - Vout	Cable (Ω)
Calculated	Measured	Load / Ω	Vout	V1+V2		
2.55	2.62	19.90	50.10	50.74	0.64	0.24
2.60	2.67	19.90	51.00	51.74	0.74	0.28
2.66	2.72	19.90	52.10	52.74	0.64	0.24
2.71	2.78	19.90	53.00	53.74	0.74	0.27
2.76	2.83	19.90	54.00	54.75	0.75	0.27
2.81	2.87	19.90	55.00	55.73	0.73	0.25
5.07	5.19	10.00	49.40	50.61	1.21	0.23
5.17	5.29	10.00	50.30	51.63	1.33	0.25
5.26	5.38	10.00	51.30	52.60	1.30	0.24
5.37	5.49	10.00	52.20	53.62	1.42	0.26
5.45	5.59	10.00	53.20	54.49	1.29	0.23
5.57	5.69	10.00	54.20	55.62	1.42	0.25
7.63	7.69	6.62	48.60	50.51	1.91	0.25
7.78	7.84	6.62	49.50	51.49	1.99	0.25
7.94	7.99	6.62	50.40	52.50	2.10	0.26
8.09	8.14	6.62	51.40	53.49	2.09	0.26
8.24	8.29	6.62	52.30	54.50	2.20	0.27
8.38	8.44	6.62	53.30	55.47	2.17	0.26
10.13	10.01	4.98	47.70	50.40	2.70	0.27
10.33	10.17	4.98	48.60	51.40	2.80	0.28
10.53	10.36	4.98	49.60	52.39	2.79	0.27
10.72	10.56	4.98	50.50	53.37	2.87	0.27
10.92	10.75	4.98	51.40	54.38	2.98	0.28
11.12	10.95	4.98	52.30	55.36	3.06	0.28

5.2 Result from experiment #2

This experiment is carried out with inlet voltage off (without inlet voltage) and all 4 batteries are connected and online. Table 5.3, Table 5.4 and Figure 5.2 to 5.5 shows the result of experiment #2.

5.2.1 Observation and discussion

5.2.1.1 Load current

From the Table 5.3, similar to experiment #1, it is observed that the measured load current is always higher than calculated load current due to the same reason that is load resistance reduce once being heated up. Lower resistance means higher current.

For example:
At the load = 19.9Ω
I = V / R
Calculated load current = 2.40A (47.66V / 19.9Ω)
Measured load current = 2.45A

5.2.1.2 Battery terminal voltage

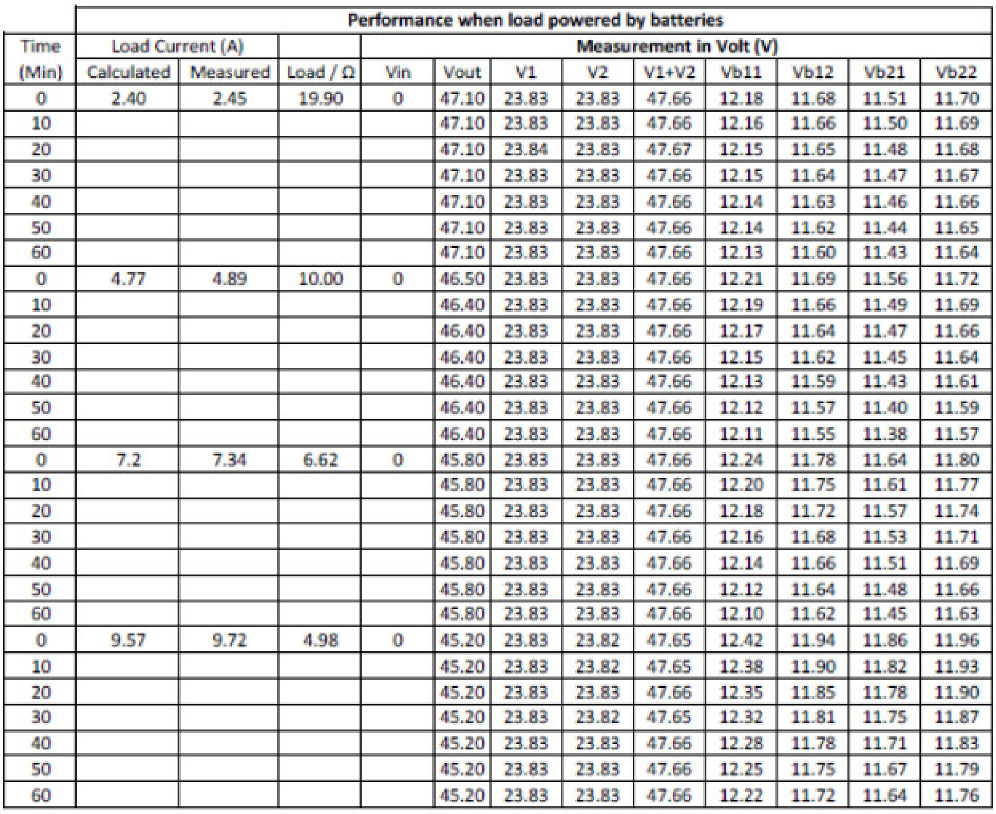
It is observed that without inlet supply (inlet supply is off); the system is powered by the 4 batteries. All 4 batteries are discharging and they are able to support the load. The terminal voltage of the individual battery (Vb11, Vb12, Vb21, and Vb22) can be found in Table 5.3. It is observed that all 4 batteries are discharging slowly.

Discharge rate at 2.45A load for Vb21 (Db21) for 60 minute = 11.51 – 11.43 = 0.08V

Discharge rate at 9.72A load for Vb21 (Db21) for 60 minute = 11.96 -11.76 = 0.22V

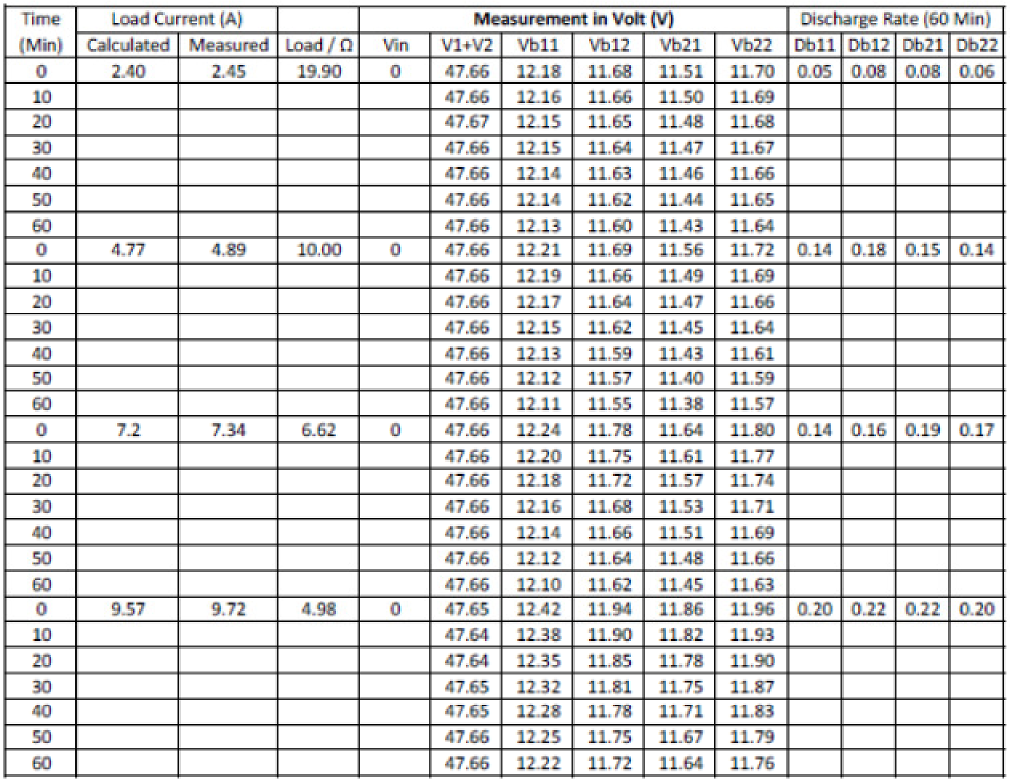
The higher the load current the more the battery discharged. Battery discharge rate for all 4 batteries is recorded in Table 5.3.

Table 5.3: Measurement is taken when the load is powered by battery



	Performance when load powered by batteries											
Time	Load Current (A)			Measurement in Volt (V)								
(Min)	Calculated	Measured	Load / Ω	Vin	Vout	V1	V2	V1+V2	Vb11	Vb12	Vb21	Vb22
0	2.40	2.45	19.90	0	47.10	23.83	23.83	47.66	12.18	11.68	11.51	11.70
10					47.10	23.83	23.83	47.66	12.16	11.66	11.50	11.69
20					47.10	23.84	23.83	47.67	12.15	11.65	11.48	11.68
30					47.10	23.83	23.83	47.66	12.15	11.64	11.47	11.67
40					47.10	23.83	23.83	47.66	12.14	11.63	11.46	11.66
50					47.10	23.83	23.83	47.66	12.14	11.62	11.44	11.65
60					47.10	23.83	23.83	47.66	12.13	11.60	11.43	11.64
0	4.77	4.89	10.00	0	46.50	23.83	23.83	47.66	12.21	11.69	11.56	11.72
10					46.40	23.83	23.83	47.66	12.19	11.66	11.49	11.69
20					46.40	23.83	23.83	47.66	12.17	11.64	11.47	11.66
30					46.40	23.83	23.83	47.66	12.15	11.62	11.45	11.64
40					46.40	23.83	23.83	47.66	12.13	11.59	11.43	11.61
50					46.40	23.83	23.83	47.66	12.12	11.57	11.40	11.59
60					46.40	23.83	23.83	47.66	12.11	11.55	11.38	11.57
0	7.2	7.34	6.62	0	45.80	23.83	23.83	47.66	12.24	11.78	11.64	11.80
10					45.80	23.83	23.83	47.66	12.20	11.75	11.61	11.77
20					45.80	23.83	23.83	47.66	12.18	11.72	11.57	11.74
30					45.80	23.83	23.83	47.66	12.16	11.68	11.53	11.71
40					45.80	23.83	23.83	47.66	12.14	11.66	11.51	11.69
50					45.80	23.83	23.83	47.66	12.12	11.64	11.48	11.66
60					45.80	23.83	23.83	47.66	12.10	11.62	11.45	11.63
0	9.57	9.72	4.98	0	45.20	23.83	23.82	47.65	12.42	11.94	11.86	11.96
10					45.20	23.83	23.82	47.65	12.38	11.90	11.82	11.93
20					45.20	23.83	23.83	47.66	12.35	11.85	11.78	11.90
30					45.20	23.83	23.82	47.65	12.32	11.81	11.75	11.87
40					45.20	23.83	23.83	47.66	12.28	11.78	11.71	11.83
50					45.20	23.83	23.83	47.66	12.25	11.75	11.67	11.79
60					45.20	23.83	23.83	47.66	12.22	11.72	11.64	11.76

Table 5.4: Battery discharge rate



Time	Load Current (A)			Measurement in Volt (V)						Discharge Rate (60 Min)			
(Min)	Calculated	Measured	Load / Ω	Vin	V1+V2	Vb11	Vb12	Vb21	Vb22	Db11	Db12	Db21	Db22
0	2.40	2.45	19.90	0	47.66	12.18	11.68	11.51	11.70	0.05	0.08	0.08	0.06
10					47.66	12.16	11.66	11.50	11.69				
20					47.67	12.15	11.65	11.48	11.68				
30					47.66	12.15	11.64	11.47	11.67				
40					47.66	12.14	11.63	11.46	11.66				
50					47.66	12.14	11.62	11.44	11.65				
60					47.66	12.13	11.60	11.43	11.64				
0	4.77	4.89	10.00	0	47.66	12.21	11.69	11.56	11.72	0.14	0.18	0.15	0.14
10					47.66	12.19	11.66	11.49	11.69				
20					47.66	12.17	11.64	11.47	11.66				
30					47.66	12.15	11.62	11.45	11.64				
40					47.66	12.13	11.59	11.43	11.61				
50					47.66	12.12	11.57	11.40	11.59				
60					47.66	12.11	11.55	11.38	11.57				
0	7.2	7.34	6.62	0	47.66	12.24	11.78	11.64	11.80	0.14	0.16	0.19	0.17
10					47.66	12.20	11.75	11.61	11.77				
20					47.66	12.18	11.72	11.57	11.74				
30					47.66	12.16	11.68	11.53	11.71				
40					47.66	12.14	11.66	11.51	11.69				
50					47.66	12.12	11.64	11.48	11.66				
60					47.66	12.10	11.62	11.45	11.63				
0	9.57	9.72	4.98	0	47.65	12.42	11.94	11.86	11.96	0.20	0.22	0.22	0.20
10					47.64	12.38	11.90	11.82	11.93				
20					47.64	12.35	11.85	11.78	11.90				
30					47.65	12.32	11.81	11.75	11.87				
40					47.65	12.28	11.78	11.71	11.83				
50					47.66	12.25	11.75	11.67	11.79				
60					47.66	12.22	11.72	11.64	11.76				

5.2.1.3 Relationship between the Vout and V1+V2

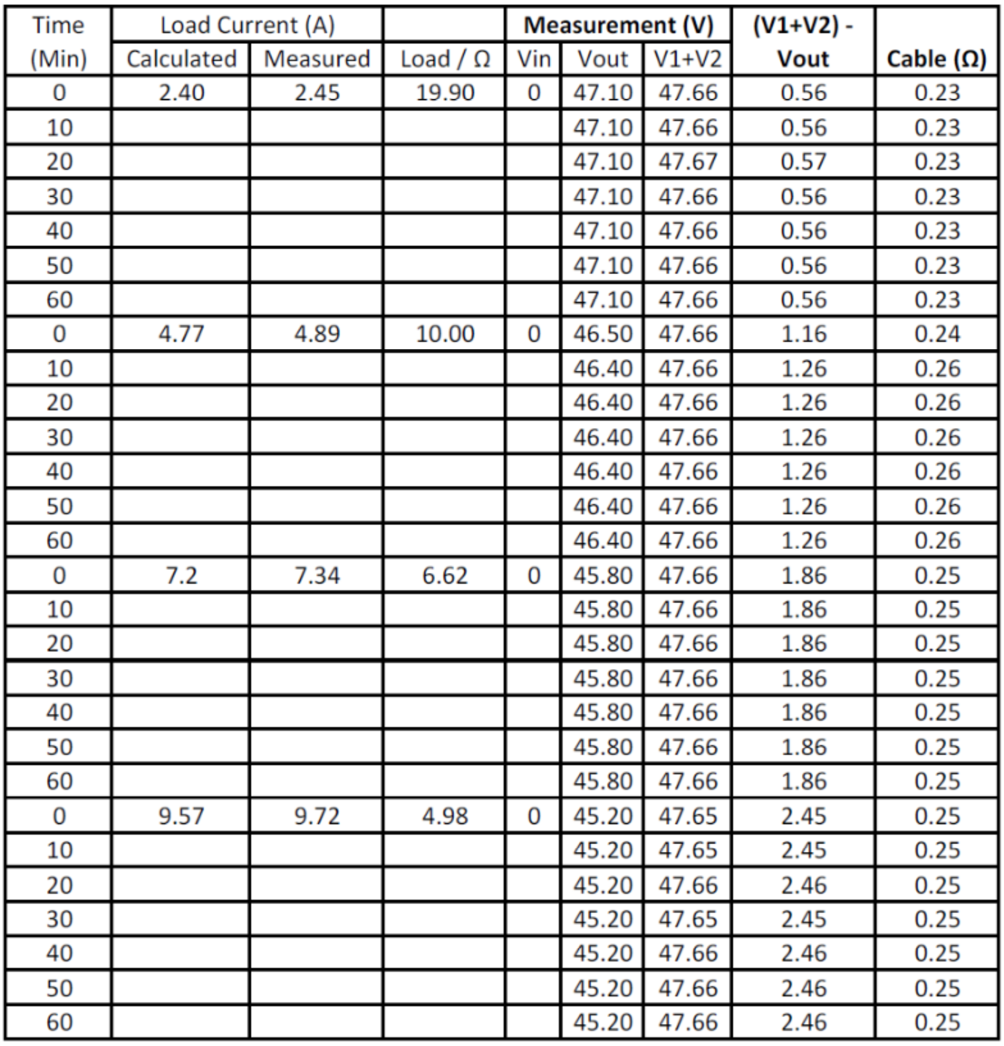
From the Table 5.5, similar to the test done in experiment #1, it is observed that there is a significant voltage drop across the cable due to the same reason (Heat). The different between Vout and (V1+V2) is the voltage drop across the interconnection cable.

The maximum voltage drop is 2.46V compare to experiment #1 which is 3.06V. This is due to lesser load current as the output voltage (V1+V2) is regulated to 47.66V (compare to Experiment #1 which is 55.73V).

The cable resistance is 0.25Ω (taking average). There is 0.01Ω different compare to experiment #1. This also proof that the cable resistance for experiment #1 and #2 are valid as the different is very small.

With the same reason, for EV application, a good quality with a bigger core and low resistance cable should be used as the current for the EV is much higher than these experiments.

Table 5.5: Voltage drop across the interconnection cables when powered by battery



Time (Min)	Load Current (A)			**Measurement (V)**			**(V1+V2) - Vout**	**Cable (Ω)**
	Calculated	Measured	Load / Ω	Vin	Vout	V1+V2		
0	2.40	2.45	19.90	0	47.10	47.66	0.56	0.23
10					47.10	47.66	0.56	0.23
20					47.10	47.67	0.57	0.23
30					47.10	47.66	0.56	0.23
40					47.10	47.66	0.56	0.23
50					47.10	47.66	0.56	0.23
60					47.10	47.66	0.56	0.23
0	4.77	4.89	10.00	0	46.50	47.66	1.16	0.24
10					46.40	47.66	1.26	0.26
20					46.40	47.66	1.26	0.26
30					46.40	47.66	1.26	0.26
40					46.40	47.66	1.26	0.26
50					46.40	47.66	1.26	0.26
60					46.40	47.66	1.26	0.26
0	7.2	7.34	6.62	0	45.80	47.66	1.86	0.25
10					45.80	47.66	1.86	0.25
20					45.80	47.66	1.86	0.25
30					45.80	47.66	1.86	0.25
40					45.80	47.66	1.86	0.25
50					45.80	47.66	1.86	0.25
60					45.80	47.66	1.86	0.25
0	9.57	9.72	4.98	0	45.20	47.65	2.45	0.25
10					45.20	47.65	2.45	0.25
20					45.20	47.66	2.46	0.25
30					45.20	47.65	2.45	0.25
40					45.20	47.66	2.46	0.25
50					45.20	47.66	2.46	0.25
60					45.20	47.66	2.46	0.25

5.2.1.4 Output voltage regulation

From the Table 5.3 and Figure 5.2 to 5.5, it is observed the output voltage (V1+V2) is maintained at 47.66V for the load current range from 2.45A to 9.45A for 4 hours.

From Table 5.3, the voltage at battery 1 (IPC1) Vb11 is above 12V dc throughout the experiment and the voltage at battery 2 (IPC1) Vb12, battery 1 (IPC2) Vb21 and battery 2 (IPC2) Vb22 is below 12V dc throughout the experiment. With this voltage level, the output still maintained at 47.66 volts for a total of 4 hours. That means a change of load current does not affect the output voltage.

The output voltage for IPC1 (V1) maintains at 23.83V indicate that the buck-boost converter is functioning. The buck-boost converter is now working as a buck converter.

The output voltage for IPC2 (V2) maintains at 23.83V indicate that the buck-boost converter is functioning. The buck-boost converter is now working as a boost converter. That means change battery voltage does not affect the output voltage.

Buck-boost converter inside the IPC can regulate the output voltage in both situations that this changing loads current and changing battery voltage. The change is 0.22V or 0.46% reference to 48V dc output with 0.12V drop (back feed protection diode) or 99.54% regulation.

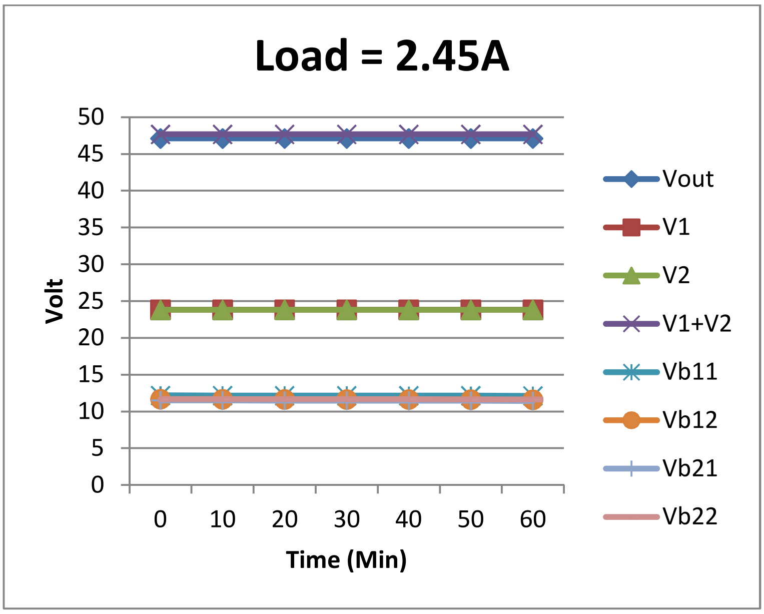


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Figure 5.2: Output voltage (V1+V2) maintain constant while the batteries are discharging (Load = 2.45A)

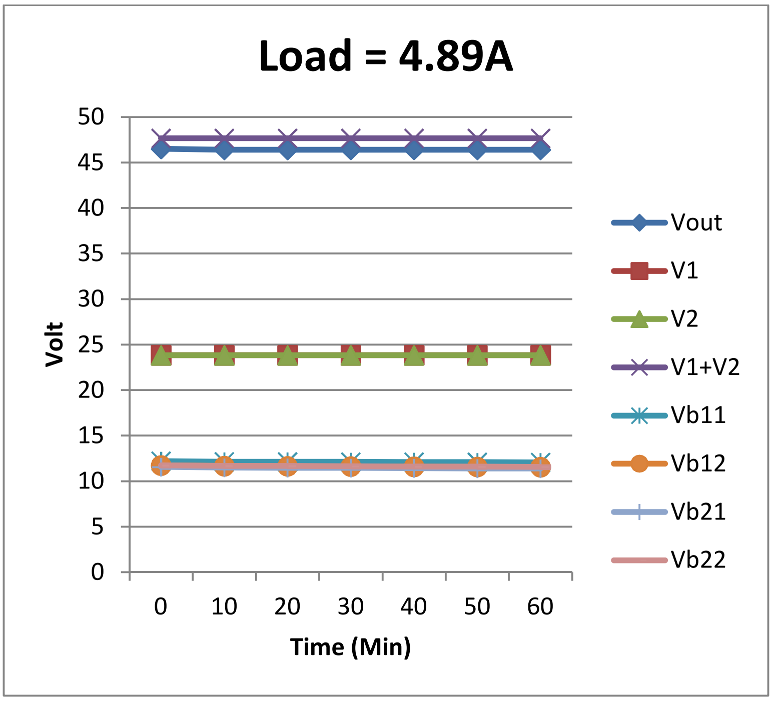


Figure 5.3: Output voltage (V1+V2) maintain constant while the batteries are discharging (Load = 4.89A)

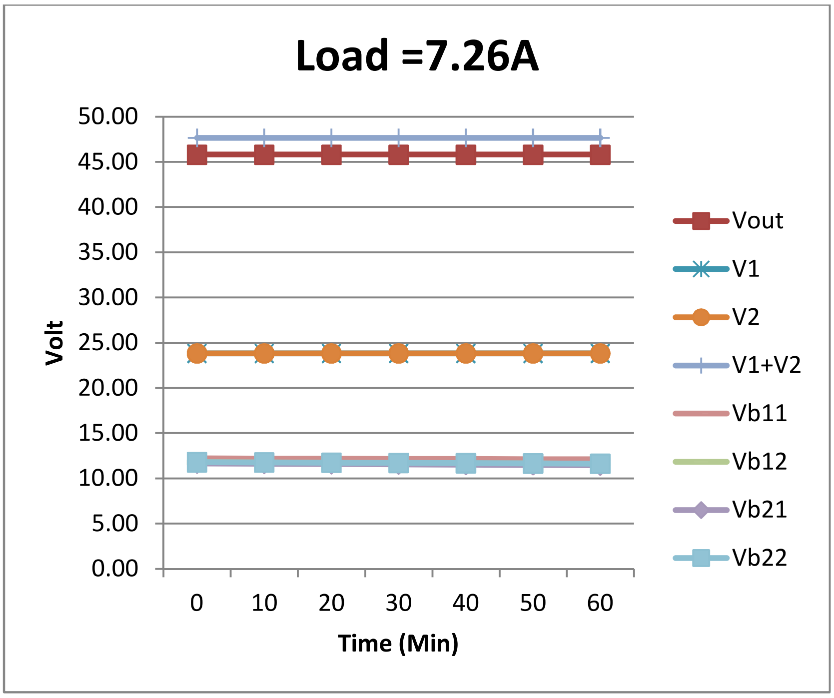


Figure 5.4: Output voltage (V1+V2) maintain constant while the batteries are discharging (Load = 7.26A)

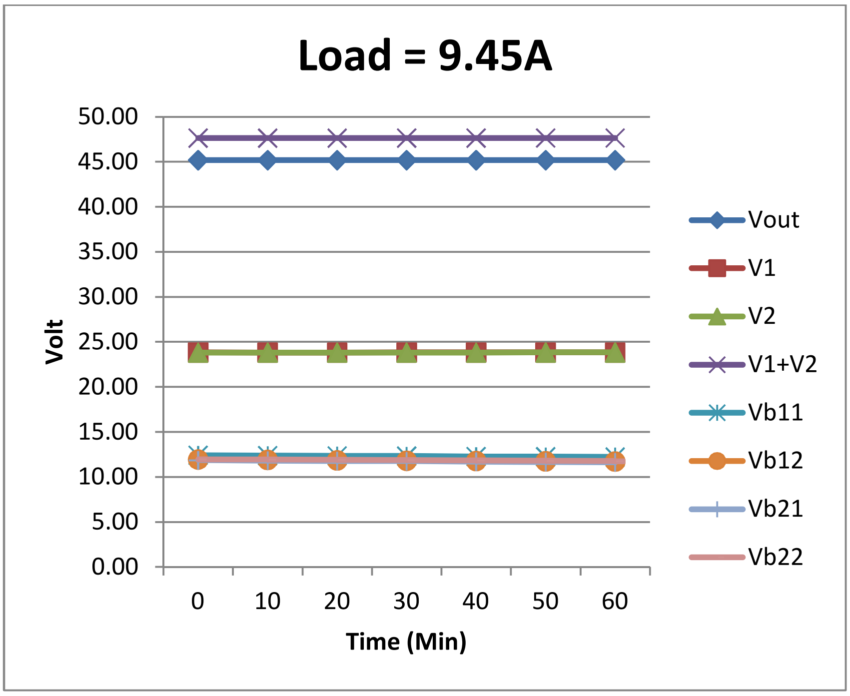


Figure 5.5: Output voltage (V1+V2) maintain constant while the batteries are discharging (Load = 9.45A)

5.3 Result from experiment #3

5.3.1 Short circuit or overload test for (a):

Figure 5.6: AC inlet power supply (AC to DC Converter)

The overload protection of the AC to Dc converter is activated. A relay contact signal is activated to indicate the power supply is overload. When the system is powered by inlet power supply (Figure 5.6), the overload protection comes from AC to DC converter, not the IPC controller.

5.3.2 Short circuit or overload test for (b):

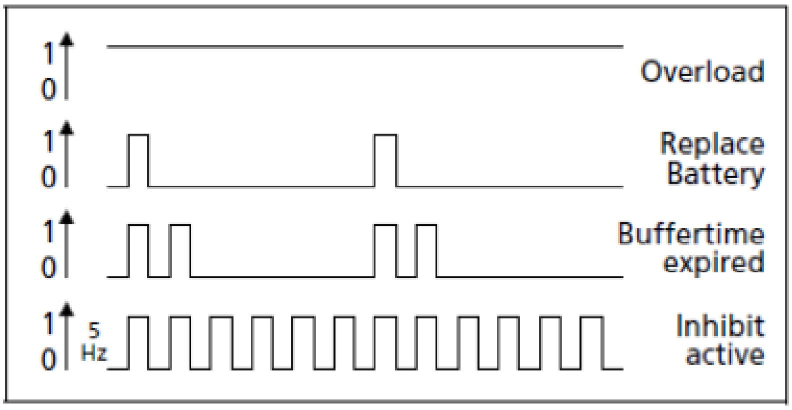
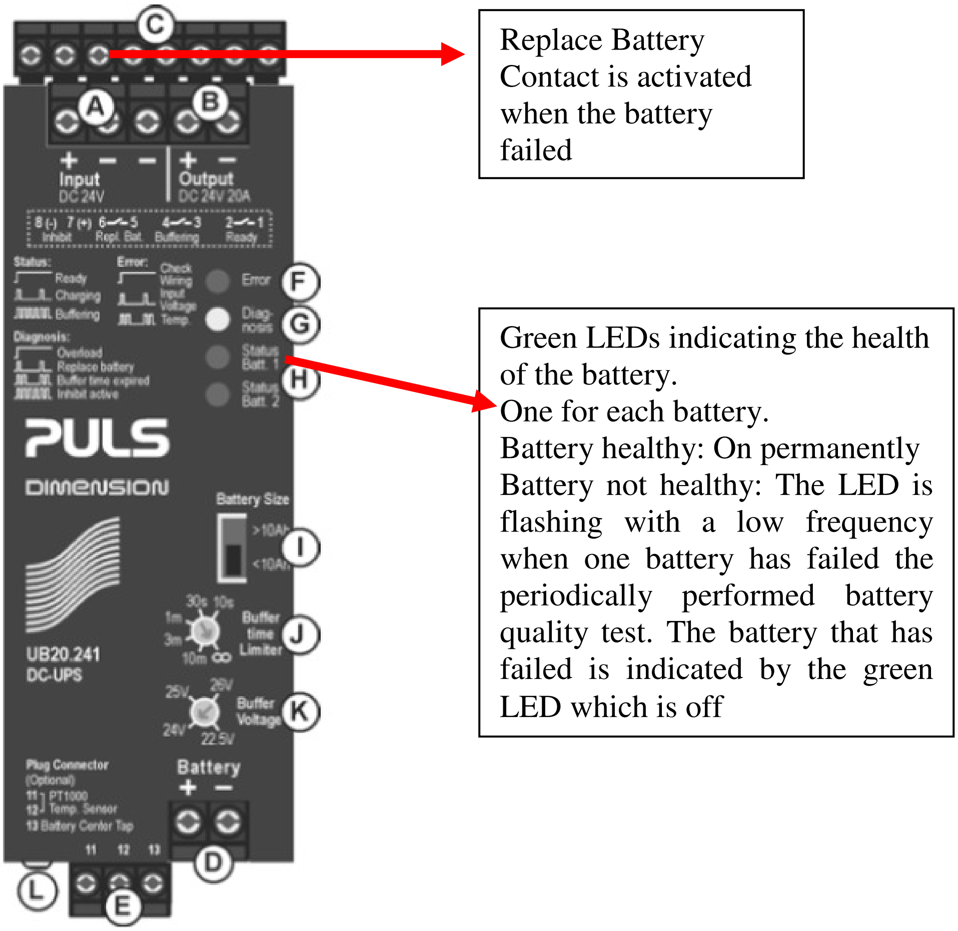


Figure 5.7: LED display pattern to indicate system overloaded

The overload protection of the IPC is activated. Yellow LED is turn on permanently to indicate the power supply is overload. See Figure 5.7.

5.3.3 Battery failure test for (c)

The test perform by experiment #3 (c) is to determine the health status of the battery. It is observed that when a failed battery is connected, the Green LED indicating the health of the respective battery will go off and the replace battery relay contact is activated. See Figure 5.8 for Battery health status LED and "Replace Battery Contact" location.



Replace Battery Contact is activated when the battery failed

Green LEDs indicating the health of the battery.
One for each battery.
Battery healthy: On permanently
Battery not healthy: The LED is flashing with a low frequency when one battery has failed the periodically performed battery quality test. The battery that has failed is indicated by the green LED which is off

Figure 5.8: Battery health status LED and "Replace Battery Contact" location.

5.3.4 Inhibit input test for (d)

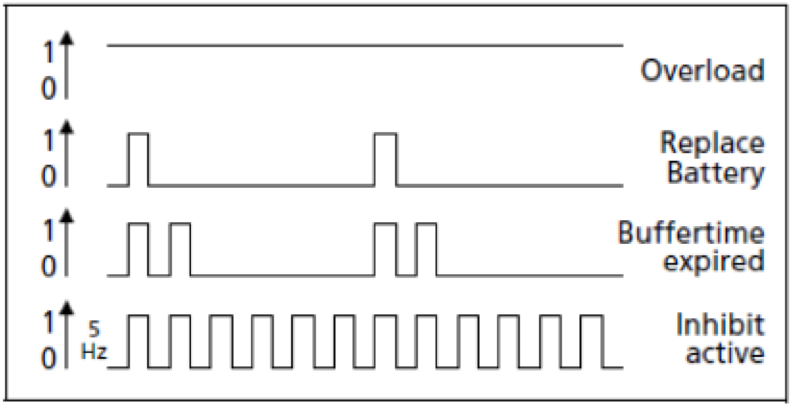


Figure 5.9: LED flashing at high frequency indicating that the inhibit signal is activated

It is observed that when the inhibit signal is activated; there will be no power to the load and the yellow LED is flashing at high frequency as shown in Figure 5.9.

The inhibit input is to disconnect the output of the IPC from the load on purpose. It is used to save battery capacity for example when EV is not in use for a long period of time no power will be delivered to the motor. This will also shorten the recharging time and battery discharge lesser.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

Experiment #1 and Experiment #2

The objective of experiment #1 and #2 is to evaluate the system output voltage with respect to source voltage fluctuation. Two sources are used here namely inlet and battery. The experiment carries out meet the objective.

With inlet voltage:

That means in charging mode, the output voltage to the load is regulated by AC to DC converter. All batteries are charging up. If this design will be using it for EV application it is important to make sure that the AC to DC converter has a good voltage regulation. The AC to DC converter used in this experiment provides 99.06% regulation at 10A load.

With the load powered by battery:

When the load is powered by the battery, the IPC managed to regulate the output voltage even with individual battery voltages fluctuation (battery cell imbalance). The regulation is 99.54% for 48V dc output with 0.12V drop due to back feed protection diode.

Recommendation:

If the design will be implemented for EV application, one additional buck-boost converter is recommended to be added to the design for overall voltage regulation.

During the experiment, it is observed that high voltage drop across the interconnection cable. Therefore it is a good engineering practice to keep the cable as short as possible. On the other hand a good qualify, low resistance cable should be used.

Experiment #3:

The objective of this experiment is to evaluate the battery cell diagnostic function. The diagnostic tested are overload (or short circuit), battery failure and inhibit input. All test performed to give a positive result.

Overload (or short circuit):

Short circuit protection is provided by AC to DC converter when is in charging mode. While in battery mode, the short circuit protection is provided by the IPC.

Battery failure:

IPC is able to detect battery failure such battery cannot be charged, taking too long than expected to charge up. A battery failure or “replace battery contact” will be activated once the IPC detect the failure.

Inhibit input test:

Once this signal is activated, the IPC will cut-off the supply to the load. This feature is catering for motor servicing.

Recommendation:

When battery failed, the IPC only provide “replace battery contact output” to inform the user to replace the battery. This is good but for EV application an indication is not good enough. Besides informing the user one of the batteries need to replace, it also needs to bypass the failed battery to continue function.

The present design is using relay output. The response time of relay contact is too slow to use it to bypass the failed battery. To use it for EV application, the design required to modify by using the battery “failed signal” to indicate battery failure and bypass the failed battery using a high speed and high power switch. MOSFET will be able to meet the requirement.

It is worth exploring the application of “Inhibit input signal” in EV application. This input can be activated when the EV is in the idle situation (example when the EV stops and not moving). It helps to save battery capacity.

Charging and discharging of the battery is very time-consuming. To speed up the design testing, it is recommendaed to test the design using standard simulation software available in the market, for example Matlab

Simscape, before prototype being build. Battery simulations can optimize the electrical system design of EV on their components used and their selection.

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Appendix 1: EUROBAT Guide

EUROBAT

EUROBAT GUIDE FOR THE SPECIFICATION OF VALVE REGULATED LEAD-ACID STATIONARY CELLS AND BATTERIES

This publication is a document commisionned by EUROBAT to increase the awareness, understanding and use of valve regulated lead acid batteries for stationary applications. More specifically, the document provides the 'User' with guidance in the preparation of his Purchasing Specification and in this revision particular reference is made to General Definitions, Product Characteristics, Design Life, Service Life, Safety and Operational Recommendations

GENERAL DEFINITIONS

VALVE REGULATED CELLS AND BATTERIES

A cell or battery which is closed under normal conditions by a non-return (control) valve which allows the escape of gas if the internal pressure exceeds a predetermined value.

The valve shall not allow gas (air) to enter into the cell and the maximum pressure reached inside the cell under any or limited sets of circumstances can be indicated by, or requested from the manufacturer.

The cells cannot receive additions to the electrolyte. This description applies equally to 'Absorbed (AGM)' or 'Gelled' electrolyte.

PRODUCT CHARACTERISTICS

QUALIFICATION

In the absence of any other agreement between the manufacturer and the 'user', the following characteristics may be qualified by test methods in the International Specification, IEC 60896-21/22.
Where a test method is appropriate the text is marked with an asterisk*

FLOAT

Most stationary batteries are electrically 'floating' across the DC supply in parallel with the rectifier and the load and thereby provide uninterrupted power to the system.
The manufacturer shall state the recommended float voltage limits, as defined in IEC 60896-21/22.

RETENTION

Charge retention is important to 'Users' who normally hold stocks of batteries.
Charge retention determines the frequency for recharging batteries held in storage.
*Manufacturers shall state the charge retained.

CAPACITY

Unless otherwise declared by the manufacturer, the Nominal Capacity is defined at 10 hours (C10) at 20°C to 1.80 Volts per cell (Vpc).
Users should note that the numerical value of the capacity quoted is dependant upon the rate, temperature and end voltage of the discharge.
For application purposes other rates of discharge may be requested for capacity.
*User acceptance capacity tests may be agreed separately with the manufacturer and will be subject to contractual negotiation.

CYCLES

This characteristic gives a measure of the endurance of the battery to repeated charge and discharge cycles.
*As a general rule 'Users' should note that the number of cycles is dependent upon the dept of discharge, load and charging regime.

3 - 5 YEARS STANDARD COMMERCIAL

This group of batteries is at the consumer end of standby applications and are popular in small emergency equipment.

6 - 9 YEARS GENERAL PURPOSE

This group of batteries is usually used when an improved life is required in comparison to the Standard Commercial product, and also in cases where operational conditions are more severe.

10/12 YEARS LONG LIFE

This group of batteries is used where high power, long life and high reliability are required.

> 12 YEARS VERY LONG LIFE

This group of batteries is used in applications where longest life and highest reliability are required.

SAFETY

FLAMMABILITY

Some 'users' have operational procedures that require the use of flame retardant plastics materials to a defined rating.

The battery manufacturer shall indicate the category of flame retardancy in accordance with the test methods FV: flame vertical specimen of IEC 60707. This method introduces three categories fo flame retardancy, FV0, FV1 and FV2. The FV0 category is the most resistant to flame propagation.

For the purposes of this publication, the flammability characteristics of valve regulated lead-acid batteries are classified as follows:

S = Standard flammability rating FV1, FV2 or lower.
H = High premium flammability rating FV0.

EMISSION

In normal conditions of use, gas emissions for valve regulated lead-acid batteries are considerably lower than flooded batteries.
Ventilation of battery rooms or cabinets shall be according to EN 50272-2.

INTERNAL RESISTANCE AND SHORT CIRCUIT CURRENTS

Internal resistance can be important to the equipment design and operation. The manufacturer shall state the value of internal resistance for a new battery.

OPERATIONAL RECOMMENDATIONS

SERVICE LIFE

The service life is the value, which is established on the basis of field experience under optimised conditions, describing the time in which a specified capacity or power can be used (optimum application and operating conditions have to be specified). Should the battery be required to perform the full specified discharge duty cycle throughout its life, then a 125% factor for age should be applied in the initial battery size calculation.

FACTORS AFFECTING SERVICE LIFE

Service life is strongly related to the working conditions of the battery.

AMBIENT TEMPERATURE

Operation of valve regulated lead acid batteries on float at temperatures higher than 20°C reduces the battery life expectancy, with 50% life reduction per 10°C constant increase of the temperature. However adjustment of the float voltage according to the ambient temperature might reduce this effect. More information should be available in the manufacturers' specification or operating guide.

In case of elevated ambient temperature float voltage compensation is recommended. Reference should be made to the Manufacturer's recommendations. Temperatures higher than 40°C can produce ever increasing float current values which can create a thermal runaway condition and cause premature failure of the battery.

FLOAT CHARGE RIPPLE

Excessive ripple on the D.C. supply across a battery has the effect of reducing life and performance.
It is recommended therefore that voltage regulation across the system including the load, shall be better than +/- 1% through 5% to 100% load, without the battery connected and under steady state of conditions.Transient and other ripple type excursions can be accommodated provided that, with the battery disconnected but the load connected, the system peak to peak voltage, including the regulation limits, falls within +/- 2.5% of the recommended float voltage of the battery. Under no circumstances should the current flowing through the battery when it is operating under float conditions, reverse into the discharge mode.

FLOAT STABILISATION RIPPLE

This form of ripple arises where the demands of the load are out of phase with the capabilities of the rectifier, and the battery is used to stabilise the system.
Some static UPS systems behave in this manner, and the condition is more like shallow cycling.
In these circumstances, normal battery characteristics no longer apply, and the manufacturer should provide the optimum operational conditions.

DEEP DISCHARGING

It is recommended that at the discretion of the user, low voltage disconnect features should be used in connected equipment.

It is however recognised that there may be circumstances, particularly for system safety reasons, where the requirements for maximum performance would preclude the use of a low voltage disconnect feature.

INSTALLATION AND COMMISSIONING

Cells and batteries should be installed, commissioned and operated in accordance with:

- Manufacturer's Recommendations/ Instructions.
- European Standard EN 50272-2 Safety requirements for secondary batteries and battery installations – Part 2: Stationary batteries.
- Regional/National/ Local Standards for the Environment.

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ACKNOWLEDGEMENTS

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EUROBAT

EUROBAT, the Association of European Automotive and Industrial Battery Manufacturers, acts as a unified voice in promoting the interests of the European automotive, industrial and special battery industries of all battery chemistries to the EU institutions, national governments, customers and the media.

With over 40 members comprising over 90% of the automotive and industrial battery industry in Europe, EUROBAT also works with stakeholders to help develop a vision of future battery solutions to issues of public interest in areas like e-mobility and renewable energy storage.

photographer VERDONCKT STANISLAS

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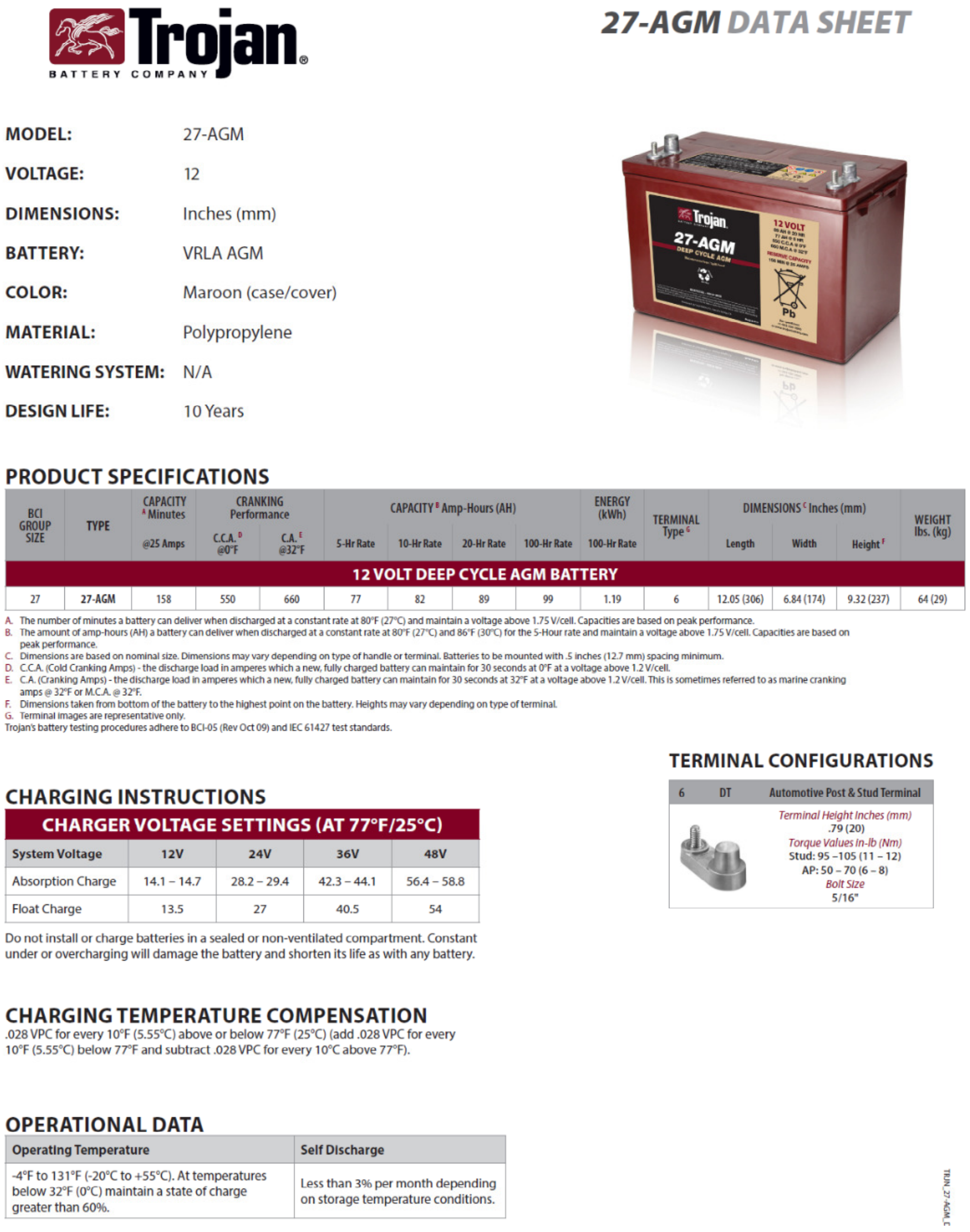
Appendix 2: Trojan Battery Data Sheet



Trojan BATTERY COMPANY

27-AGM DATA SHEET

MODEL: 27-AGM

VOLTAGE: 12

DIMENSIONS: Inches (mm)

BATTERY: VRLA AGM

COLOR: Maroon (case/cover)

MATERIAL: Polypropylene

WATERING SYSTEM: N/A

DESIGN LIFE: 10 Years

PRODUCT SPECIFICATIONS

BCI GROUP SIZE	TYPE	CAPACITY [A] Minutes	CRANKING Performance		CAPACITY [B] Amp-Hours (AH)				ENERGY (kWh)	TERMINAL Type [G]	DIMENSIONS [C] Inches (mm)			WEIGHT lbs. (kg)
		@25 Amps	C.C.A. [D] @0°F	C.A. [E] @32°F	5-Hr Rate	10-Hr Rate	20-Hr Rate	100-Hr Rate	100-Hr Rate		Length	Width	Height [F]	
12 VOLT DEEP CYCLE AGM BATTERY														
27	**27-AGM**	158	550	660	77	82	89	99	1.19	6	12.05 (306)	6.84 (174)	9.32 (237)	64 (29)

A. The number of minutes a battery can deliver when discharged at a constant rate at 80°F (27°C) and maintain a voltage above 1.75 V/cell. Capacities are based on peak performance.
B. The amount of amp-hours (AH) a battery can deliver when discharged at a constant rate at 80°F (27°C) and 86°F (30°C) for the 5-Hour rate and maintain a voltage above 1.75 V/cell. Capacities are based on peak performance.
C. Dimensions are based on nominal size. Dimensions may vary depending on type of handle or terminal. Batteries to be mounted with .5 inches (12.7 mm) spacing minimum.
D. C.C.A. (Cold Cranking Amps) - the discharge load in amperes which a new, fully charged battery can maintain for 30 seconds at 0°F at a voltage above 1.2 V/cell.
E. C.A. (Cranking Amps) - the discharge load in amperes which a new, fully charged battery can maintain for 30 seconds at 32°F at a voltage above 1.2 V/cell. This is sometimes referred to as marine cranking amps @ 32°F or M.C.A. @ 32°F.
F. Dimensions taken from bottom of the battery to the highest point on the battery. Heights may vary depending on type of terminal.
G. Terminal images are representative only.

Trojan's battery testing procedures adhere to BCI-05 (Rev Oct 09) and IEC 61427 test standards.

CHARGING INSTRUCTIONS

CHARGER VOLTAGE SETTINGS (AT 77°F/25°C)

System Voltage	12V	24V	36V	48V
Absorption Charge	14.1 – 14.7	28.2 – 29.4	42.3 – 44.1	56.4 – 58.8
Float Charge	13.5	27	40.5	54

Do not install or charge batteries in a sealed or non-ventilated compartment. Constant under or overcharging will damage the battery and shorten its life as with any battery.

TERMINAL CONFIGURATIONS

6	DT	Automotive Post & Stud Terminal
		Terminal Height Inches (mm) .79 (20) *Torque Values in-lb (Nm)* Stud: 95 –105 (11 – 12) AP: 50 – 70 (6 – 8) *Bolt Size* 5/16"

CHARGING TEMPERATURE COMPENSATION

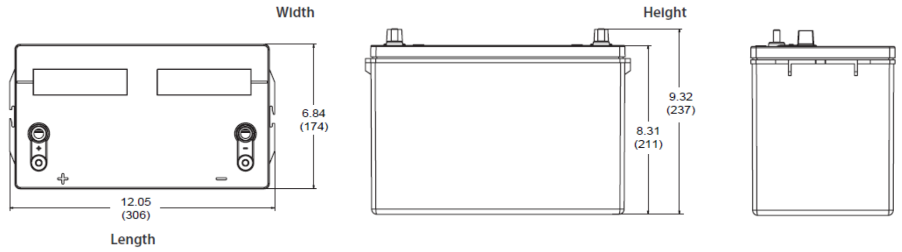
.028 VPC for every 10°F (5.55°C) above or below 77°F (25°C) (add .028 VPC for every 10°F (5.55°C) below 77°F and subtract .028 VPC for every 10°C above 77°F).

OPERATIONAL DATA

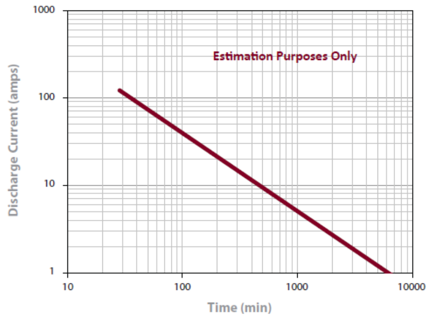
Operating Temperature	Self Discharge
-4°F to 131°F (-20°C to +55°C). At temperatures below 32°F (0°C) maintain a state of charge greater than 60%.	Less than 3% per month depending on storage temperature conditions.

TRJN_27-AGM_C

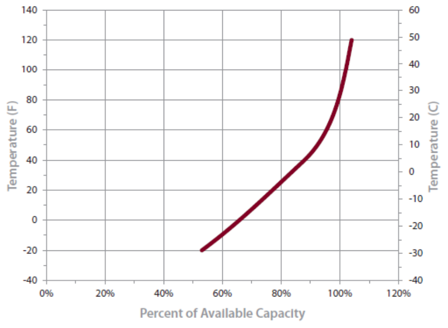
BATTERY DIMENSIONS (shown with DT)



TROJAN 27-AGM PERFORMANCE



PERCENT CAPACITY VS. TEMPERATURE



Trojan's battery testing procedures adhere to BCI-05 (Rev Oct 09) and IEC 61427 test standards.

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IEC
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Appendix 3: Electric Vehicle Charging Standard

EV Charging Standards

Professor Thomas Bräunl
The University of Western Australia
Technical Director WA Electric Vehicle Trial

Quite a lot of progress has been made in EV charging standards over the last few years. This following is a brief summary of the technology and terminology used in EV charging standards IEC 62196, IEC61851 and IE15118.

1. Level

The charging level describes the power level of a charging outlet:

Level 1: Home charging, max. 2.4kW in Australia.
For our 23kWh EV-Works Ford Focus vehicles, this means
10 hours charging from empty to full

Level 2: Fast AC charging, either 7kW (32A single phase) or 21 kW (three-phase). We are using 7kW stations in the WA trial, which means
3 hours charging from empty to full

Level 3: Fast DC charging, up to 50kW, which means
20min. charging from empty to 80% full (for DC charging, the last 20% take a very long time, so DC charging is usually measured up to 80%)

2. Mode

The charging mode describes the safety communication protocol between EV and charging station. These standards are identical worldwide.

Mode 1: Home charging from a standard power outlet with a simple extension cord, without any safety measures. Although this is what many (private) EV conversions use today, “Mode 1” has been outlawed in several countries and Australia is likely to follow.

Mode 2: Home charging from a standard power outlet, but with a special in-cable EVSE (EV Supply Equipment), aka “occasional use cable”, usually supplied with an EV from the manufacturer. This cable provides:

- In-cable RCD
- Over-current protection
- Over-temperature protection
- Protective Earth detection (from wall socket)

Power will only follow to the vehicle if the EVSE has detected:

- Protective Earth is valid
- No error condition exists (over-current, over-temperature, etc.)
- Vehicle has ben plugged in (detected via *pilot* data line)

- Vehicle has requested power (detected via *pilot* data line, usually linked to the car's central locking mechanism)

Mode-2 cables provide a moderate level of safety and are the minimum standard today for charging an EV. (And we have already found a number of incorrectly wired power outlets by using Mode-2 cables). However, most automotive OEMs accept "occasional use cables" (as the name suggests) only for occasional use, e.g. when visiting a friend's house and insist on installing a proper Mode-3 home charging station ("wall-box") in the EV owner's garage for continuous use. Some car manufacturers even make the customer sign an agreement confirming installation of a wall-box at the time of ordering an EV.

Figure 1: Occasional use cable

Mode 3: Wired-in AC charging station, either in public places or at home, allowing a higher power level than Mode 2. The safety protocol is identical to Mode 2.

Figure 2: Charging station at EMC Solar, West-Perth

Mode 4: Wired-in DC charging station, either in public places or at home. In DC charging stations, the charger is part of the charging station, not part of the car.

3. Type

The type of a charging station (or vehicle inlet) describes the actual connector being used. Unfortunately, there are several different world standards and Australia as of today has not yet adopted one of them. The terminology is:

socket:	on charging station
plug:	on cable towards charging station
inlet:	on EV
connector:	on cable towards EV

Type 1: The connector/inlet pair used in the U.S and Japan, aka "SAE 1772" after the corresponding U.S. standard. As the U.S. and Japan do not have a three-phase power grid, this standard is limited to single-phase and lower power output than Type 2. Also note that for Type 1, the charging cable is permanently fixed to the charging station.

Type 2: The connector/inlet and plug/socket pairs used in Europe, aka "Mennekes" after the company first proposing this standard. Type 2 supports both single-phase and 3-phase charging at higher power rates than Type 1. This is why it is expected that Australia will eventually adopt the Type 2 charging standard.

For Type 2 charging stations, the charging cable is detachable, so a Type 2 station can charge both, Type 1 cars and Type 2 cars with the correct charging cables. A Type 1 charging station on the other hand can only charge Type 1 cars, as the cable is fixed to the station and the usage of adapters is prohibited.

Figure 3: Type 2 (left) and Type 1 (right) charging cables

Type 3: France and Italy are campaigning for yet another connector/inlet and plug/socket solution, which has "shuttered contacts", i.e. contacts that are physically covered by a non-conductive cover when not in use. Proponents of Type1 or Type 2 (both non-shuttered) point out that these are safe without shutters, as current can only flow when an EV connection has been detected.

China: One notable exception because of their large market is China. While the Type 2 standard continued to evolve and underwent a number of changes in the last few years, China decided to freeze an earlier (and now incompatible) version of the Type 2 standard as the Chinese standard.

It is expected that Type 2 will be the standard in all countries with 3-phase power grids, which countries without them will adopt Type 1. Type 3 is unlikely to be adopted outside France and Italy. The fact that Standards Australia has not made a recommendation for either Type 1 or Type 2 is not a good situation, as in the mean time both station types and both vehicle types are being imported into the country, creating a legacy problem.

All charging stations installed the WA Electric Vehicle Trial and the EV Charging ARC Linkage Project are Level 2, Mode 3, Type 2 stations. They can AC fast-charge at 7kW (provided the EV has an AC fast charger on board, such as the EV-Works Ford Focus), and can charge either Type 2 cars (all UWA-built cars and EV-Works Ford Focus), as well as Type 1 cars (incl. the currently imported Mitsubishi i-MiEV and Nissan Leaf).

4. DC Charging

While the first DC charging standard was the Japanese CHAdeMO, the leading eight automotive OEMs have now agreed to support the new Combo charging standard, which combines AC and DC charging in a single connector/inlet. CHAdeMO in contrast, is a DC-only standard. So cars with CHAdeMO (such as Mitsubishi i-MiEV and Nissan Leaf) always require two separate connector/inlet pairs, one for AC and one for DC (in many cases even under separate hatches), which makes the car more expensive than necessary. As Combo is incompatible to CHAdeMO, it is expected that CHAdeMO will be replaced by the Combo charging standard in all countries (including the U.S.) except Japan.

Since Combo is compatible to AC-only charging (e.g. at an AC charging station or by using the AC “occasional use cable”), the distinction between Type 1 and Type 2 also exists for Combo stations.

5. Inductive Charging

Inductive charging will be the next big advancement for EV charging over the next decade. A large number of companies are working on getting this technology ready for the next generation of EVs. With this, the debate over which type of charging connector to use might finally be over.

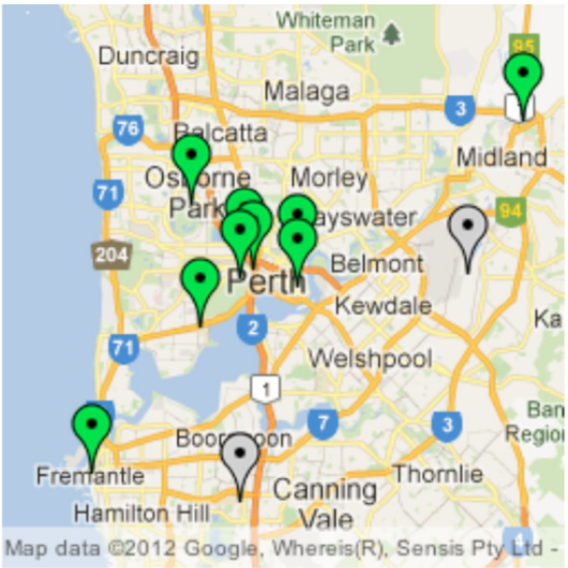

Figure 4: Networked Charging Stations in Charging Linkage Project and WA EV Trial

Contact

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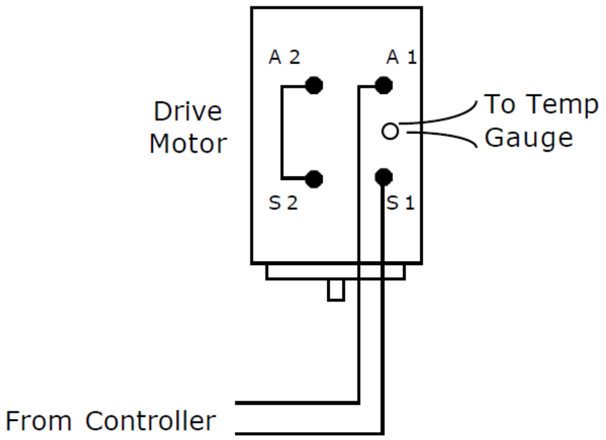
Appendix 4: Wiring Diagram for ADC Motor (Model FB1-4001 144Vdc)

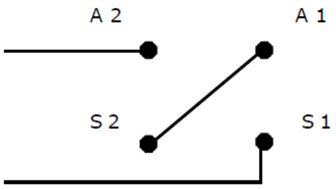
WIRING FOR ADVANCED DC MOTORS

CCW ROTATION

View of Motor Hook-up



CW ROTATION (e.g. Honda)
Phase angle of brushplate needs to be shifted for continuous use and optimum efficiency, or be ordered from factory.



Please contact EVM for any further information/support.

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