UNIVERSITY OF BIRMINGHAM

Energy Storage System for Railway Applications & Analysis and Modelling of Electrochemical Batteries for Conductor Rail Gap DC Railway

Thesis submitted in accordance with the requirements of the University of Birmingham for the degree of Master of research

In

Railway Systems Engineering and Integration

College of Engineering, School of Civil Engineering

By

Siavash Hajiabady & Supervised By Dr Pietro Tricoli

September 2013

Acknowledgements

First and foremost, I would like to express my sincere appreciation to my supervisors Dr Pietro Tricoli, for his support, guidance, inspiration and patience during my MRes study. I have greatly benefited from his knowledge and experience.

I am also grateful to Dr Stuart Hillmansen for his support and advices during my research. I would like to thank Dr Farzad Hayati for his help during my project.

Finally, I would like to thank my family and all my friends. Without their encouragement, support and understanding, this thesis would not have been possible.

ABSTRACT

A new model of energy storage has been created by using electrochemical batteries, which is helpful to analyse the possibility of using batteries for traction systems of DC railway. As a result, there are two opportunities of using batteries energy storage for traction system in DC railway: one is to build On-board applications for covering the discontinuous power supply over the gap; and the other is to build Stationary storage or track side application for recovering the braking energy used by batteries. This model can be used to identify the appropriate batteries for different applications.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
AT	Auto transformer
BR	British Rail
BT	Booster transformer
C	Nominal capacity
CAES	Compressed air energy storage
DC	Direct Current
DOD	Depth of discharge
EDLC	Electronic double layer capacitor
ESS	Energy storage system
FBs	Flow batteries
FES	Flywheel energy storage
GWR	Gloucestershire Warwickshire Railway
LMSR	London, Midland and Scottish Railway
LNER	London and North Eastern Railway
Li-ion	Lithium-ion
Li-polymer	Lithium polymer
Ni.Cd	Nickel–cadmium
Ni.MH	Nickel metal hydride
Pb-Acid	Lead-Acid
ROS	Remote Operation System
SOC	State of charge
SR	Southern Railway
SLI	starting, lighting, ignition
VRB	vanadium redox battery
V_{oc}	open circuit voltage
V_t	Terminal voltage

Chapter 1

Literature Review, Objectives and Methodology of the Project

1.1 Introduction

Energy storage technologies have made significant strides in helping to alleviate major issues in the railway domain. They help to reduce overall peak energy demand of the railway system. Kadhim (2009) identifies the powering of using energy storage in railway, which can be classified as three aspects:

1. Diesel vehicle (and fuel cell) hybrids;
2. Electric vehicles using batteries only (on-board energy storage);
3. Trackside applications on DC electrified lines (stationary energy storage).

Energy storage technologies face four major challenges that are:

1. Cost,
2. Lifetime,
3. Size,
4. Weight.

This project aims to evaluate the feasibility of the usage of energy storage systems in the railway. This document will also investigate ways to mitigate the problems arising due to DC electrification gaps on the lines. This would help reduce the capital costs associated with electrifying these sections, bring energy savings and improve the overall safety and reliability of the systems.

1.1.1 Brief History of British Rail

The history of British Rail (BR) can be traced back to post-war rail travel in the UK, and it is undoubted that the development of BR reflects the overall development of the national railway network.

BR had played a significant role in transforming a collection of exhausted and post-war steam operators into the modern network between 1948 to 1997. (rail.co.uk, 2013)

In 1948, the UK government decided to modernise its fleet of steam traction with diesel and electric power locomotives. With the ever increasing share of road haulage in freight this move was to help the railways become more competitive in the freight market.The closure of the coal mines and the privatisation of the ports led to a decrease in demand for rail transport. The passenger segment, which until then was viewed only as an additional income, became vital to the railways' finance book. Dr. Beeching's reports (Beeching, 1963) in 1963 led to the closure of one thirds of the national railway network. (rail.co.uk, 2013)

The year of 1962 can be regarded as a milestone of BR that became an independent statutory corporation following the nationalization of the "Big Four" UK railway companies, i.e LNER, LMSR, GWR and SR. Meanwhile, it took the responsibility of overseeing the transformation of the UK network until its privatisation in the 1990s (rail.co.uk, 2013).

1.1.2 Different Type of Railway Feeding Systems

Currently, almost 40 per cent of the British rail network is electrified (Rail, 2009). The railways use both AC and DC feeder systems. The UK standard for AC systems is to use an overhead line configuration electrified by 25kV, 50Hz. AC systems use high voltage in order to reduce power loss. DC system uses 3000, 1500, 750 or 600 Volts (3000 Volts DC is not use in UK); also, they are available either for overhead lines or a third rail.

Distances between substations in DC are about 3 to 5 km (Oura, 1998); typical DC railway system is shown in Figure 1:

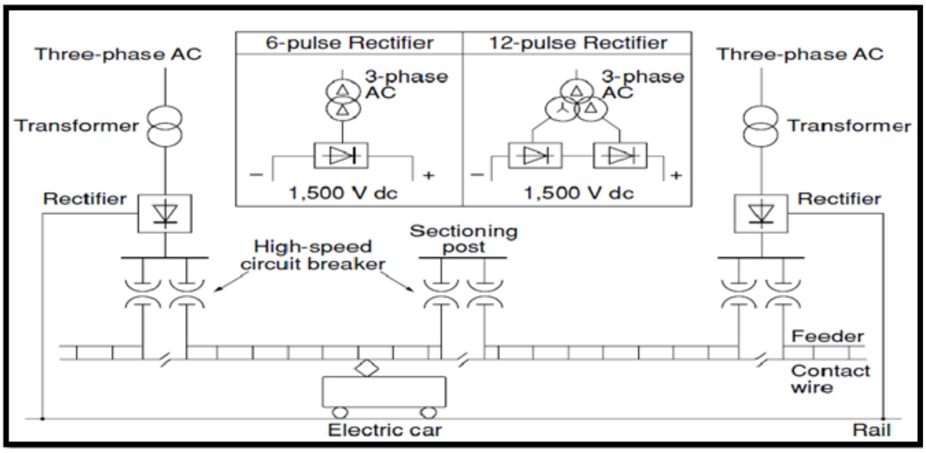

Figure 1 Structure of DC Feeding System (Oura, 1998)

AC feeding system has two types of feeding systems: auto transformer (AT) and booster transformer (BT). A BT is installed every 4 km along the track to boost the return circuit current on the negative conductor; the BT feeding systems is presented in figure 2. In the AT feeding system, the feeding voltage of the substation is doubled the voltage supply to the train. An AT, each 10 km along the contact wire, and reload the current from the rail to the overhead line voltage (Oura, 1998); which is performed in an AT feeding system in Figure 3.

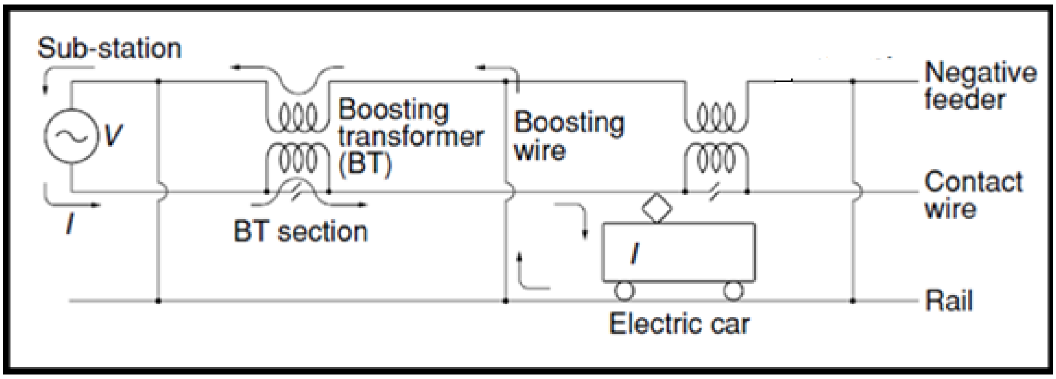

Figure 2 BT feeding system (Oura, 1998)

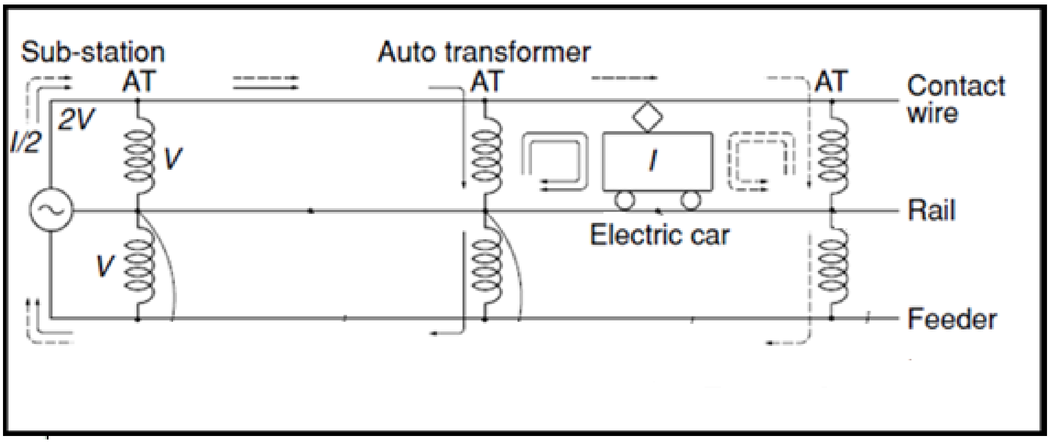

Figure 3 AT feeding system (Oura, 1998)

1.2 Review of Electrical Energy Storage

Parfomak claims that energy storage technology has great potential to improve electric power grids; in order to allow expansion in renewable electricity generation, and provide an alternative to crude oil based fuels in the transportation sector. (Parfomak, 2012)

Electrical energy storage devices essentially convert electrical energy into other forms of energy, chemical energy, which can be stored and used when required. The option of the ESS for an application is dependent on its power, energy ratings, response time, weight, volume, and operating temperature. Table 1, shows the details of different types of energy storage systems.

Table 1: Energy storage systems (Vazquez, 2010)

ENERGY STORAGE SYSTEMS

Type	Energy Efficiency (%)	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life (cycles)	Self Discharge
Pb-Acid	70–80	20–35	25	200–2000	Low
Ni-Cd	60–90	40–60	140–180	500–2000	Low
Ni-MH	50–80	60–80	220	$<$ 3000	High
Li-Ion	70–85	100–200	360	500–2000	Med
Li-polymer	70	200	250–1000	$>$ 1200	Med
NaS	70	120	120	2000	–
VRB	80	25	80–150	$>$ 16000	Negligible
EDLC	95	$<$ 50	4000	$>$ 50000	Very high
Pumped hydro	65–80	0.3	–	$>$ 20 years	Negligible
CAES	40–50	10–30	–	$>$ 20 years	–
Flywheel (steel)	95	5–30	1000	$>$ 20000	Very high
Flywheel (composite)	95	$>$ 50	5000	$>$ 20000	Very high

1.3 Different Types of Energy Storage

There are several technologies employed in the energy storage system industry. However, this report shall consider only the systems that are suitable to use on the railway system: Battery, Super Capacitors, and Flywheel. Each will be introduced and explained in the flowing sub-chapters. However Superconducting Magnetic Energy Storage (SMES) (ltd, 2012) also can be consider for railway industry, but currently this type of energy storage has not been used for many railway applications.

1.3.1 Batteries

A battery is made by electro-chemical cells, which normally consists of an anode, a cathode, and an electrolyte; all the equipment's are fitted in a container. Batteries convert chemical energy into electrical energy.

For choosing correctly a battery pack, the specific application must be considered; therefore, it is essential to understand some more details on battery. In order to use batteries for railway application first of all, it is necessary to know the characteristics of trains, such as input voltage, maximum power, maximum current, and characteristic of the electrification system.

(David Linden, 2002) Then, the battery pack should be chosen on the basis of voltage required by the railway and power required by the train.

Besides, the capacity of battery is dependent on the system current. For example, when it is displayed on battery data sheet that the capacity is 100Ah@20 hour, it means that 100 Ah can be released if the battery is discharged in 20 hours. Therefore, when the battery is discharged in 5 hours, the capacity of battery would be less then100 Ah. (David Linden, 2002)

In order to choose a battery pack, the C-rate of a battery must be considered. The C-rate is normally used for indicting the charge and the discharge currents of a battery. Most portable batteries are rated at 1C, which means that 1Ah battery provides 1A for one hour when it is discharged at 1C rate; in other words, 1C is 1 hour or 0.2C is 5 hours. (Buchmann, January 2004)

The battery data sheet is based on the assumption that the battery is fully charged. It is therefore necessary to make ensure that a battery is 100% charged in order to collect accurate information on the battery during testing.

There are various approaches to measure the State of Charge (SOC) of a battery. The most common method relies on using the voltage across a battery cell, in order to determine the SOC of a battery. For example, 12V Li-ion battery has 14.4V when the state of charge is 100%; however, its complete discharge is only 9.6V. Consequently, different voltages of battery reflect different SOC. (Lee, 2007)

1.3.1.1 Different Types of Batteries

Batteries remain one of the most commonly used energy storage solutions today. There is no lack of choice on the type of battery to use in a particular situation. The following sections discuss the types of batteries which are available commercially.

1.3.1.1.1 Lead Acid Batteries

The oldest rechargeable electro-chemical batteries are known as Lead acid batteries, which have been in use since the mid-1800s. (Vazquez, 2010) Lead acid batteries are made in different categories by size, and they range from the small 1 Ah units to the large units of 3000 Ah. Lead-acid battery normally has a cell potential of 1.2V, specific energy of 35-50

Wh/kg, and energy density of 100 Wh/L. Lead-acid batteries are normally have C/20 discharge rate, where C is the capacity of the battery in Ah. (Bullock, 1994) Figure 4 shows different part lead Acid batteries.

Figure 4 Cross section of Lead Acid Battery (REUK, 2006)

1.3.1.1.2 Nickel Metal Hydride Batteries

A nickel–metal hydride battery is one type of rechargeable battery. It uses a chemical composition of either lithium-nickel or titanium-nickel alloy; also, it makes use of potassium-hydroxide electrolyte, to reform the NiMH cell. Nickel metal hydride batteries have high capacity, but its cell potential is only 1.35V. Nickel–metal have a higher energy density and longer cycle life than lead acid batteries. The specific energy is approximately 95 Wh/kg and the energy density is roughly 350 Wh/L. (Kadhim, 2009).Figure 5 shows how nickel–metal hydride battery is made.

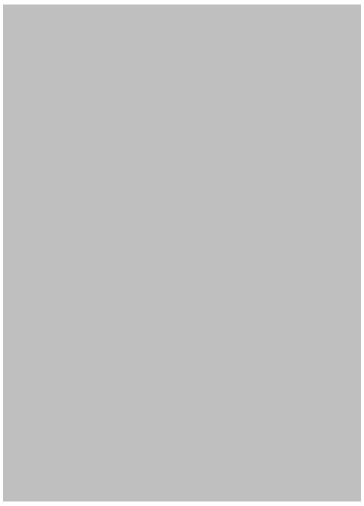

Figure 5 Cross section of Nickel Metal Hydride Batteries (Rosch, 2001)

1.3.1.1.3 Lithium-Ion Batteries

A lithium-ion cell contains a Lithium-manganese-oxide alloy as cathode and the anode is carbon. The cell voltage of lithium ion batteries is as high as 4.1V when the circuit is opened, the specific energy is around 125 Wh/kg, and the energy density is more than 300 Wh/L. The most important advantages of this battery technology are high energy-to-weight ratios, no memory effect, and a low self-discharge rate. (Lee, 2007). It is very appropriate for hybrid vehicle applications due to its large energy density. Figure 6 shows charge mechanism of Lithium-ion and Figure 7 displays discharge mechanism of Lithium-ion.

Figure 6 Lithium-ion charge mechanism (Brain, 2006)

Figure 7 Lithium-ion discharge mechanism (Brain, 2006)

1.3.1.1.4 Sodium - Sulphur (NaS) Batteries

A sodium–sulphur battery belongs to the category of molten-salt batteries, which is made by liquid sodium (Na) and sulphur (S). Its characteristics can be summed up as: a high energy density, high efficiency of charge/discharge (89–92%), and a long cycle life, as a result, it has low cost. Besides, it has a solid electrolyte membrane between the anode and cathode. During discharge possess positive Na ions flow through the circuit of the battery producing about 2 Volts. This process is reversible when current is supplied from an external source. Figure 8 illustrates the cross section of a sodium–sulphur battery (Blog, 2006).

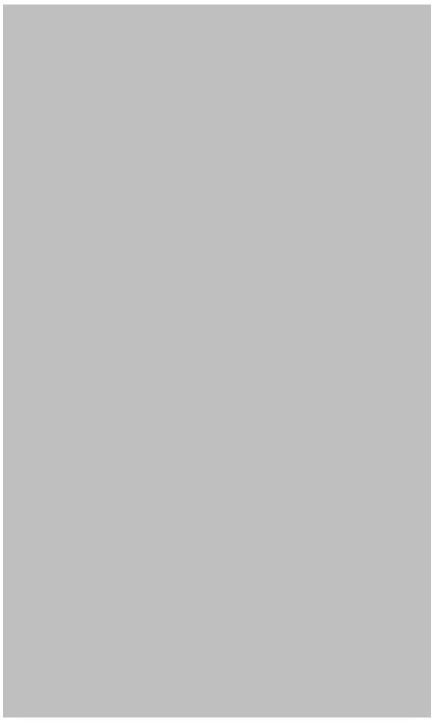

Figure 8 Cross section of a sodium-sulphur battery (Blog, 2006)

1.3.1.1.5 Flow Batteries

As a potential technology, flow batteries (FBs) are available to decouple the total stored energy from the rated power, which mainly depends on its reactor size; when the auxiliary tank volume is depended on the stored capacity. As a result, FB is undoubtedly a better choice for supplying large amounts of power and energy required by electrical applications. FBs have similar operational principles as hydrogen fuel cells (FCs) due to its two major structures. They use two electrolytes, which are stored in different tanks, hence eliminating self-discharge. The micro-porous membrane allows only selected ions to cross through it in order to create an electrical current, but it separates the electrolytes physically. The following Figure shows how flow batteries are work.

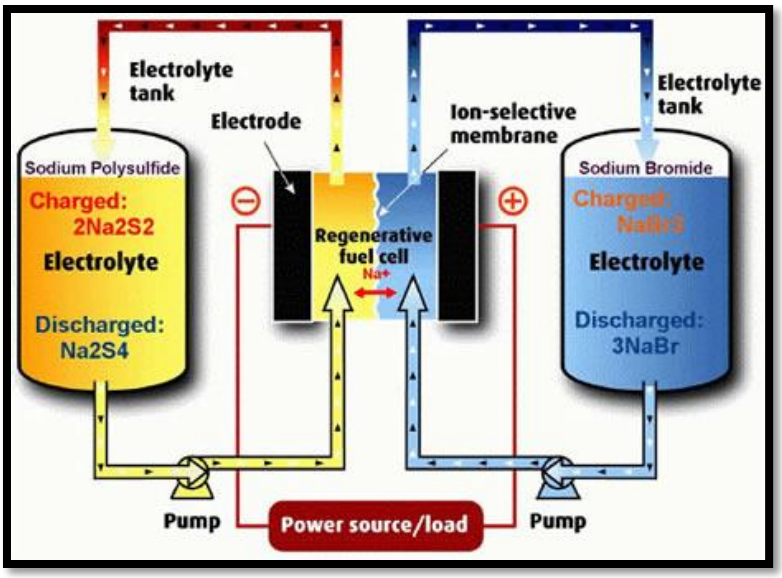

Figure 9 Schematic of flow battery (THOMAS, 2007)

1.3.2 Super-Capacitors Technology

Capacitors store energy by separating two metal foil plates by a dielectric film. Super capacitors on the other hand rely on a different principle for storing charge. Charge is stored in the form of a Helmholtz double-layer. This is formed at the interface between the surface of an electrode and the surface of an electrolytic solution. The distance of separation of charge in a double-layer is of the order of a few angstroms (0.3-0.8 nm) and it is static in origin. Super-capacitors are also known as electric double layer capacitors (EDLC) (Conway, 1999). They do not have a conventional solid dielectric film. Figure 10 shows structure of electric double-layer capacitor. (Hanmin Lee*, n.d.)

Figure 10 Figure 10 Structure of electric double-layer capacitor (Hanmin Lee*, n.d.)

Charge dissipation in super-capacitors occurs at the interface, rather than occurring in the electrode material itself. That's why they have fast pulse response times; also, they have longer life cycle than electro-chemical cells, by orders of several magnitude. Super capacitors, in terms of life time, depth of discharge, operating temperature range, and power specific ratios, are better than batteries. However, they don't have good specific energy compared with batteries (Kadhim, 2009).

South Korea Railway is a good example in this case, who attempts to build ELDC to regenerate energy from braking. It is reported by Korea Railroad Research Institute that, 90% of Railway energy is used for traction while 10% of Railway energy is spent on back-up supply; besides, 40% of energy consumption is wasted on braking. In other words, it is possible to save up to 40% of train power for the power supply; in order to accelerate the train. (Hanmin Lee*, n.d.)

1.3.3 Flywheels for Energy Storage

Flywheels are one of oldest systems for storing energy, and it has been used for hundreds of years. Generally, flywheels energy storage systems utilize kinetic energy that is stored in the rotor, which is known as mechanical batteries (Whittingham, 2008). Their specific energy is around 130 (W/kg) while their specific power is about 500 (W/kg).

Flywheel has typical capacities starting from 1 kWh (Whittingham, 2008) onwards, with the capability of providing megawatts of power for a few seconds. Unlike batteries, they are not suitable to store energy for a longer period of time. Finally, they are approximately 80% efficient. (Whittingham, 2008). Figure 11 displays one type of flywheel energy storage.

Figure 11 Flywheel (Schoenung, 2002)

1.4 Energy Storage in Different Railway Applications

The applications for using energy storage in railway can be classified into two major types:

1. Stationary storage applications or trackside energy storage applications,
2. On-board energy storage system or mobile storage application

The following sections provide greater detail on each of these types.

1.4.1 Stationary Energy Storage Application

Stationary energy storage systems are a popular choice for industrial transmissions and distribution power networks in most countries, chiefly in the United States of America. (Kadhim, 2009) Stationary storage (or track side application) is made by installing one or more energy storage systems alongside the tracks. It helps recover the braking energy from the line during periods of low demand. However, this type of system is configured for use only on DC electrified railways as AC electrified railway systems are inherently receptive. Because AC electrified system normally have lower levels of transmission loss, which is one of the main reasons to use stationary energy storage on a DC railway. ((STIB), 2011) . Figure 12 illustrates DC voltage network with stationary energy storage.

Track side application has the following of advantages.

1. It is available for all vehicles running on the same line.
2. It reduces of the peak power demand by averaging loads over a period of time.
3. Storage devices could be useful to increase the number of vehicles without the improvement of the electrical supply systems.
4. It is environment friendly ((STIB), 2011); as it helps to reduce and remove heat caused due to mechanical braking from a closed environment like a tunnel. This especially helps in reducing air-conditioning costs in the tunnel for underground metro networks.
5. Lastly, it is available in different sizes and configurations to meet the demand of each railway.

On the other hand, track side application has some assignable disadvantages as well.

1. Its capability depends on the distance from the train. It cannot account for the losses due to transmission from the location of the train.
2. It cannot recover all the braking energy and some energy could still be lost in the barking resistors.
3. It is impossible to have catenary-free for trains.
4. Lastly, its position, alongside the track, may create a problem in some situations. ((STIB), 2011)

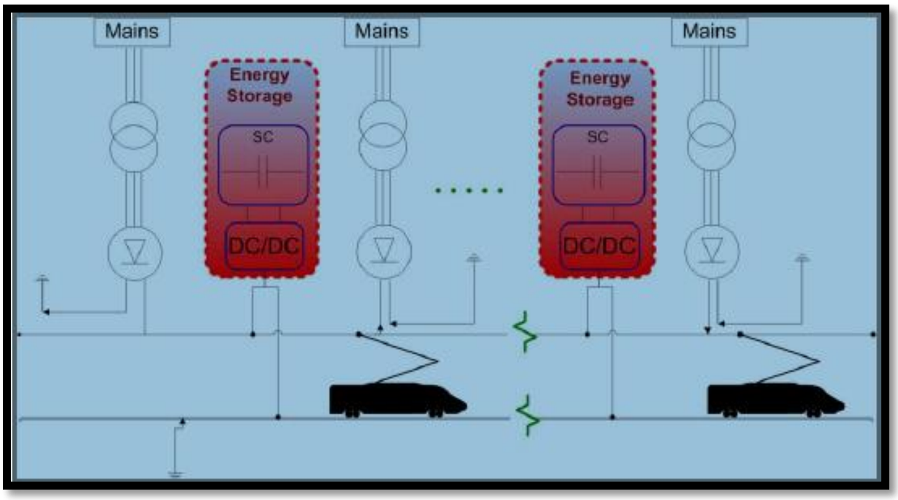

Figure 12 DC voltage network with stationary energy storage (R Barrero1∗, 2009)

1.4.2 Onboard Energy Storage Application

Onboard or mobile energy storage application is generally placed on the roof of the vehicle ((STIB), 2011). As a result, the operation of each onboard system is independent, that recovers braking energy and sends the energy directly to the storage energy system which is also located on the train. Therefore, the energy will be available for using anytime when the train requires it; for example, when the train needs to accelerate out of a station from a standing stop, when the train requires power supply for complex situations such as when there is a break in the third rail or overhead line or when the train face some sections of neutral electrification such as in tunnels or on bridges. ((STIB), 2011) Figure 13 presents onboard energy application.

Figure 13 On-board energy storage application (Steiner, 2005)

There are three possible situations where a locomotive can face a discontinuity in power supply. In each of these cases different energy storage design should be considered, it can be designed as following:

I. For the case of gaps having short length (10 to 20 metres), it is unnecessary to have energy storage.
II. For the cases of small breakings which electrification has 100s of metres, small energy storage such super capacitors and flywheel can be used. This usually happens at crossovers, junctions, level crossings, brides, and so on. In this case, super capacitors are the preferred choice. (Kadhim, 2009)
III. For the case of long discontinuous electrification that energy storage powers a train for a long distance, such as few kilometres, battery is greater. Kadhim defines this system as discrete electrification. (Kadhim, 2009)

Three different discontinuous power supplies are shown in Figure 14.

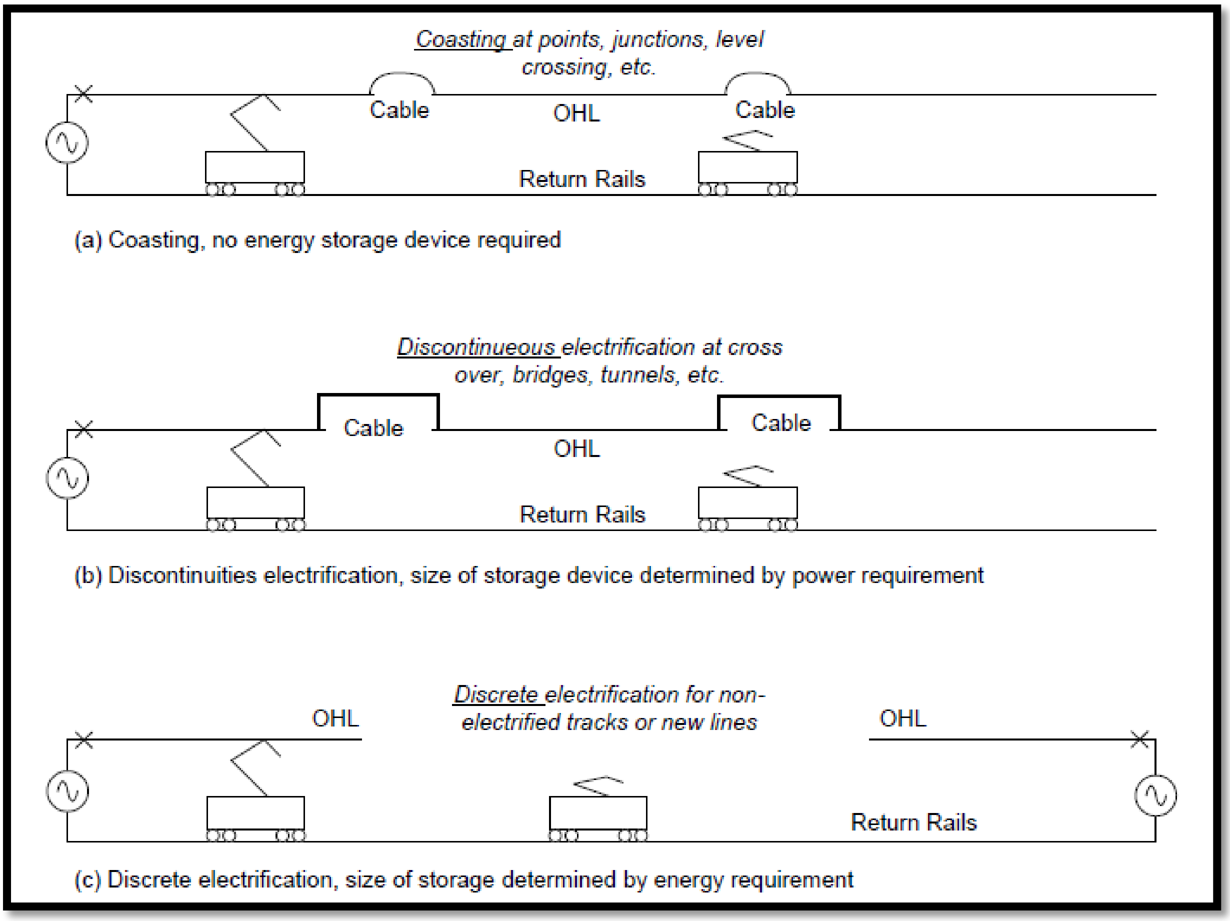

Figure 14 Figure 14 discontinuous power supplies (Kadhim, 2009)

1.5 Power Converters

Power converters, in their broadest sense, have the function to transform electrical power from one type to another. According to traditional literature, they can be classified as four types: AC/DC, AC/AC, DC/AC, and DC/DC converters.

Two different types of AC/AC and DC/DC converters are available, which are step-down and step-up. In the step-up converter output voltage is higher than input voltage; in step down converter output voltage is lower than input voltage.

Another type of type of DC-to-DC is buck–boost converter, which has an output voltage magnitude that is either bigger or lower than the input voltage magnitude.

In order of use batteries as energy storage for railways, Bidirectional DC/DC converters are essential. Bidirectional DC/DC converters have both features of step-down and step-up converters.

Railway voltage supply demands that a large number of battery cells are connected in series. This leads to the possibility of unbalancing of the cells' voltages over time. Such unbalancing occurs when a number of cells are connected in series. Each individual cell in a battery has fairly different capacity and may be at different State of Charge, therefore causing the entire batter to have an unbalanced voltage (Arendarik, 2012).

Hence power converters play a vital role in order to use energy storage on a railway. Firstly, they help to step-up the voltage, hence reducing the number of cells in series. Secondly, they help manage the discharge and recharge of batteries.

Theoretically, the imbalances of battery cell voltage are typically caused by the differences among cell residual capacities, internal resistances, degradation, and the ambient temperature gradient during charging or discharging. (Lee, 2006)

In the absence of a converter the current from the batteries is subject to internal resistance. But with use of the converter, it is possible to control the flow of current from and to the battery, so control of charge and discharge cycles is gradable.

Figure 15 Shows diagram of Bidirectional DC/DC converter.

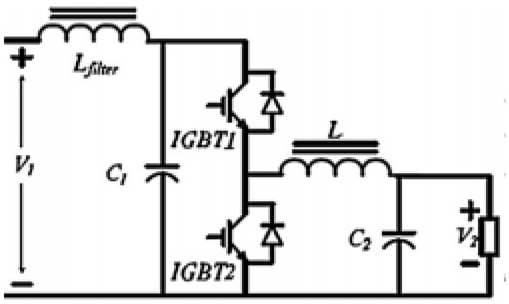

Figure 15 Bidirectional DC/DC converter

1.6 Summary and Discussion

Energy storage technology has great impacts on transportation sector. Besides, the categories of energy storage are various. The report is emphasized on introducing three common storage types for railway system: batteries, super-capacitors, and flywheels. A battery is made up by a large number of electro-chemical cells, which normally consists of anode, cathode, and electrolyte. Batteries simply convert chemical energy into electrical energy and vice versa.

Many battery technologies are currently available: Lead Acid, Nickel Metal Hydride Battery, Lithium-Ion Battery, NaS, and FB. As a result, it is essential to understand different applications, purpose, and the details of different batteries. Super-capacitors get charge from the separation of charge in the Helmholtz, double layer at the interface between the surfaces of a conductor electrode and an electrolytic solution electrolyte. Compared to batteries, they have better performances on life-time, deep of discharge, operating temperature range, and specific power. Flywheels are regarded as one of the oldest systems for storing energy, and have been used hundreds of year. Their characteristics are similar to those of super-capacitors, with high power densities and a very large number of charge and discharge cycles.

Additionally, the applications for using energy storage for railways can be classified as two categories, stationary storage application or trackside energy storage application, and on-board energy storage application or mobile storage application. General speaking, stationary energy storage system is a popular choice. On-board or mobile energy storage application is independent, which recovers braking energy and sends the energy directly to the storage energy system that is also located on the train.

Finally, converters are discussed in this chapter. It can be classified as four types: AC/DC, AC/AC, DC/AC, and DCDC converters. It is functional to transform electrical power from one type to another. Meanwhile, it is useful to mitigate the problem of the imbalance caused by the series connection of battery cells.

1.7 Project Objectives

The most important objective of this project is to develop a method to design a battery storage system to powering the train over the conductor rail gap as the power supply, in order to do that model of battery must be designed.

In order to model the battery it is necessary to develop a method which can determine the key parameters of batteries from the discharge tests. The proposed methodology is a model based approach, that is, to develop a mathematical model of the battery which can represent the dynamic performance and battery status and characteristics can be investigated through the analysis of the model.

The first stage of the project is to produce a mathematical model of battery. The dynamic model is expected to reflect the relevant behaviours of battery when being discharged including the characteristics of State of Charge, Discharge Current, Battery Voltage and Terminal Voltage. The unknown parameters in the model will be identified by using battery cycler with the laboratory experimental data.

The focus of this work is to develop a suitable method for parameter identification for common battery systems for DC railway application. The lead-acid battery has been chosen because it has relatively well defined properties and there is a wealth of literature describing the performance of these types of batteries. From an experimental view point they are also readily available of low cost.

Furthermore this project focuses on conductor rail gap which has issue in supply power system. In order to establish an ideal gapping arrangement, this model is developed in MATLAB to show the effect of gaps on train performance. It also simulates the potential solution for this issue. Finally this project focuses on London underground conductor rail gapping issue and therefore tried to discover the most convenient type of energy storage in order to keep train performance remain the same during each gap.

1.8 Methodology

In order to establish the most suitable solution for this project, there are number of steps that need to be considered:

1- In order to identify and inspect electrochemical batteries (or other types of energy storage) and inspect their behaviour, a test must be designed to be able to model the batteries based on different scenarios and requirements.

2- To understand how DC railway works, DC railway traction system with conductor rail gap models should be designed. The MATLAB/ SIMULINK computer program tool can be used to model the traction system based on real data's provided from the London underground.

3- An example of design the energy storage system has been designed based on the real data's provided from London underground for the DC railway traction system while the train passes the conductor rail gaps for London underground- Victoria line. In order to find the most suitable type of Energy storage system for this design.

Figure 16 demonstrate the block diagram of DC railway with use of energy storage system, which must be design in this project.

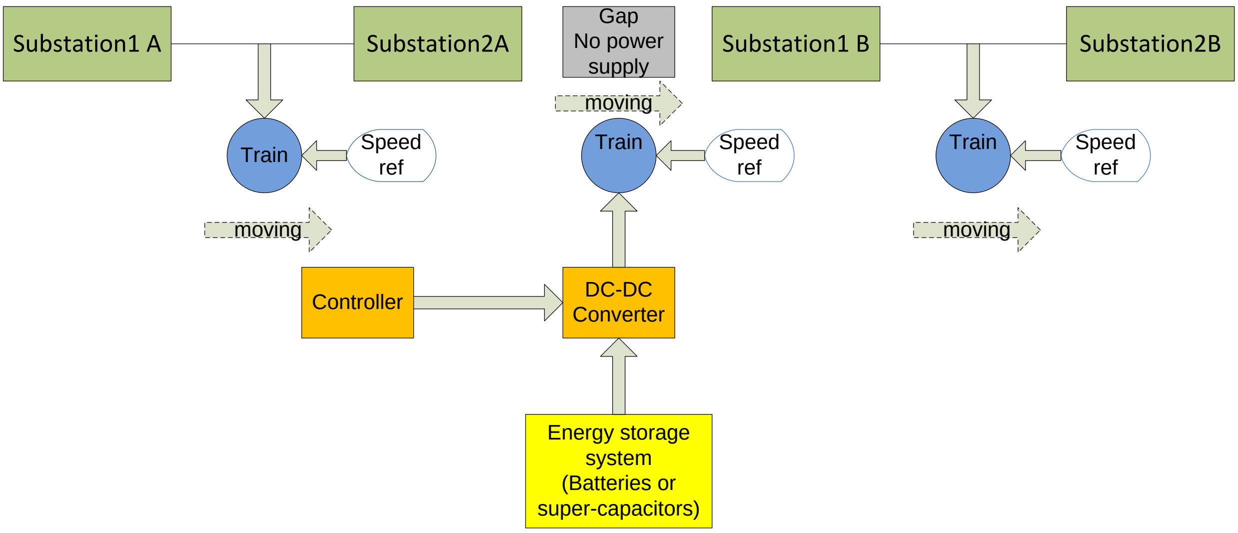

Figure 16 Block diagram of DC railway

1.9 Outline of the Thesis

The thesis is organised into five chapters and the first chapter presents the background and motivation of the research project. The remaining chapters are briefly described as follows:

Chapter 2: Throughout this chapter a Lead-Acid (model 689-5854) battery has been tested. There are numbers of tests carried out about charges and discharges of the battery with different rate of current to characterise this type of battery.

Chapter 3: Throughout this chapter the MATLAB/ SIMULINK computer program tool is used for modelling the DC railway traction system with conductor rail gap. Energy storage system has been designed in simulation to contribute enough power for the train while passing each gap.

Chapter 4: Design the suitable energy storage for DC railway traction system through the Conductor Rail Gap for London Underground- Victoria line. Therefore, in this part in order to keep the train performance remain the same during the gaps, different types of energy storage such as batteries and super capacitors has been designed to find the suitable solution for powering up the trains though the gaps.

Chapter 5: This is the final chapter. This chapter contains the conclusions of the project and possible future work.

Chapter 2

Battery Designs for Different Applications

The use of lead-acid batteries is widely seen in many applications. Therefore various designs are required due to the nature of the working environments and duty cycles. One of the most commonly used lead – acid batteries in the industry today are known as SLI batteries which are designed for a burst of energy needed to cold – crank an engine. Once the engine is started the battery will be recharged immediately. SLI battery is widely used in applications where high electric current is required over a short period of time which has led to its unique and effective design of a larger surface area of electrode plated comparing to other types of lead – acid batteries. Although the repeated deep discharge of the battery may reduce its lifetime, however; the deep cycle batteries are designed to withstand frequent and deep discharge cycles as the plates used in these batteries are typically very thick. On the other hand the smaller surface area of a deep cycle battery results to its lack of ability to provide as much power as the SLI types.

In addition; marine batteries are also used to backup power supplies and providing power in emergency circumstances. Standby batteries are amongst the most frequently seen marine batteries used in applications where long lifetime and large capacity is required and repeated discharge and high current drain does not occur frequently. On the other hand; traction batteries are designed for regular deep discharge cycles and higher current drain. This leads to these types of batteries to be slightly bigger and heavier than the other types of the lead – acid batteries.

2.1 Mathematical Descriptions of Lead-acid Batteries

Throughout this chapter, the studies and researches that have been carried out on a lead – acid battery to investigate behaviour of batteries and described in depth using concepts such as: Capacity, State of Charge (SOC), Depth of Charge (DOD), internal resistance and quantitative descriptions of these concepts.

2.1.1Capacity

The capacity of a battery represents the amount of the electrical charge available and it is often described in Ampere-hours (Ah). The capacity of a battery depends on the construction factors of the cells that include the materials contained in the electrodes and the acid solution. Besides the capacity of a battery is not a fixed quantity but depends on to the discharge rate. According to the Peukert's law (LUC FRUCHTER, 1986)

$C_p = I^k t$ **Equation 1**

Where C_p is the capacity at one-ampere discharge rate, and it is a constant.

I is the discharge current (A)

t is the time of discharge (h)

k is the Peukert constant and for a lead-acid batteries has a value between 1.1 and 1.3 (varies for each individual battery)

It is common to refer to "*Cn*" as the capacity of battery in Amp-Hours which corresponds to complete discharge of the battery in *n* hours. "*n*" is a subscript that represents the discharge rate. In industry, the capacity under ten-hour discharge rate (*C10*) is usually taken as the nominal capacity.

2.1.2 State of Charge and Depth of Discharge

State of charge (SOC) and depth of discharge (DOD) are variables which describe the battery charge. The main difference between the two is that the SOC describes the percentage of remaining charge relative to the nominal capacity while the DOD represents that relative to the actual capacity under a specific discharge current rate. These two variables can be obtained by calculating the charge supplied and the battery capacity:

$SOC = 1 - Q_e / C$ **Equation 2**

$DOC = 1 - Q_e / C_I$ **Equation 3**

Where Q_e is the charge consumed by the load (Ah)

C is the nominal capacity (Ah)

C_I is the actual capacity under the discharge current I (Ah)

Figure17 illustrates the Mathematical model of lead-acid battery which has been selected to demonstrate SOC of a battery under the different discharge current and the time taken to discharge the battery, which is calculated by equation4.

$$SOC = 1 - \frac{\int_0^t I_m(\delta)d\delta}{C_{I_m}} = 1 - \frac{I_m}{C_{I_m}}t \quad \text{Equation 4}$$

I_m is sicharge current rate.

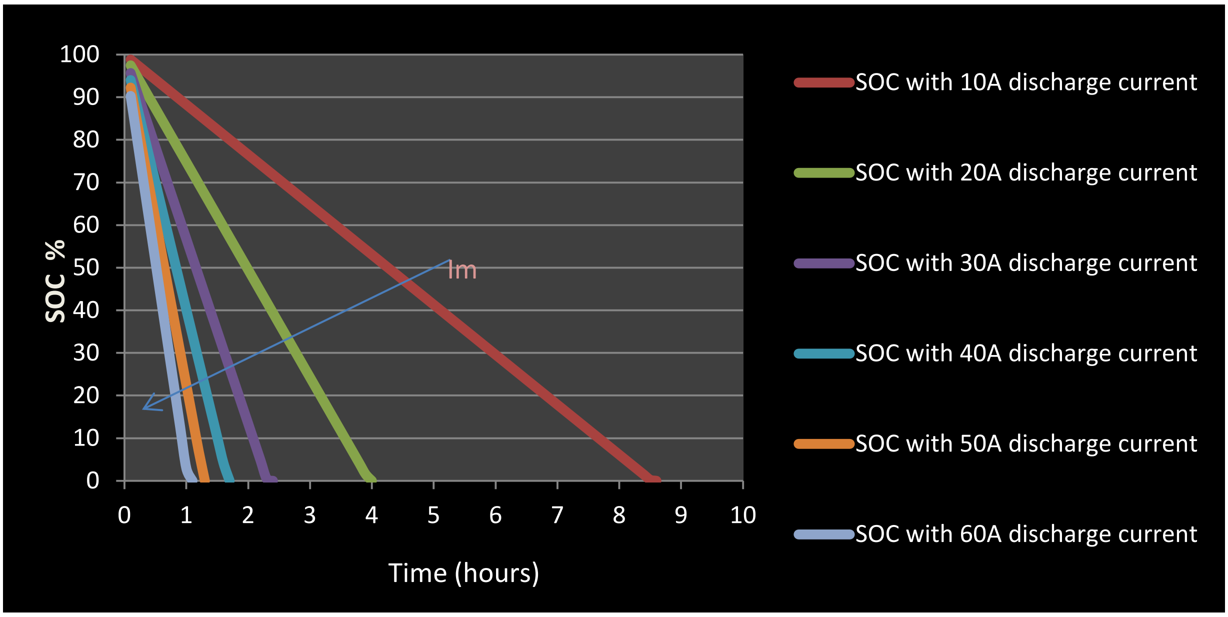

Figure 17 Mathematical model with SOC

2.1.3 Internal Resistance and State of Health

The internal resistance of a lead - acid cell is the equivalent resistance of the cell. The value of the internal resistance depends on many factors. But it could be calculated using the equation below:

$$r = \frac{V_{oc} - V_t}{I} \quad \text{Equation 5}$$

Where V_{oc} is the open circuit voltage (V)

V_t is the terminal voltage when discharging (V)

I is the discharge current (A)

Although the factors in equation 5 are only a method of calculating the internal resistance and not the determinants, it is shown in various applications that the internal resistance of a lead-acid battery will increase when discharging as the SOC and the DOD drop. This because transport effect, basically when the state of charge is going on battery has modifications of two electrodes, where the reactance are basically transformer products. These products accumulated around electrodes, so this increase resistance for new products to go towards the electrodes. Therefore there is increase in the equivalent resistance of batteries.

When a battery undergoes repeated discharged and charged in a number of duty cycles, it suffers a capacity loss which indicates the weak and inability to supply the same amount of charge in aged batteries.

State of health is a variable which indicates weakness level of the battery and further represents the percentage of remaining capacity comparing to the initial capacity when the battery is brand new and is calculated using equation 5 shown below: (Okoshi, 2006)

$$SOH = \frac{C_{weak}}{C_{new}}$$ **Equation 6**

Where C_{weak} is the remaining capacity of a weak battery (Ah)

C_{new} is the capacity when the battery is brand new (Ah).

One of the main causes of capacity loss is known as sulphation. It is a process when the amorphous lead sulphates, which are easily converted, back to lead, lead oxide and sulphuric acid, converts to a stable crystalline form coating the electrodes. This form of lead sulphate cannot conduct electricity and cannot be converted back to lead, lead dioxide and lead sulphate under normal charging conditions. The internal resistance of a lead-acid battery therefore increases and less charge can be provided when discharging. Complete or repeated deep discharges of a battery at low current densities that lead excessive utilization of the active material, are the most critical reason for capacity loss, for example a discharge of a traction battery that draws more than 80% of its nominal capacity (Berndt, 1993)

2.2 DESIGN STRUCTURE

The design aims to collect data for choosing the appropriate electrochemical batteries pack. Its objectives are twofold: firstly, it can be used for modelling all kinds of batteries; secondly, it can be used for identifying the characteristics of different batteries before being used in DC railways.

This test also must ensure that the batteries are always 100% fully charged before discharge. This could be achieved by programming the battery cycler and identifying the maximum energy which the battery can be discharge with different discharge currents in different periods of time.

In order to arrange a test to characterise a lead – acid battery in various forms a 12V Lead-Acid battery modal 689-5854 was selected and the battery cycler model ABC-170 has been used to run the test. Before any procedure is carried out a safety box has been designed to protect the battery cycler, prevent any possible damage and / or harm to the equipments and comply with the safety precautions as shown in figure 18. The designed box consists of 3 current fuses of 60A, 30A and 10A arranged from left to right respectively as shown in the figure below. This enables various currents to be tested.

Figure 18 Safety box

Figure 19 illustrates the arrangement between the safety box connecting the battery to the battery cycler. In addition; the cables and connectors used in this experiment are able to withstand high current to reduce any risk of fire. Appendix 1 demonstrates more about the experiment plan and risk assessment for Operating the battery cycler with the aim of charging and discharging.

Figure 19 Structure of connection between battery and battery cycler

2.2.1 System Block Diagram

Figure 20 illustrates the system block diagram of ABC-170 structural design.

The AC Inverter connects to the utility by means of an internally installed isolation transformer. The DC Converter and AC Inverter shift power via an Intermediate DC Bus and use a RS-485 data bus to communicate. In addition; the DC Converter communicates to the ABC-170 Remote Operation (ROS) System via an RS-232 data link, or CAN data link based on system arrangement. The DC Converter also provides the DC interface to a load (or possibly two separate loads) in one of two configurations. As it shows in the block diagram of ABC-170 has two channels, A and B. Therefore in this test just channel B has been used.

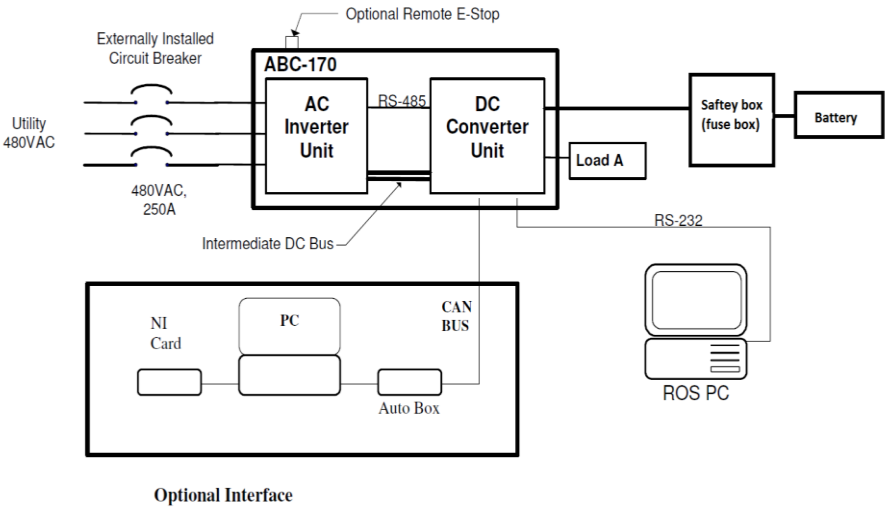

Figure 20 Block diagram ABC-170 structural design

2.2.1.1ABC-170 Remote Operation System (ROS)

The ABC-170 ROS is used as a personal computer based system in order to control the ABC-170. The system consists of the computer and any peripherals, and the ABC-170 ROS application.

The ROS software interface provides graphical test control and data display, test scripting and script management functions, and output file control for test data and logs. Using a graphical user interface for controlling and monitoring along with the command language interpreter which allows a simple implementation of complex test programs makes communication with ABC-170 system easy and provides option of integrating external data acquisition devices into the system. Figure 21 indicates remote operation systems graphical test control software.

The channel information consists of three parts: (Vironment, 1998)

1-Status area

2-Control area

3-Display area

STATUS: This area consist of the current state of both channels A and B as well as the operating limits, the present voltage, current and power values.

CONTROL: The left control area contains information about the mode of both channels, remote or local control. The right control area shows one of three views at any time.

1. **Test Plan:** In this view, the user selects Manual or Automatic Control. An output file can be created to collect data as testing is accomplished. For Automatic Control, the test script and associated data acquisition interfaces, if required, are also selected here.
2. **Manual Control:** The user may select control modes and control values or change operating limits manually, similar to the local control capabilities on the front panel.
3. **Automatic Control:** The user may start, stop, and pause the test, and also view the elapsed test time, present command time, and cycle status, if any.

DISPLAY: This area may be configured by the user to have one or more display windows. The log file is always displayed. Each window is either a display of alpha-numeric data or a graph. The script file can also be displayed.

Any data variable in the main program loop, including those received from data acquisition systems, may be displayed or graphed and multiple displays or graphs may be opened at once, allowing complete user control over how to monitor the test. The control area may be hidden to provide a larger display area.

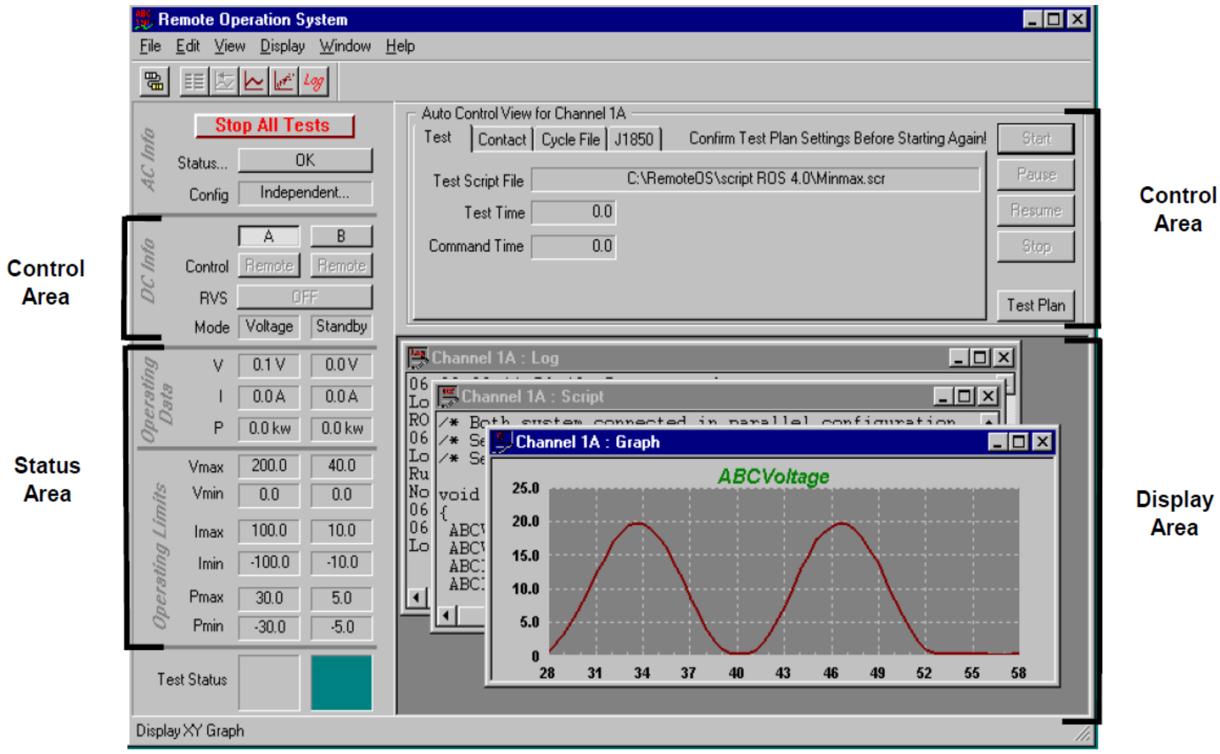

Figure 21 Remote Operation System Graphical Test Control

2.2.1.2Planning a Test

Certain parameters have to be determined in order to carry out the test with the battery cycler. The following checklist may be used as a guideline for preparation:

What load configuration is required?

- Independent: It means each channel has its own test plan and they are independent from each other, therefore two loads may be controlled independently by converter A and converter B. Each load is attached from the positive terminal of a converter to the negative terminal of the same converter.
- Parallel: It means channels A and B are connected in parallel and they are using same test plan for the operation, therefore one load is attached to the positive and negative terminals of converter A
- Differential (available in ABC-170 models): One of the possible load configurations available on ABC-170models (see also independent and parallel). The load is attached from the terminal of converter A to the terminal of converter B.

What should the operating limits be?

- Upper voltage limit: Vdc. This is maximum voltage which can be use to charge the battery. Therefore maximum voltage should not be chosen more than 100% charged battery voltage.
- Upper current limit: Adc. Amount of maximum current which will be use to charge or discharge.
- Upper power limit: Watts. This is depends of maximum current and voltage which are chosen for the battery cycler.
- Lower voltage limit: Vdc. The voltage of 0% SOC of battery should be chosen for lower voltage limit.
- Lower current limit: Adc. This is should be chosen very small to make sure battery is fully charge. For discharge the battery this is not apply, because battery will discharge with constant current.
- Lower power limit: Watts. Lower power limit: Watts. This is depends of minimum current and voltage which are chosen for the battery cycler.

Will this test be controlled locally or remotely?

- Locally. It means do not use the software and put the value of voltage and current on battery cycler without using computer.
- Remotely. Using ROS software to control the battery cycler.

If remote operation, what test script will be used?

What control mode is required?

- Voltage mode. Control the charging and discharging operation by variable voltage, basically voltage will control operation.
- Current mode. Control the charging and discharging operation by variable currant, basically current will control operation.
- Power mode. Control the charging and discharging operation by variable power, basically power will control operation.
- Combination of above modes. This is possible to use combination of above mode by using the script in this software.

Automatic and manual are the two control modes made available within the software that enables the user to specify whether the test will be run automatically (using a test script) or manually (with the preferred input commands). As for this experiment automatic mode has been chosen for the charging operation and the manual mode is selected for the discharging operation.

2.2.2 Charging Operation

As mentioned earlier for charging the battery the automatic mode was selected. In this method a test script has been written to control the battery cycler. In addition; the flexibility of the test script language and the versatility of the language programming almost similar to "C" enable refined test scripts to be created and control the battery cycler in every practical way. (Vironment, 1998).

Figure 22 illustrates the use of the automatic mode of the software; there is script which has been written in this project. When program running the written script, on left side can be seen in real time the actual value of voltage and current of battery and the limit has been set by the script not by manual command. To find out more about test script all the code are available in appendix 2.

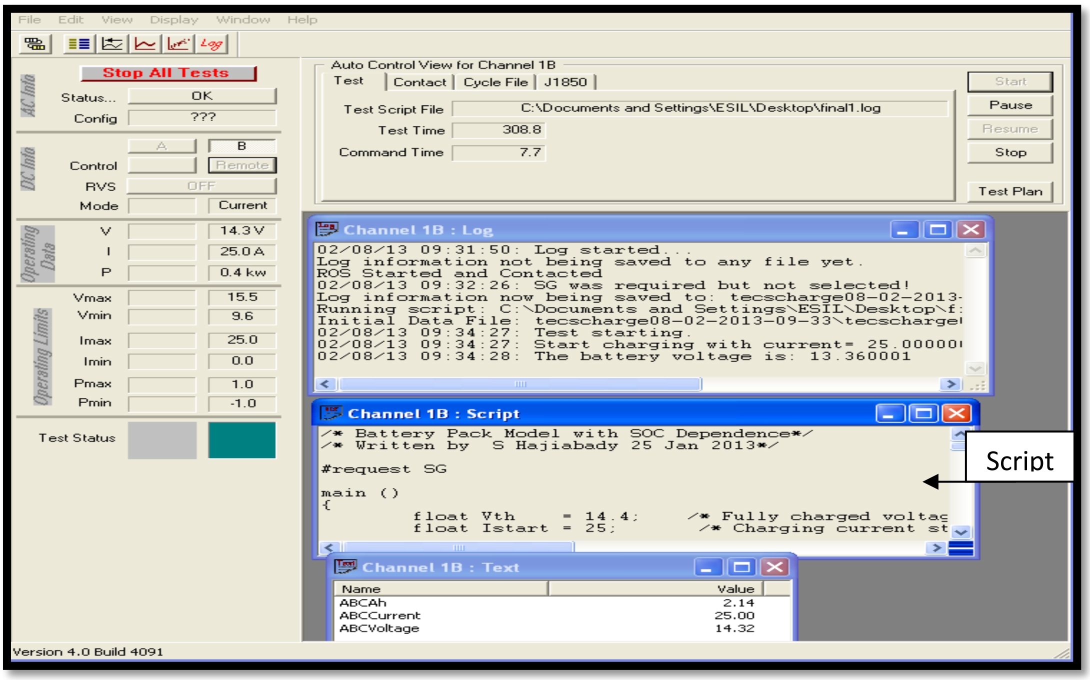

Figure 22 Automatic mode of ROS software

The Figure 23 shows the results obtained at the end of the charging process. Firstly; the battery is charged with the current of 25A with the battery cycler set on the current mode meaning the current controls the charging operation, after the maximum voltage of 14.4V is achieved the battery cycler switches to the voltage mode which means the voltage controls the operation of the charging, therefore; the voltage stays constant and the current reduces until it reaches almost 1A. This continues until the current becomes constant which indicates that the battery is fully charged. In this charging test battery was in initial 0% SOC, when battery reach 100% SOC the total 79Ah was charged.

There are reasons why the recharge voltage of battery is limited .The first reason is because of electrolysis of water. When the voltage a across the cells is bigger than 1.44 then voltage is strong enough to electrolysis of water, so the water inside the electrolyte start to separating the oxygen and hydrogen. That is the reason if keeping increasing voltage this reaction become more important and in some point is possible to get explosions. Another reason why it needs to have two different mode of charging is because if charging the battery with same current after period of time battery will reach the maximum voltage, but this is not meaning that battery is fully charged, therefore if stop charging the battery after period of time it can be seen the voltage of battery is decreasing, therefore is clearly shows that battery is not fully charged. To ensure that the battery is fully charge, when battery reached the maximum voltage by constant current than it need to change current mode to voltage mode. Therefore battery will charge with lower current, this process need to be continue till voltage and current both are established.

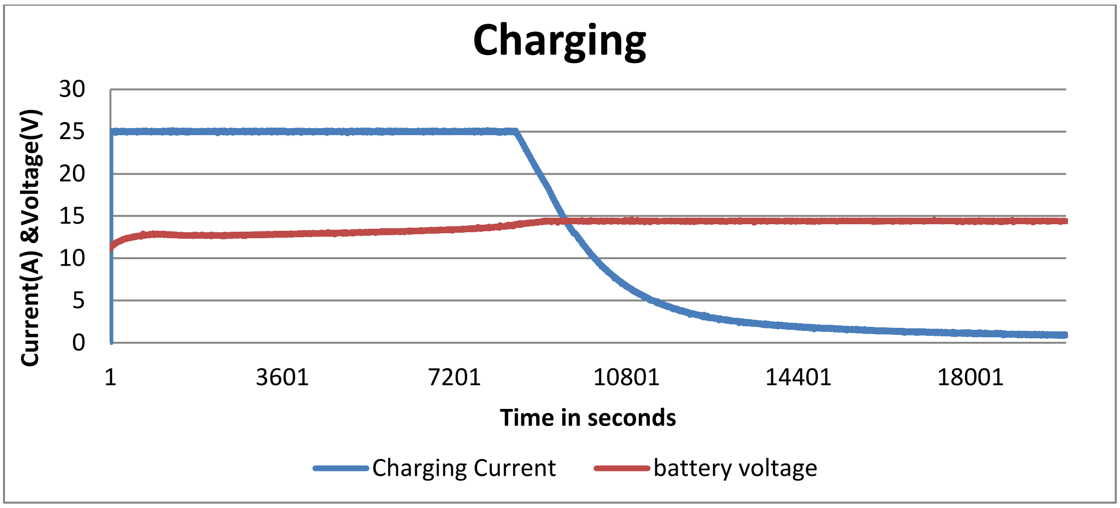

Figure 23 Charging operation

2.2.3 Discharging Operation

Manual mode has been used to discharge the battery which enables manually controlling commands and operating limits without the use of the test script. Figure 24 indicates manual mode of this software.

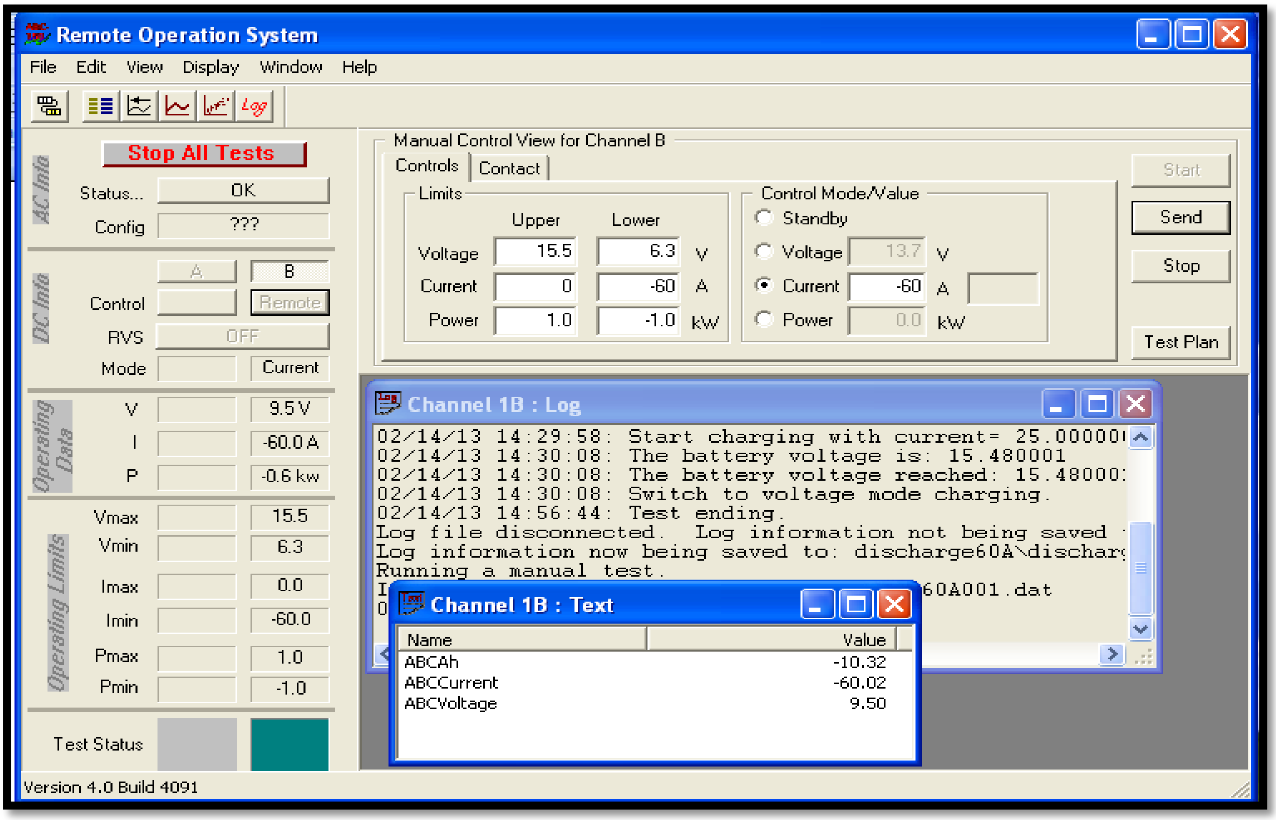

Figure 24 Manual mode of ROS software

In the following the step by step procedure of the operation of the manual mode is show:

Start button Click the start button to begin the procedure which would enable manual controls. If the "Start" button is not available, i.e., it is greyed out, ensure that the test plan is complete and the channel is in Remote operation. If the start is successfully clicked the status box will turn green, on the other hand; if the status box is gray, it is an indication that no test is in progress.

Limit Controls On the left part of the Manual Control View the Limit Controls are presented. The appropriate upper and lower limits for current, power and voltage must be filled in. the send button is clicked at this stage. Prior to any other action the operating limits must be checked which would also protect the load during the test.

Command The Command Controls are in the middle of the Manual Control View.

Controls These operate similarly to the buttons on the front panel of the AV PPS, allowing selection of the control mode and command value by the user.

Standby mode which is indicated as darkened standby button indicates that the test is started. At this stage another mode, Voltage, Current or Power must be selected by clicking on the button for that mode. The system will not change modes until the user enters a control value and presses "Enter" or clicks the "Send" button. Using the manual test enables the user to return to Test Plan View in order to recall the test name or check the data interfaces selected whilst the test is in progress, however; no alterations must be made to the Test Plan nor a new test could be started until the test has been stopped.

Stop Clicking the “Stop” button in Manual Control View would start the test. The “Stop All” button can also be used when both channels need to be paused. (Vironment, 1998).

2.2.3.1 Discharging Operation Results and Discussion

Using the manual mode of the ROS software to discharge the battery assists to identify the maximum Ampere hours (Ah is unit of electric charge) which could be discharged by different ranges of current. Figure 25 demonstrates the six tests that have been taken, based on the discharge currents starting from 10A to 60A. It is clearly noticeable from the graphs that when the discharge process is carried out with a lower current more capacity of the battery is discharged over a longer period of time. In addition; discharging the battery with a higher current results in the maximum capacity that could be extracted to be reduced and as a result the timer taken to discharge the battery is also reduced. It is important to mention that the same current could not be used in order to fully discharge the battery and keep the voltage above the minimum level. Therefore; when the minimum voltage state is reached when discharging the battery, the discharge current has to be reduced in order to be able to extract more capacity of the battery, is the same state is occurred in the same process the discharge current is to be set at a lower value.

The test above has been proven to be very useful and effective in DC railway applications. It assists the experts to be able to select the most suitable batteries yet effective types considering its usage / application criteria and appropriate number of the battery cells depending on its application. Furthermore; the selection of the suitable battery with enough capacity could reduce the number of the battery cells that has to be placed in an electrical circuit in parallel connection to be able to provide enough power for the train. Compact size, less volume and weight of the battery used as energy storage for the railway are amongst the 3 most effective factors when designing and/or introducing energy storage solutions.

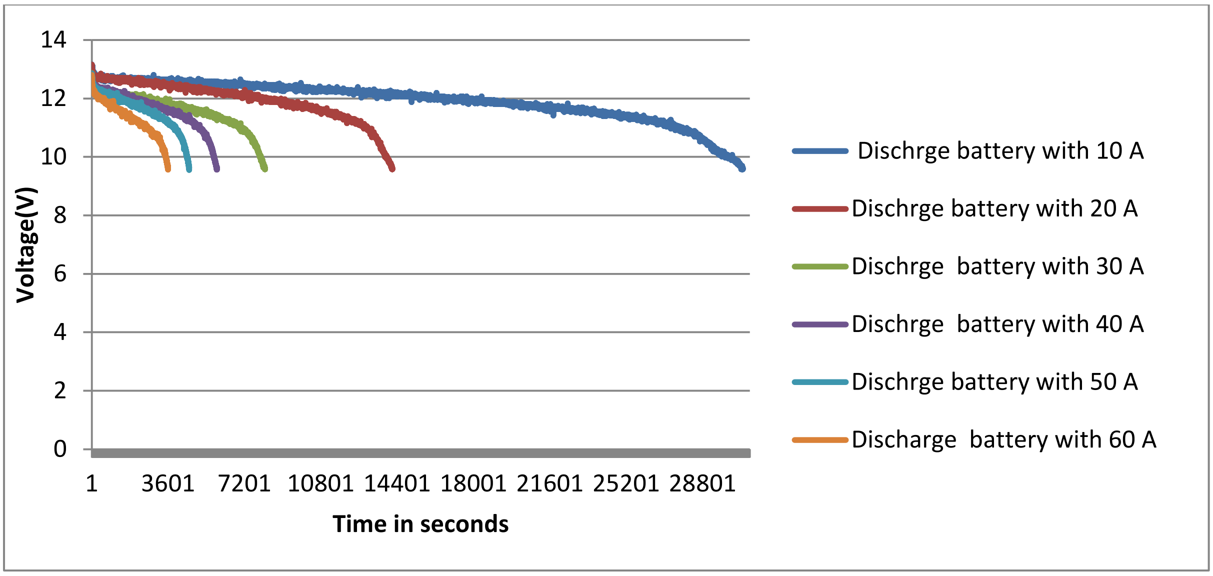

Figure 25 Discharging Operation

Table 2 shows the Ampere hours (Ah) discharged with different currents, besides; the time taken for the tests carried out using different currents is shown in the table. In other words, battery capacity decreases as the discharge rate increases.

Table 2 Capacity of battery for different discharge current

Discharge Current	Discharge time in hours	Maximum Ah
Discharge with 10 A	8.52	85.2
Discharge with 20 A	3.94	78.8
Discharge with 30 A	2.31	69.3
Discharge with 40 A	1.67	66.8
Discharge with 50 A	1.29	64.5
Discharge with 60 A	1.03	61.8

As mentioned before different discharge current values are used for the test ranging from 10 A to 60 A as also shown in table 2. The capacity of the battery during the laboratory tests is presented in the following figure as function of the output current.

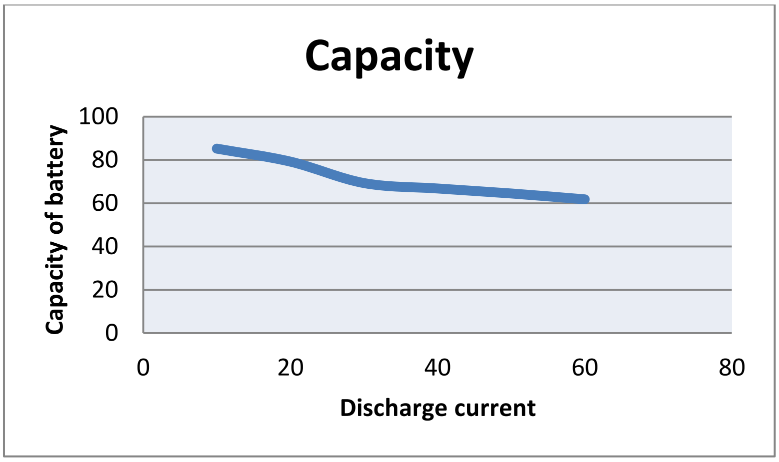

Figure 26 Capacity of battery

The state of charge could be calculated by measuring the voltage during the discharge operation. Basically; the battery has 100% charge when the voltage is on maximum and the charge current is close to zero, also when the voltage shows minimum and the charge current is close to zero, the battery is considered to be flat. Voltage of the battery during the discharge and the open circuit is proven to be different; this is caused by internal resistance of the battery. The following figure illustrates the SOC of a battery whilst discharging with a current of 60A. Same battery has a different SOC curve once discharged with different discharge current. In order to get SOC in the following figure, 3 steps have been done:

1. Starting point of SOC is 100%, because battery charged completely.
2. Battery has been discharged with 60A constant current. $I_d = 60A$ (I_d is discharge current)
3. Finally SOC has been calculated out of following equation.

$$SOC = SOC_0 - \frac{\int I_d . dt}{360 Q_b (I_d)}$$ Equation 7

SOC_0 is the initial SOC.

Q_b is the capacity of battery.

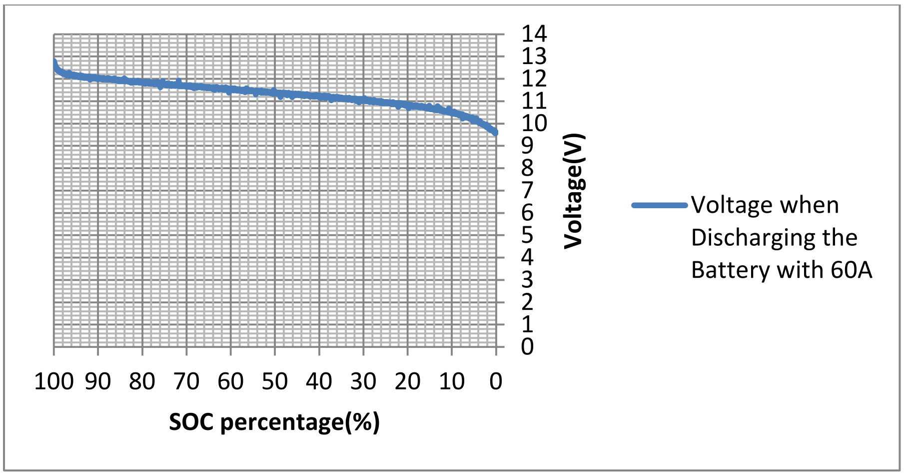

Figure 27 SOC of battery during 60 A discharge current

In other to simplify the result obtaining process, the lead acid battery has been modelled in MATLAB environment based on the data collected from the battery cycler as shown in figure 28, based on which; the value for the voltage is obtained by simply clicking on an area of the designed battery which hold a particular SOC and discharge current value. Therefore; by simply clicking elsewhere on the battery these values would change. To find out more about MATLAB code for this model look at appendix 3.

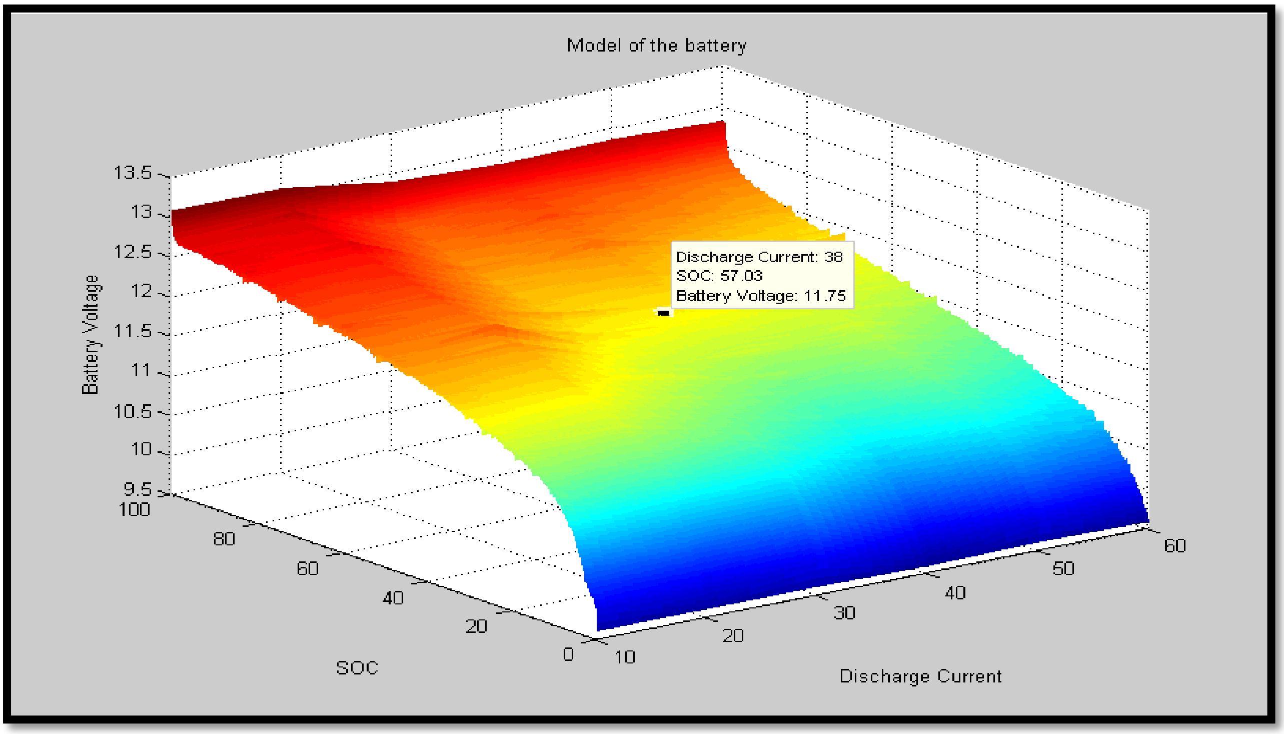

Figure 28 Battery model of lead acid battery in MATLAB

Voltage values of a battery are known to be different at the terminal and at the source (represents an ideal battery). This is caused by the "internal resistance" as shown in the following figure.

Figure 29 illustrates the simplified model of an electrochemical battery.

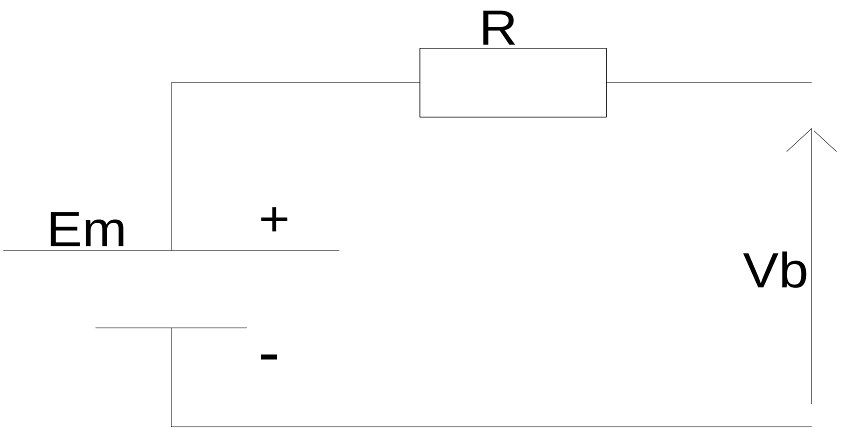

Figure 29 Simple model of battery

The following equation is used to calculate the voltage source of battery:

$$E_m = V_b + (R \times I_m)$$ **Equation 8**

Where;

E_m is ideal battery or voltage source of battery

R is internal resistance of battery

V_b is the terminal voltage of battery

It is important to mention that this formula just can calculate the approxmely voltage source of battery. In order to calculated exact value of voltage source, battery must be open each time to measure the voltage source, which is not possible.

In order to calculate internal resistance of a battery, the voltage of the battery in both the open circuit and whilst discharging need to be measured. The difference between these two voltages divided by the discharge current will reveal the internal resistance value as shown in equation 7.

$$R = \frac{\Delta V}{I_m}$$ **Equation 9**

It is important mention that when measuring the no load voltage, it should not just put the current to zero and measure the voltage, therefore we wait have to wait until the chemical reaction of battery get steady again, then measure the no load voltage.

Furthermore; the battery has been modelled using excel software in order to obtain the voltage source of the battery as shown in figure 30.

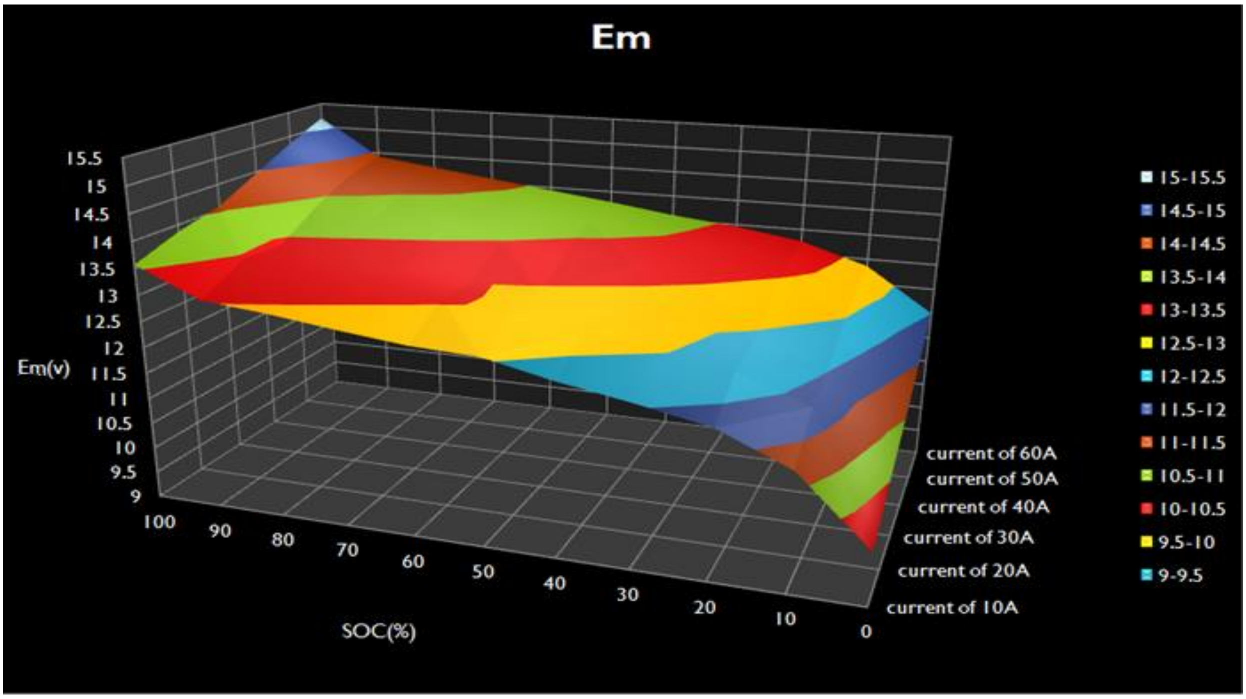

Figure 30 Voltage source of battery

2.3 Summary and Discussion

Concisely; a new modelled was designed in this part of the project in order to identify and inspect the behaviour of the electrochemical batteries when put to test based on different scenarios and requirements. In order to collect correct set of data and choosing the appropriate battery pack cell, the design ensures that the batteries are always 100% fully charged before starting the discharge process. It also identifies the maximum energy which the battery could be discharged using different discharge currents over different period of time.

Once the model is tested, it is made easy to identify the maximum energy that could be discharged using different ranges of current once discharging the battery using this method. This could be very useful once used in industrial scale in DC railways as it assists the nomination of the correct batteries and the number of battery cells.

Chapter 3

3.1 Design and Model DC Railway Traction System with Conductor Rail Gap

The MATLAB/ SIMULINK computer program tool is used for modelling the traction system. The integrated model of a DC traction system is shown on figure 31 which consists of two substations, track section and train driven module. It is assumed that the train starts from substation 1 to substation 2 and total length of the track section was also considered to be 5km. This project mainly focuses on the conductor rail gap issues. Therefore; MATLAB/ SIMULINK was used in order to simulate the problem. Throughout the next chapter of the project the solution is designed and introduced.

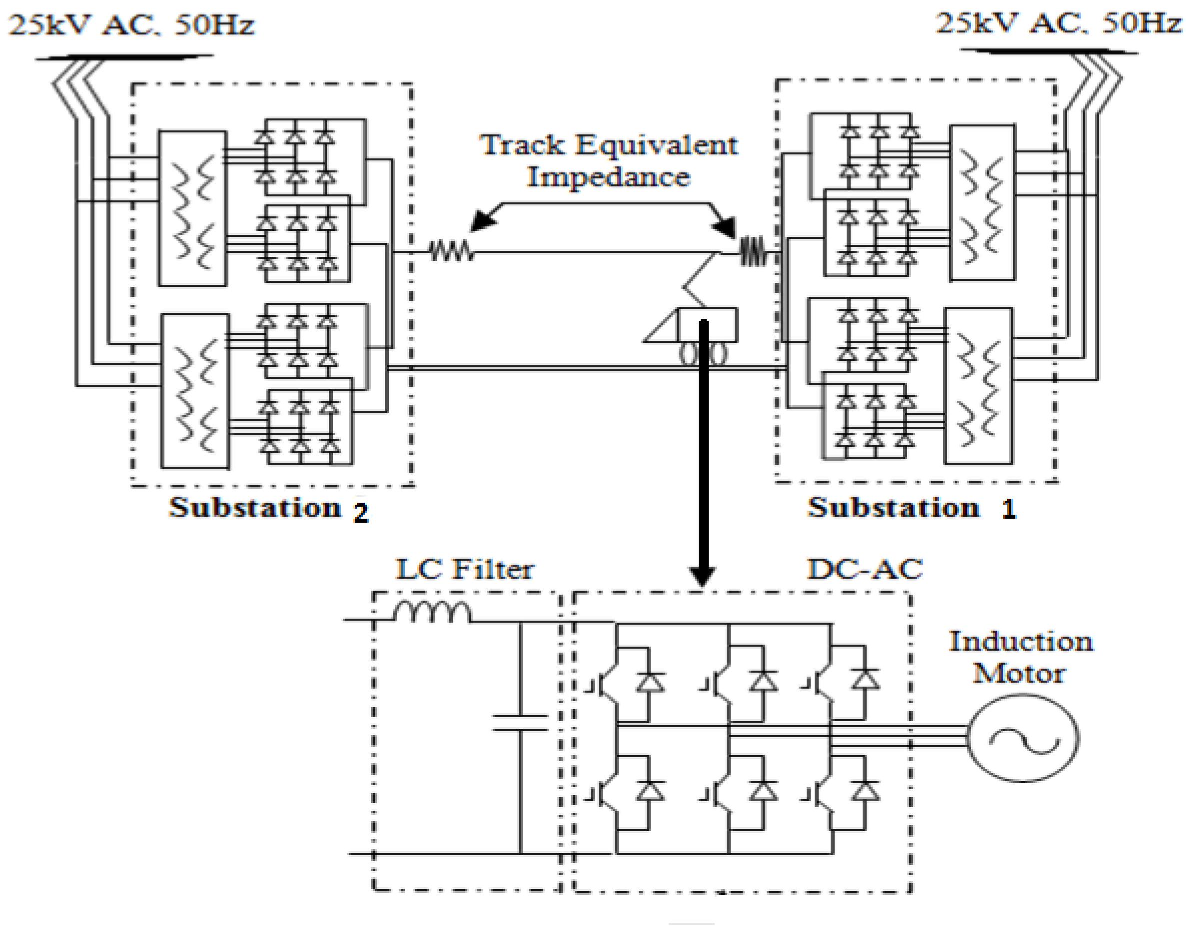

Figure 31 Model of a typical DC traction system

3.1.1 Design DC Substations

Prior to designing a DC railway the DC substation must be configured and designed. The substations are fed by AC voltage. Using the transformers in the substation the voltage is reduced as required by the railway, in addition the AC in converted to DC by using the rectifiers. There are 3 different rectifiers are available 24, 12 and 6 pulse rectifiers. In order to use then for DC railway, 24-pulse rectifier is very expensive for that reason they would not use them for DC railway and 6-pulse rectifier is not good enough to make good ripple. Consequently a 12-pulse rectifier has been used to do this job.

3.1.1.1AC-DC 12 Pulse Transformer Rectifier Modelling

The 12-pulse rectifier is connected to a variable frequency AC bus which provides the DC power required to all DC loads. This convertor is known for its high reliability and low input current harmonics. As shown in figure 32 which illustrates the structure of the 12-pulse rectifier, the convertor consists of 2 full bridges rectifiers such that each bridge contains 6 diodes. 12-Pulse Rectifier connected to Y: Y: Δ transformer to cause a phase shift 30^0 on the secondary side which reduces the input harmonic currents and improves the power factor (PF).

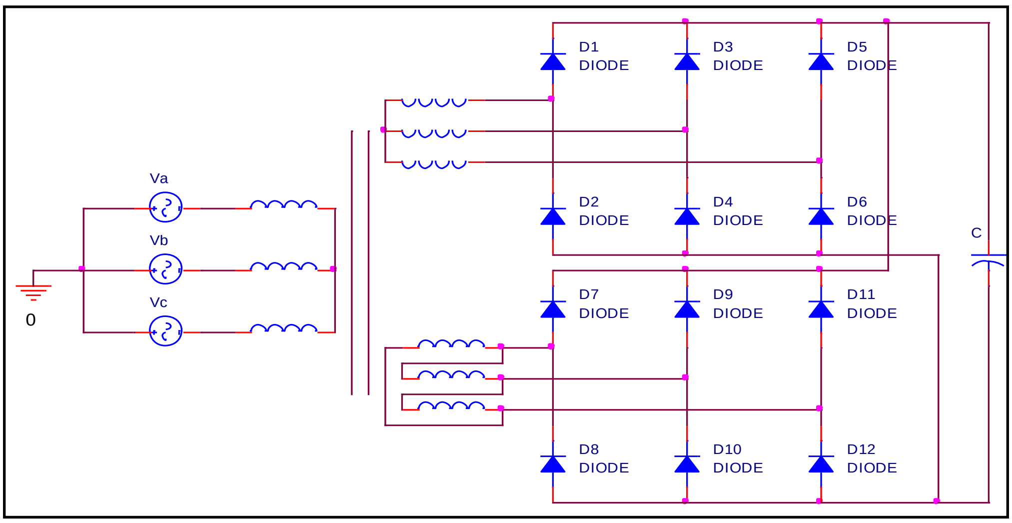

Figure 32 12-Pulse Rectifier

The average output voltage from the 12-Pulse Rectifier across the dc capacitor can be calculated by using the following equation (Rashid, 2004):

$$V_{dc} = 3\frac{\sqrt{3}}{\pi} V_{peak,line-neutral} = \frac{3}{\pi} V_{peak,line-line} = 3\frac{\sqrt{2}}{\pi} V_{rms,line-line}$$ **Equation 8**

Theoretically, since the requirement for the generator in substation is to supply $560\ V\ rms$ line to line voltage at $50\ Hz$ frequency. Therefore; the DC output voltage from the 12-Pulse Rectifier across the DC capacitor could be determined as shown below:

$$V_{dc} = 3\frac{\sqrt{2}}{\pi} V_{rms,line-line} = 3\frac{\sqrt{2}}{\pi}(560) = 1.35(560) = 756\ V$$

3.1.1.2 Overall design of substation in MATLAB/SIMULINK

Using MATLAB/SIMULINK computer program a substation was built as shown in figure 33. The three phase AC source is required in order to generate the AC power in to the substation. In addition; Δ:Δ: Y transformer is needed to produce a phase shift of 30^0 on the secondary windings in order to reduce the input harmonic current and also to improve the power factor. Furthermore; AC-DC 12 pulse uncontrolled full bridge rectifier consisting of two full bridge rectifiers is connected in parallel through inter-phase transformer to produce 12 pulses as DC output voltage.

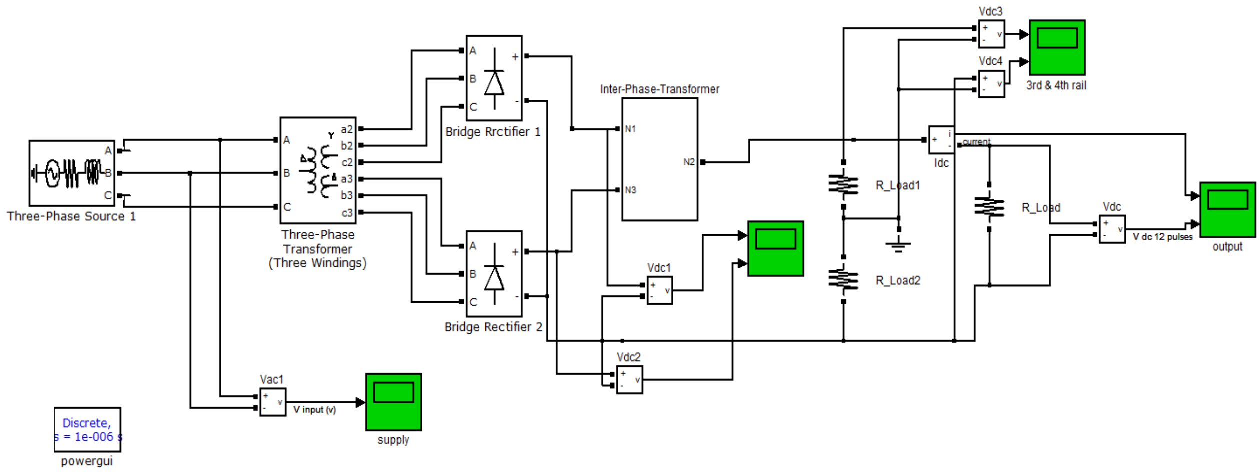

Figure 33 MATLAB/SIMULINK model of one substation

As London underground has 3rd rail and 4th rail, therefore inter phase transformer has been design in the model to split the voltage as it shows in figure 34.

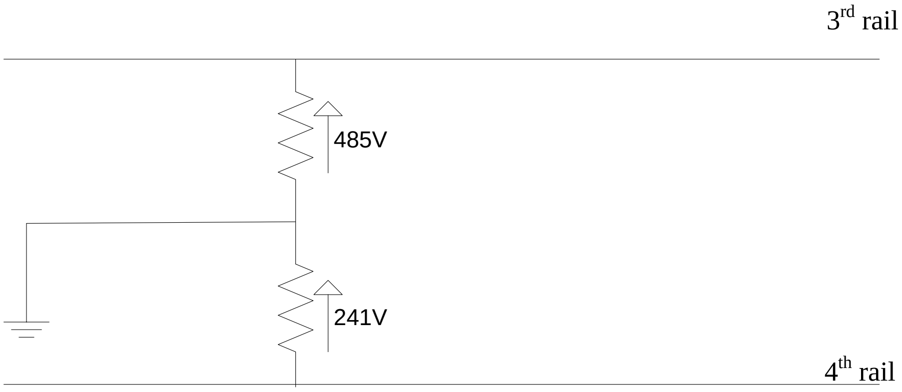

Figure 34 Inter phase transformer

Table 3 and 4 shows all of parameters that were used in the substation model. The default vale was selected because other value was tested and it would make lots of changes.

Table 3 Parameters of three phase source

Parameters	Data	Source of Data
Phase-to-phase rms voltage (kV)	11	London Underground data
Frequency (Hz)	50	Standard value
3-phase short-circuit level at base voltage(MVA)	100	MATLAB default value
Base voltage (kVrms ph-ph)	11	MATLAB default value
X/R ratio	7	MATLAB default value

Table 4 Parameters of three phase transformer (three windings)

Parameters	Data	Source of Data
Nominal power [MPn(VA)]	2.5	London Underground data
Frequency (Hz)	50	Standard value
Winding 1 parameters [V1 kPh-Ph(Vrms) , R1(pu) , L1(pu)]	[11 , 0.002 , 0.08]	London Underground data
Winding 2 parameters [V2 Ph-Ph(Vrms) , R2(pu) , L2(pu)]	[560 , 0.002 , 0.08]	Calculated value
Winding 3 parameters [V3 Ph-Ph(Vrms) , R3(pu) , L3(pu)]	[560 , 0.002 , 0.08]	Calculated value
Magnetization resistance Rm (pu)	500	MATLAB default value
Magnetization inductance Lm (pu)	500	MATLAB default value

The following figure shows the results once simulating the designed model of a substation rectifier connected to a pure DC resistive load of 1500 kW. By inspecting the results it is clear that the voltage between the 3rd rail and the earth is around 485V, on the other hand; the DC output voltage between the 3rd rail and the earth is around 241 V, by adding the two voltage values a combined voltage value of 736V is obtained which is clearly less than the typical DC output voltage from the substation (750 V DC) due to the voltage drop across rectifier as the transformer. It is clear that the current drawn by the load is around 1.94 kA, which matches the theoretical value (1500/750 =2.00 kA).

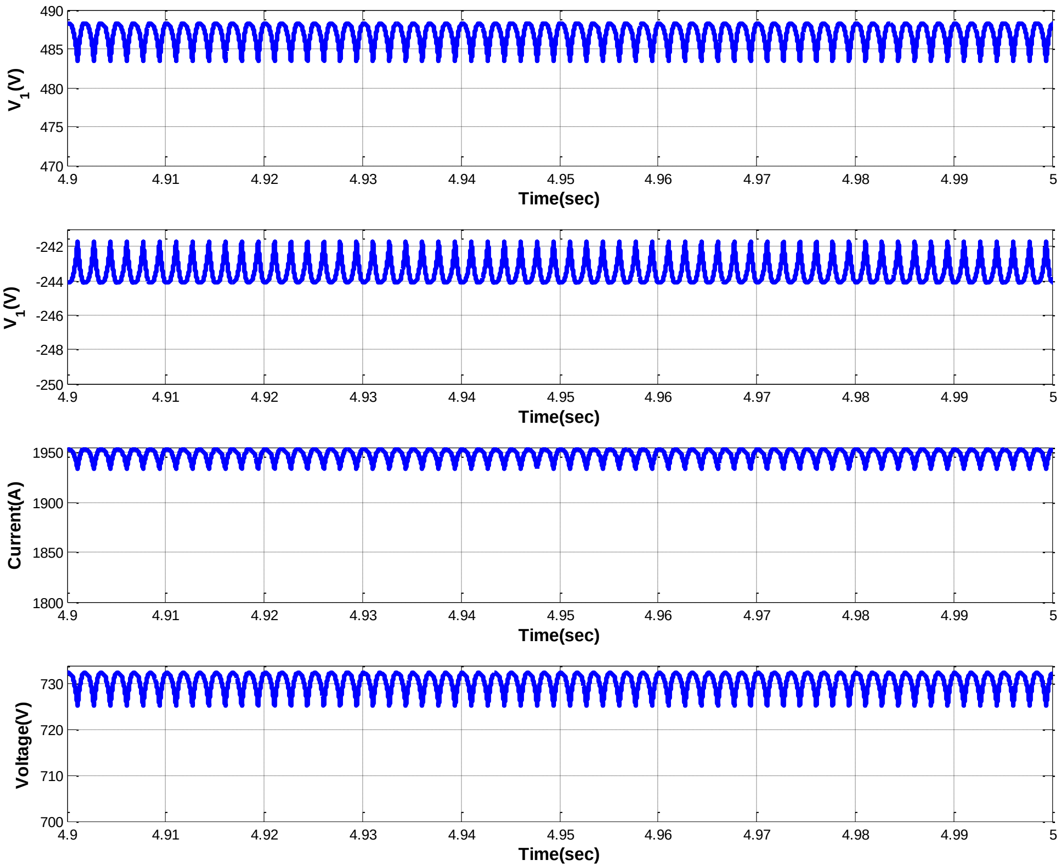

Figure 35 Simulation results of the modelled one substation rectifier

3.1.2 Design DC Railway with Two Substation and Moving Train

Figure 36 shows the integrated MATLAB/SIMULINK model of two substation rectifiers connected to each other through the track model. The train has been also modelled as resistor of 1500 kW. The train is moving from substation 1 into substation 2 and the distance between the two substations is assumed to be 5 km. Block diagram of controller 1 and controller 2 will describe latter in figure 38.

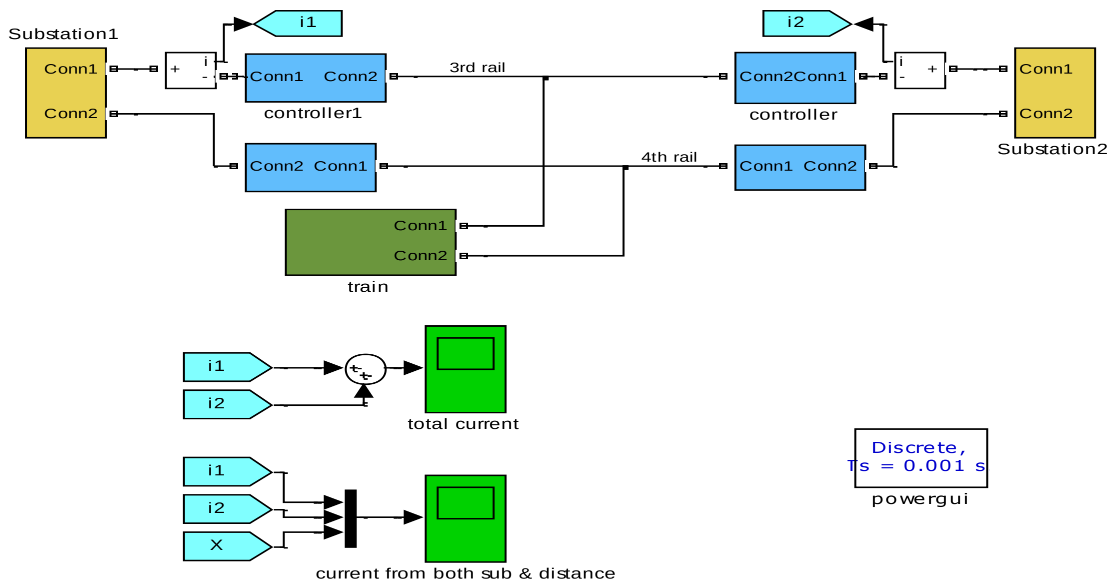

Figure 36 MATLAB/SIMULINK model of two substations

In the simulation it is assume that train is a resistance, base on London underground data 2009 Tube train has been used for this simulation. This tarn has 24 motor therefore 24 resistances which are connected in parallel are used in the summation. Table below shows the parameters which are used to simulate the train.

Table 5 Parameters of train

Parameters	Data	Source of Data
Nominal voltage Vn (Vrms)	750	London Underground data
Nominal frequency fn (Hz)	50	London Underground data
Active power P (MW):	1.8	London Underground data

Figure 37 shows another simplified MATLAB/ SIMULINK model of the two substations connected to each other through the track, which is modelled as a controlled voltage source such that the controlled signal depends on the actual speed of the train. Each substation is also modelled as a DC voltage source of 750 V DC.

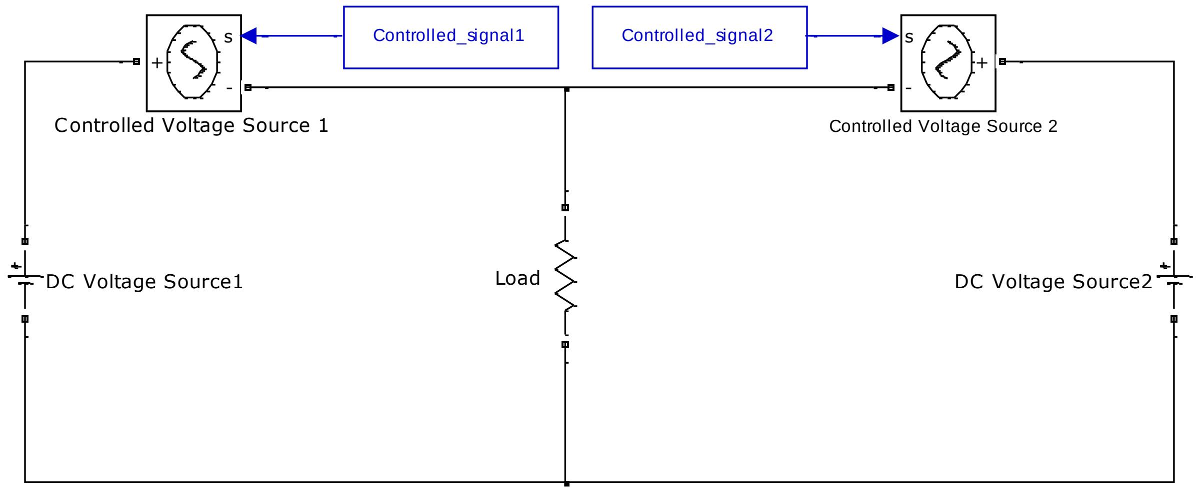

Figure 37 Simple MATLAB/ SIMULINK model of the system

Figures 38 shows the suggested controlled signals of the track controlled voltage sources.These controlled signals are modelled based on the following two equations:

$V_{drop\,1} = \frac{R_{total}}{l_{total}} i_1 \int x(t)dt$ Equation 9

$V_{drop\,2} = R_{total} i_2 - \frac{R_{total}}{l_{total}} i_2 \int x(t)dt$ Equation 10

Where;

$V_{drop\,1}$: Voltage drop across the track between substation 1 and the train

$V_{drop\,2}$: Voltage drop across the track between substation 2 and the train

R_{total} : Total track resistance

l_{total} : Total track length

i_1 : The DC current generated by substation 1

i_2 : The DC current generated by substation 2

$x(t)$: The distance between the train and substation 1

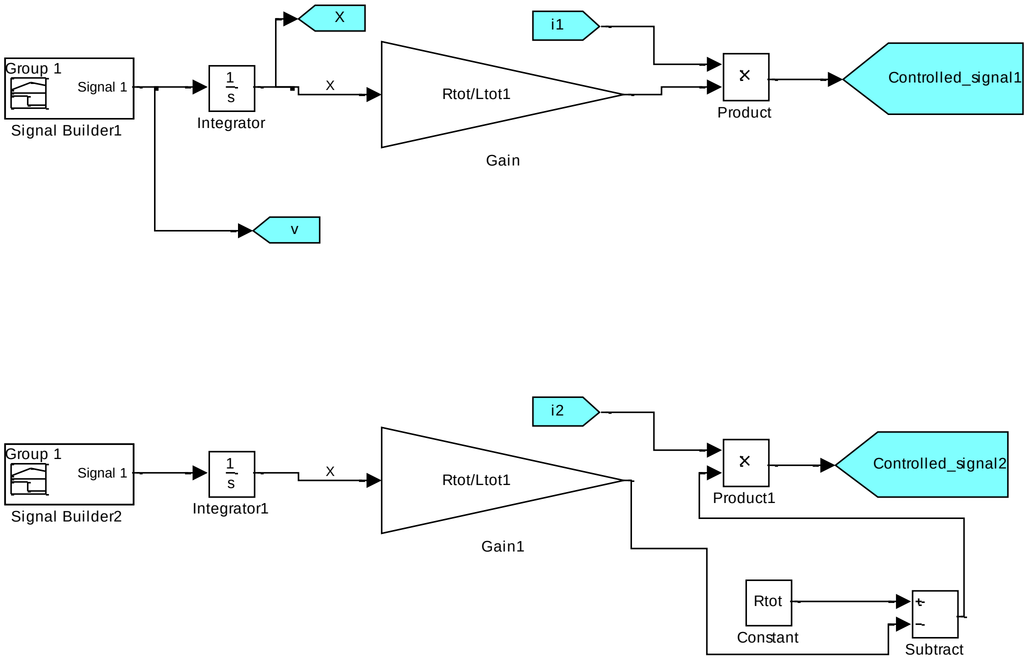

Figure 38 The mathematical model of track, voltage drops and their controlled signals

Figure bellow shows the signal builder, which is control the speed of train during the simulation.

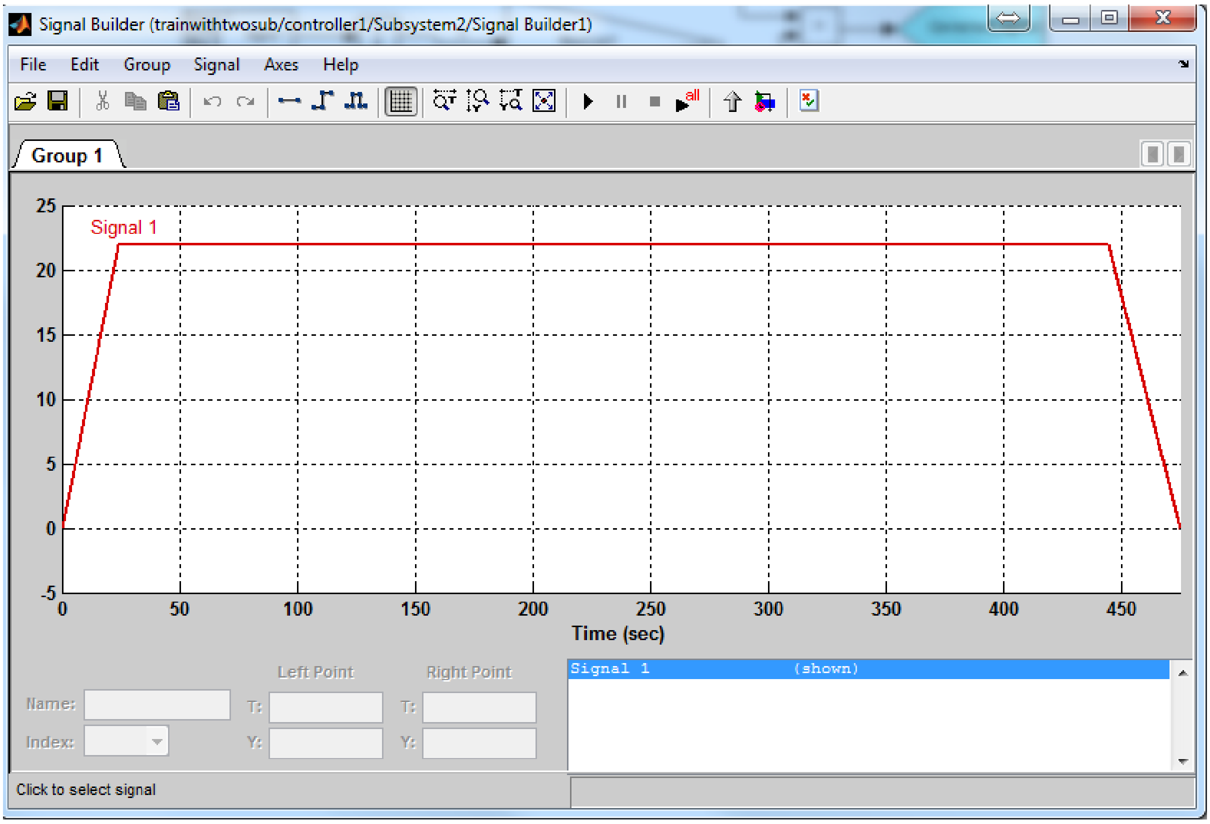

Figure 39 Signal builder

The Figure 40 shows the simulation results of the previous simplified MATLAB/ SIMULINK model. The graph shows both DC currents, which are generated by the two substations. Yellow line shows the current taken by train from first substation; purple line illustrates the current taken by train from second substation and the distance between the train and the substation 1 is shown by the blue line. The total length of the track was assumed to be 5 km. In this particular case, the range of x (as used in equations 9 and 10) should be between 0 and 5 km. When the train arrives at the midpoint between the two substations at the intersection point where 2.5 km, the two DC currents are equal to each other as shown in the simulation results.

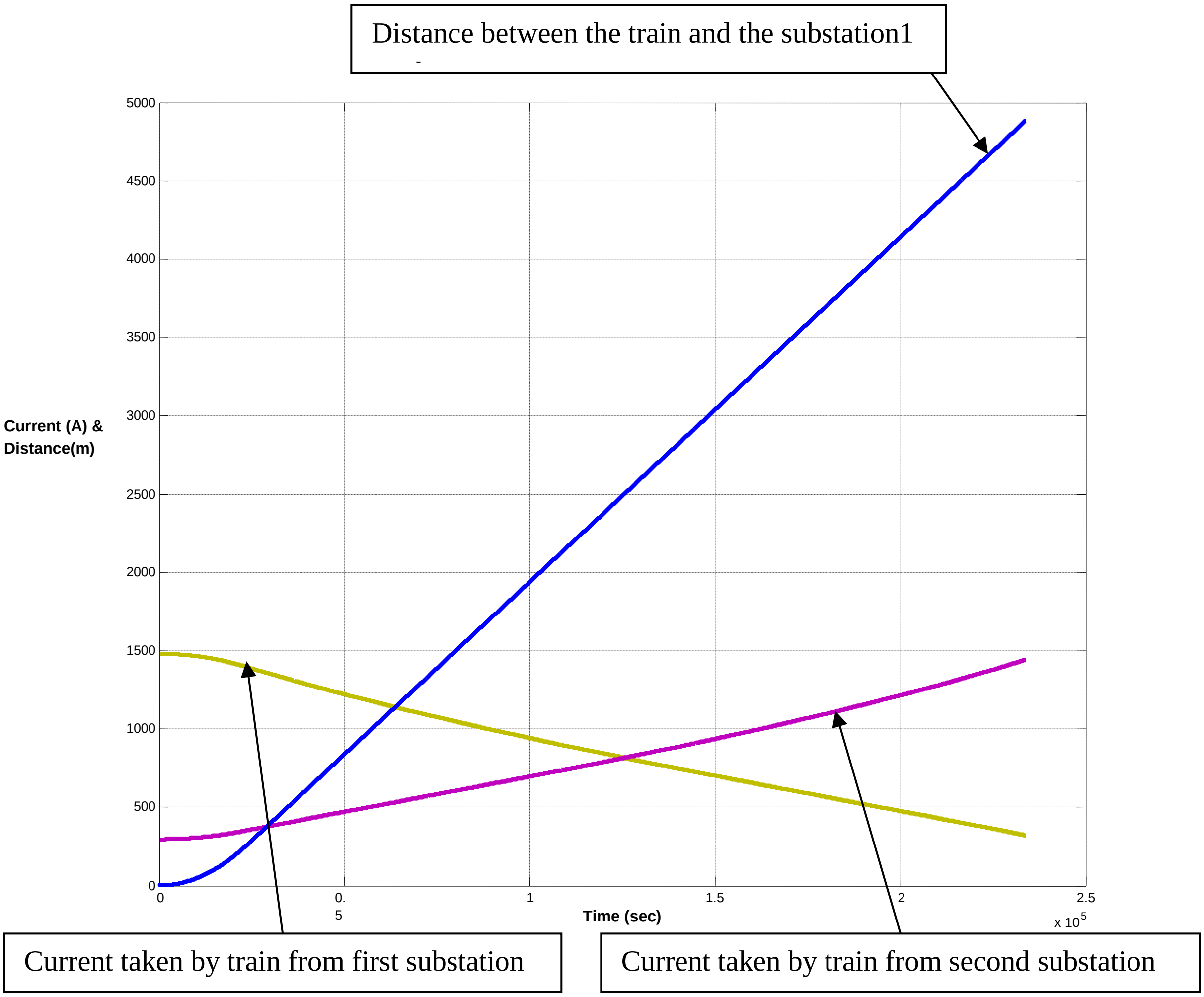

Figure 40 Simulation results model of two substations

3.1.3 Design DC Railway with Conductor Rail Gap

In this part of project conductor rail gaps has been designed to show the effect on the train when passing through the gaps. A section of London underground Victoria line has been used as reference for this analysis. Therefore figure 41 shows the integrated MATLAB/SIMULINK model of the part DC railway model taking into consideration the gap mentioned earlier. As shown in the model, the ideal switches have been used to disconnect the DC power delivered to the train when it passes through the gap, which is known to be 15 m according to London underground data. Note that these ideal switches are just used for modelling purposes. However, in reality once the train passes through the gap, there is no DC power delivered to the train motors. To find out more about MATLAB function which are used in this SIMULINK see appendix 5.

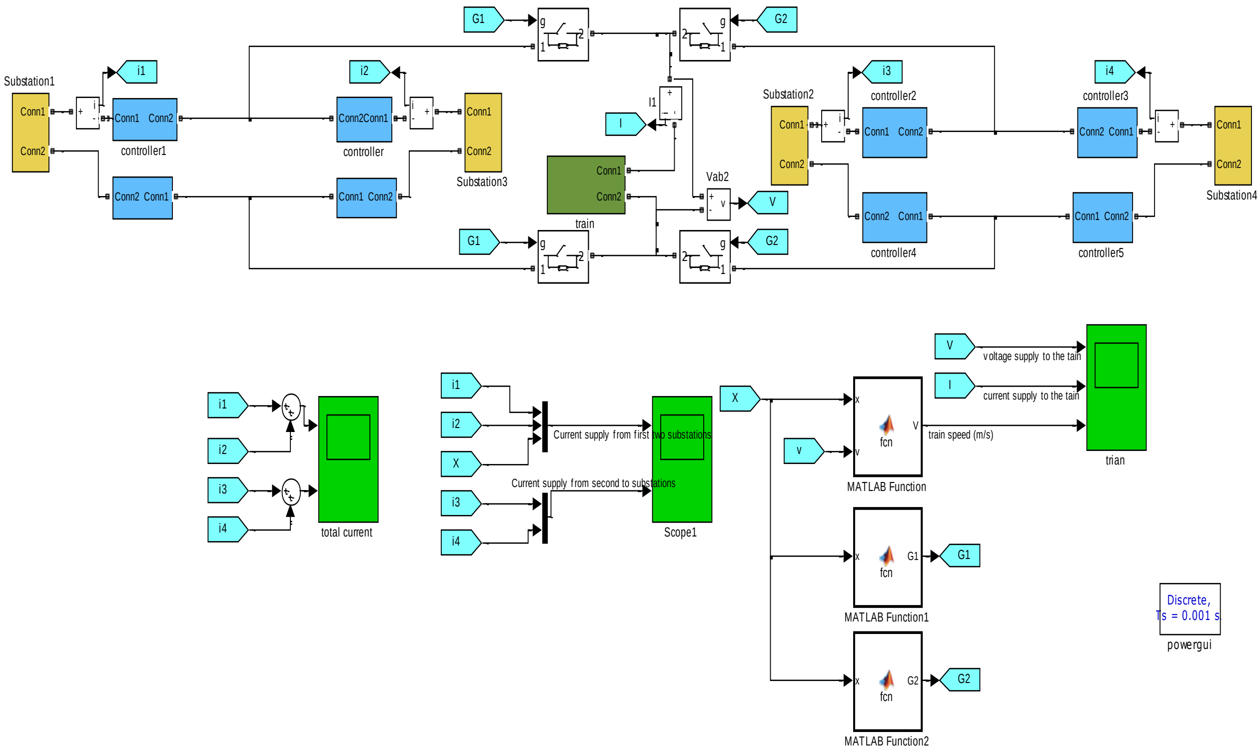

Figure 41 Dc Railway with Conductor Rail Gap

Based on the simulation results shown in Figure 42, it is clearly noticeable that the supplied DC currents by the first two substations collapses to zero when the train passes through the gap at the point where x= 5km from substation 1, then the train motors are fed by the other two substations as shown below in the simulation results. Moreover, according to the next simulation results in Figure 43, when the train passes through the gap, the voltage and current collapses to zero and also the train speed slightly changes.

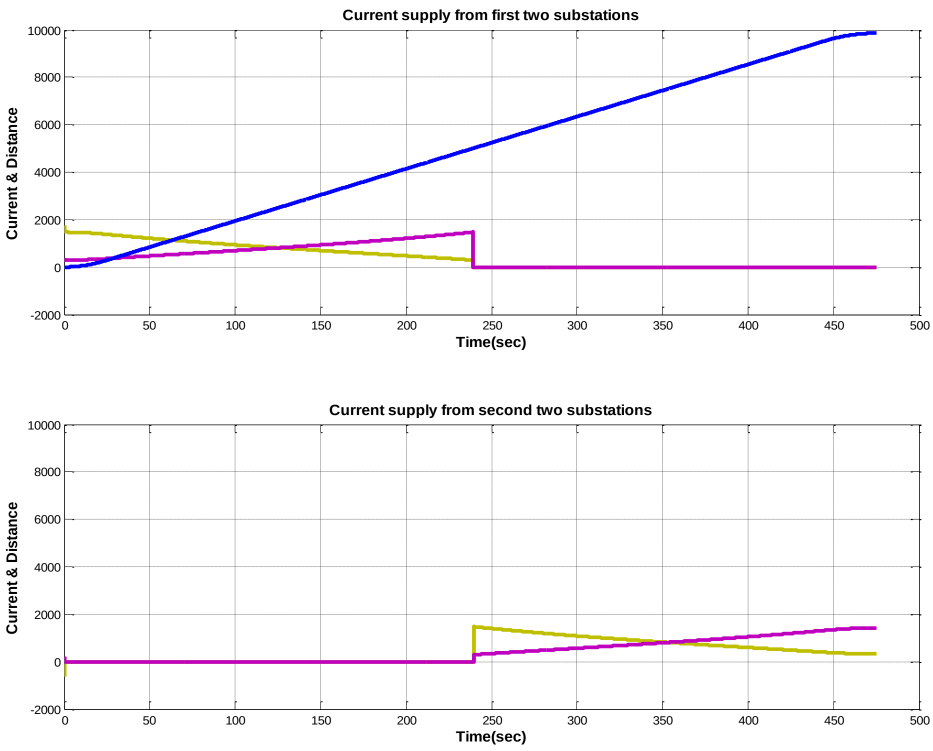

Figure 42 DC railway current supply

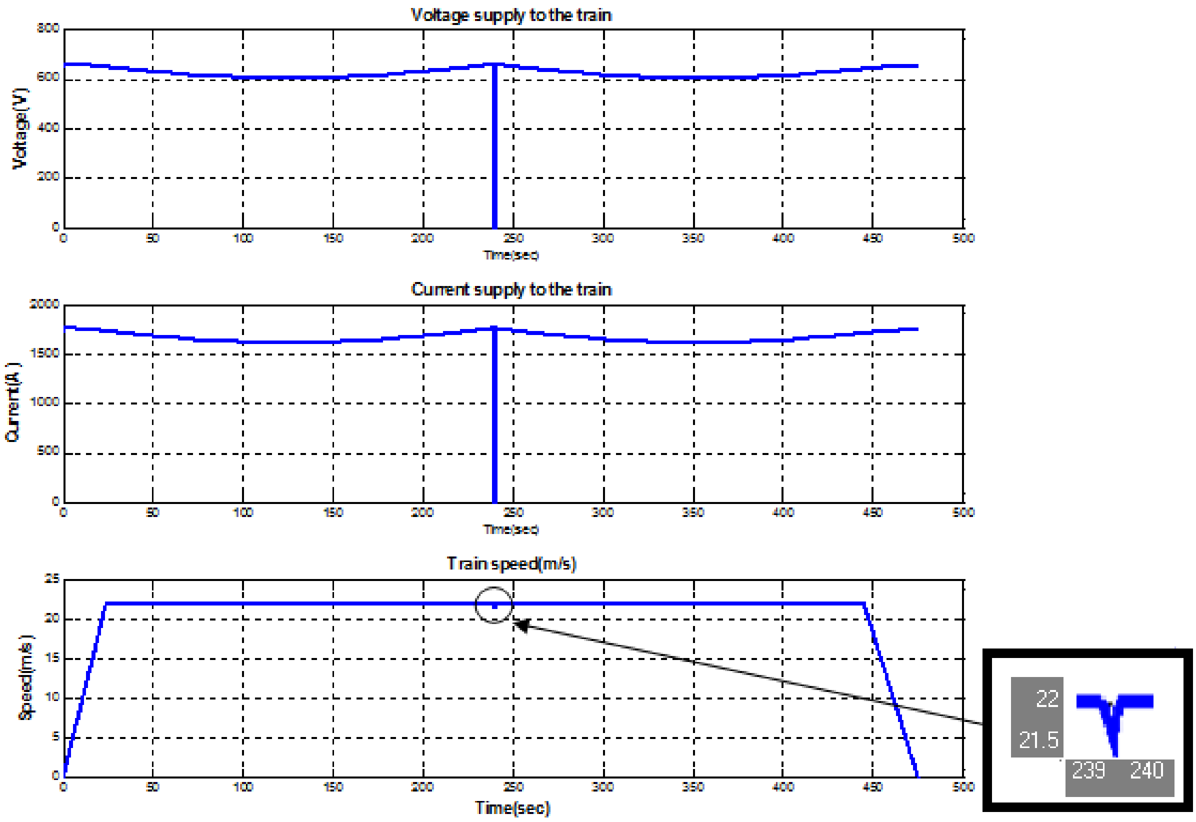

Figure 43 Train performance over the gap

In the ideal situation the train would not experience the effect from the gap and as a result it would not lose any performance. Could be overcome the issue and become closer to the ideal situation by using an energy storage system has been designed in the simulation as shown in figure 44. The purpose of the design is to create the ability of providing the power to the train as equal to the power provided by the conductor rail power supply while the train passes through the gap, consequently; the train motors do not experience power cut. Chapter 4 will explain in details how energy storage is chosen for conductor rail gap.

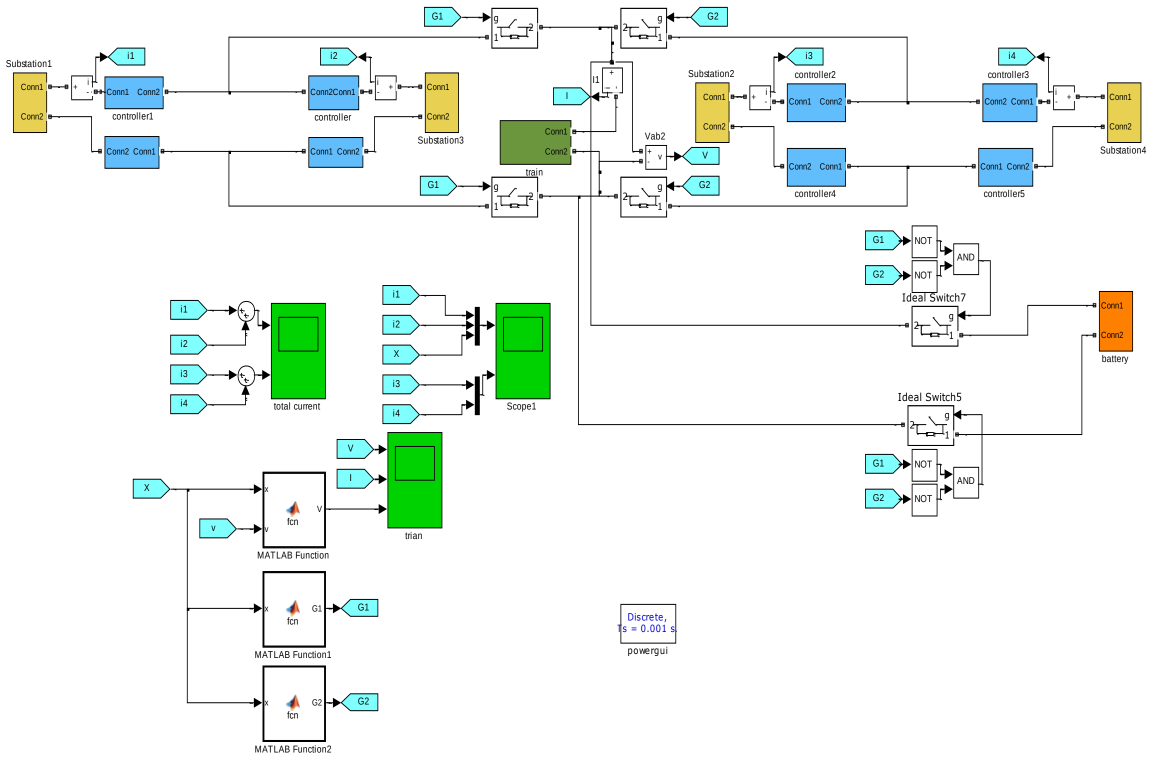

Figure 44 DC Railway with energy storage design

The following figure illustrates the results from simulating the DC railway with the energy storage imposed. It is clear that once the train passes through the gap the voltage and the current remain the same and consequently; the speed also remains unaffected. Furthermore; the train does not experience any loss in its performance and functionality.

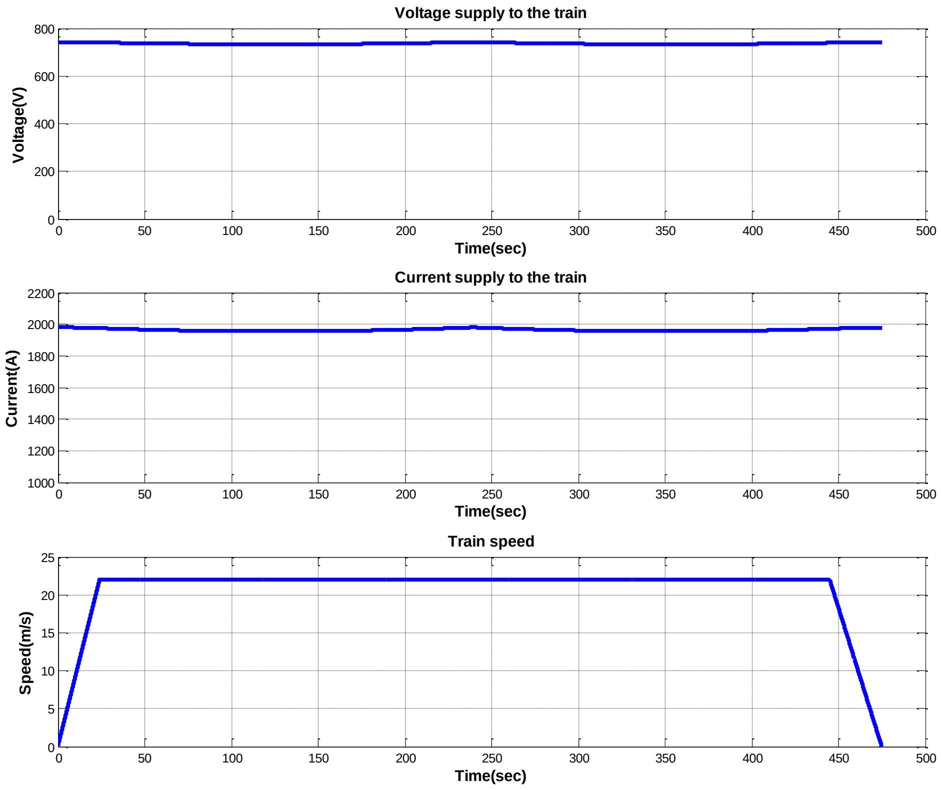

Figure 45 Simulation results of DC railway with energy storage

3.2 Summary and Discussion

To summarize the findings of this chapter are the simulations with and without the energy storage system, conductor rail gap introduce small deep to the speed of train and will disturb the train performance. Therefore energy storage was designed for the train, in order to pass through the gap without losing performance. Energy storage designed provides the same DC voltage as output voltage from the substation. Since the train requires high DC voltage and it could becoming an expensive solution to use the energy storage alone to provide such voltage, on the other hand; to be able to provide such voltage a large number of energy storage cells are required which results in a bigger and heavier and requires more space and by taking into consideration the limited space available on the train for this purpose, a DC-DC converter is introduced to the design which could increase the voltage provided by the energy storage cells to the preferable amount required by the train. In the next chapter the two main factors known to be capacity and life cycle, which must be considered when using the energy storage, are discussed along with relative issues to design suitable energy storage for the conductor rail gap issues.

Chapter 4

4.1 Design the Energy Storage for DC Railway Traction System through the Conductor Rail Gap for London Underground- Victoria line

From an electrical power perspective, the ideal supply arrangement to rolling stock should have no discontinuities, via rail gaps. Hence, the load would be connected via moving contacts – the train shoes - to the conductor rails. This system would only need main and local isolations. This is not practicable because items require maintenance and this requires physical gapping in many cases.

Therefore, in this part of project in order to keep the train performance remain the same during the gaps and establish an ideal gapping arrangement, different type of energy storage such as batteries and super capacitor has been designed to find the suitable solution for power up the train though the gaps.

There are two possibilities to design energy storage for the train such as on board and stationary energy storage. But in this project, the design is only related to London underground – Victoria line. There are some gaps placed at junctions therefore there are no places for stationary energy storage, consequently the onboard energy storage is the only option that could be considered for this specific conductor rail gaps solution.

4.1.1 Train Specification

In order to design the energy storage for train, train specification data is required. Traction data is required in order to design Energy storage of a train in the Victoria line London underground use 2009 Tube (Stock, 2009).

This train uses Bombardier 3 phase AC motor, 2009 tube stock consists of 8 vehicles which in terms of traction are arranged in 4 pairs. Each pair is defined as a local traction system. Only one vehicle in a pair has shoe gear. The figure 46 shows the arrangement of traction systems and shoe gears.

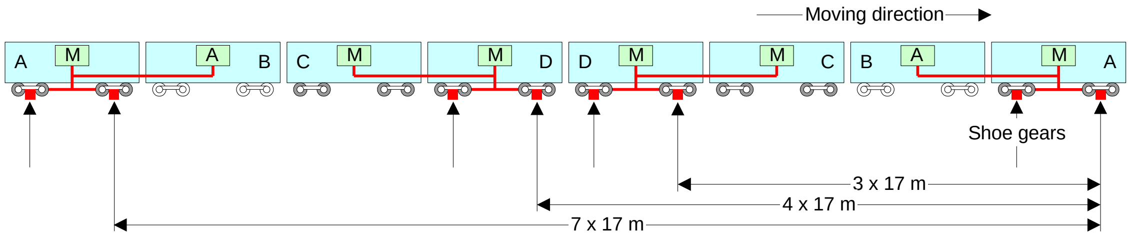

Figure 46 The arrangement of traction systems and shoe gears

There are 24 motors in this train and 75% of vehicles are motored therefore each motored vehicles has 4 motors. Each motor rated at 75kW with Regenerative and Rheostatic braking (Stock, 2009). Tare weight of 8-car train without including passengers is 197.3 tonnes. This train has capability to have 864 passengers, if assume each passenger as average has 75 kilogram, than total weight of passengers is about 64.8 tonnes. In order to design energy storage for train the mass of passengers also must be considered, therefore in this design mass of train with passengers is proximately is 262.1 tonnes.

4.1.2 Train Performance

Train performance tool is software which London underground used to simulate the trains performance for different lines and between all stations. London underground is using this software to estimate energy consumption, train speed, time taken and all other behaviour of train for this specific route. And this is the screenshot of software, where is possible to see specific route. In particular the actual speed and energy consumption has been used for this project. In addition in this project the route between Brixton and Stockwell has been selected on the Victoria line. Figure 47 shows the train performance tool software.

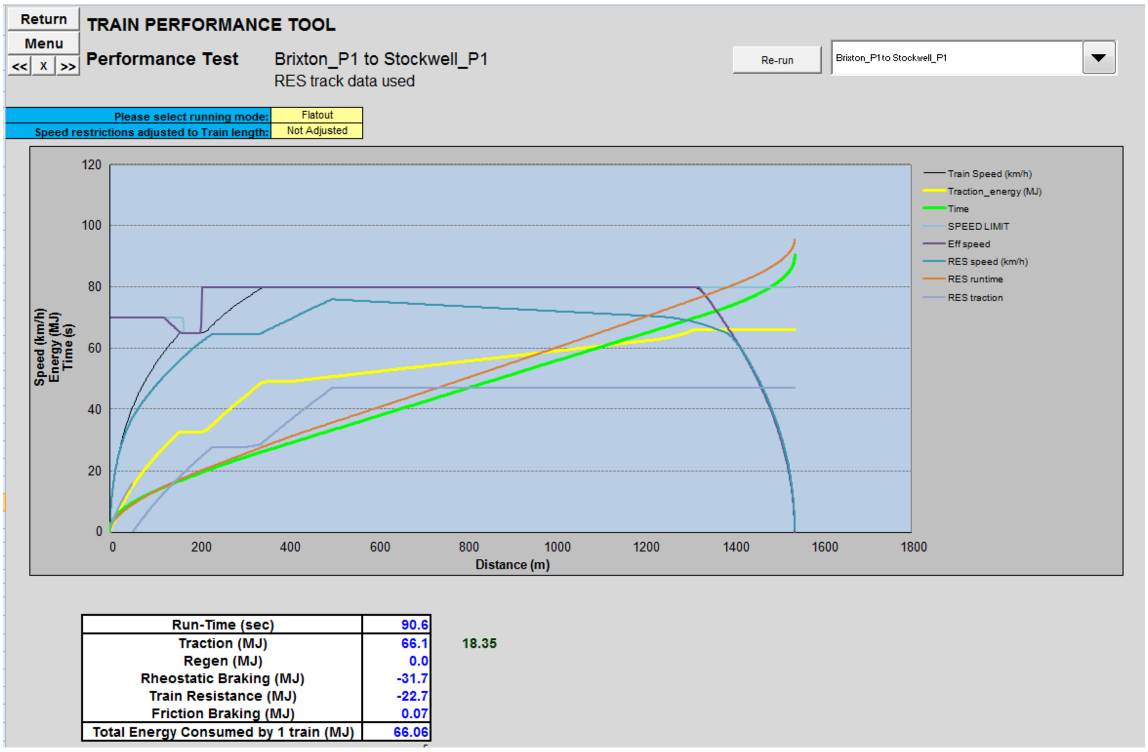

Figure 47 Train performance tool software

4.2 Design Structure

London underground trains are supplied at 630V DC. In order to use batteries as energy storage for London underground, battery cells need to be connected in series. A Battery cell voltage is depends on electrochemistry of the batteries and the ranges of voltage for battery cells are usually between 1 to 4 V. Furthermore in order to achieve 630V by the series connection of the cells, many of them are required. In order to reduce the number of cells in series, DC-DC converter can be used. Bidirectional DC-DC converters are needed because when the train is powered by the conductor rail the battery cells can be recharged. For design of energy storage of London underground in this project interleaved bidirectional DC-DC converter with the ratio of three have been used, therefore instead of 630V just 210V is required by energy storage to supply, which this can reduce the number of battery cells by a third. Is not really possible to use the bigger ratio of converter and this is because of the resistance of inductance. If want to increase the booster ratio, in that side of converter which is connected to the battery it has a bigger current and smaller voltage. Therefore at some point most of energy is dissipated across the inductance, because of high current, so it is not efficient to use bigger ratio. Typical limit of this converter is three. (Jih-Sheng (Jason) Lai, 2007) Bidirectional DC-DC converter can also be designed with multiphase interleaving.

Figure 48 shows a three-phase converter for both LV and HV sides. (Jih-Sheng (Jason) Lai, 2007)

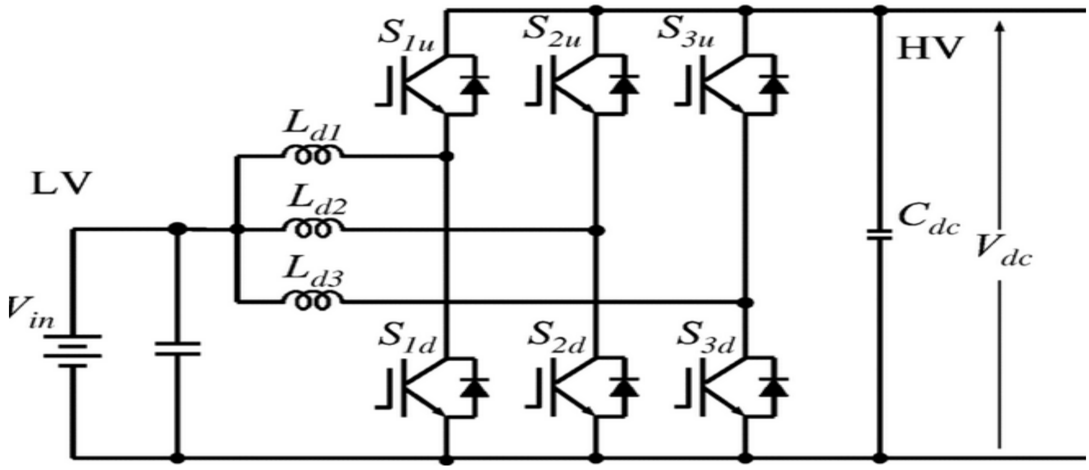

Figure 48 Three-phase non isolated bidirectional dc–dc converter (Jih-Sheng (Jason) Lai, 2007)

4.2.1 Battery Based Energy Required by the Train

When the train is passing across each gap, it would be ideal if the speed of the trains would be not affected by the power cut, consequently train performance should remain the same. Therefore the chosen energy storage for the train should be capable of supplying the same amount of energy as the 3rd rail power supply (Conductor rail) to the train for the length of the gap in London underground. The capacity of energy storage depends on the mass, velocity of the train and length of gap. Gaps are normally 15 meter in London underground, therefore Figure 49 shows how much energy in kWh is needed to run 2009 Tube Stock train over 15 meter gap for different speed of train.

As it shows in the figure 49 there are 4 regions has been identified for energy consumption of the train on the graph.

1- If the gap is close to station, than the train needs to be accelerate to reach the maximum speed. Therefore energy usage by the train is increasing.
2- In this stage, in order to increase the speed of train gradually, the train has constant acceleration as result energy also is constant.
3- In this region the train is close to reach the maximum speed, therefore acceleration is reducing to control the speed of train as result energy consumption is also reducing.
4- In the final region train has been reach the maximum speed, as result acceleration is zero therefore energy also is zero.

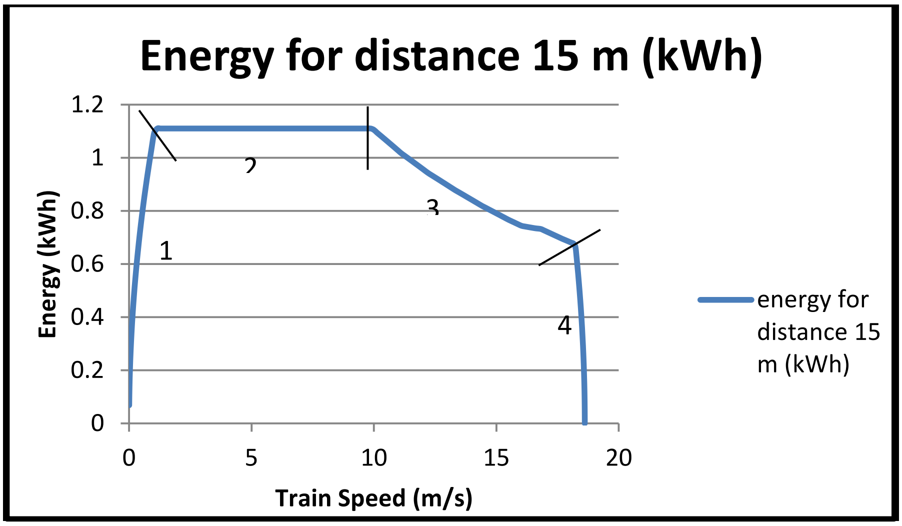

Figure 49 Energy in KWh is needed to run 2009 Tube Stock train over the 15m gap

In this project the capacity of energy storage for different distance/ train speed has been calculated. Figure 50 demonstrate the calculation results of how much energy required by train to pass the gap in kWh and illustrated the calculation results of how much capacity of energy storage required for different speed in different distance in Ah. In order to choose the right capacity of energy storage, the maximum energy required by train must be considered, so in this design energy storage must be capable to provide approximately 1.15 kWh energy. Capacity of energy storage must be atleast 5.5 Ah.

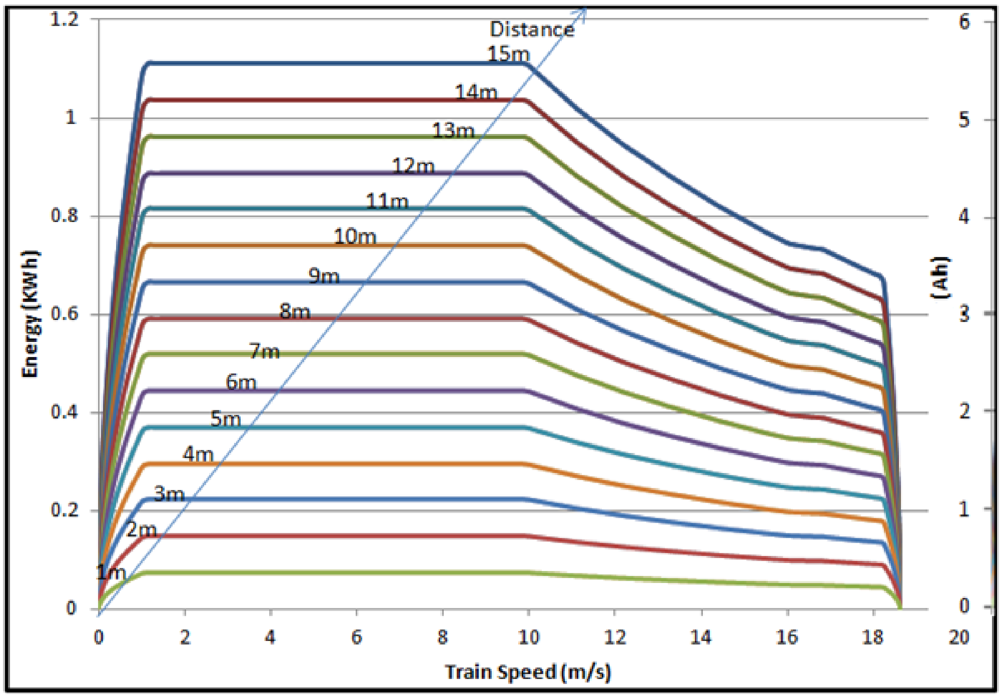

Figure 50 Energy required by train to pass the gap in KWh and Capacity of energy storage for different distance in different train speed

Capacity of energy storage is not the only thing that needs to be considered and the discharge current rate is also important therefore the energy storage needs to be capable to discharge enough high current as required by train. There are 8 cars available in 2009 Tube Stock trains and 6 of them are motored cars. In total the train has 24 motors; hence there are 4 motors per car. From the train performance tool software, traction power of the train is already known. In order to calculate the current required by the train, the traction power needs to be dividing by 630V which is the voltage of the DC supply. Not all the shoes in the train are connected together, hence different design should be considered for different cars. A car has their own shoes and there are 2 A cars in this specific train available as it shows in figure 46. Each A car require to have energy storage enough for 4 motor. In order to calculate the current required by each A car, firstly the amount of current that can be taken by each motor have to be calculated, this could be achieved by dividing the total current of train by 24. Consequently this result simply needs to be multiply by 4 (There are 4 motors per car) in order to calculate the current required by each A car.

In this train there are 2 D cars and 2 C cars. Each D car is connected parallel to one C car; therefore they have the same shoe gear to get the power from the conductor rail. For each D and C cars one set of energy storage is better to be designed, because it could be save some cost by reducing one converter and extra connection. The method of calculation is similar to A car but the only difference is that the results of calculation needs to be multiply by 8 instead of 4. The current required by each A car during the journey from route of Brixton to Stockwell in London underground has been shown below in figure 51, which it demonstrate the maximum current required (680A) by the train. As the energy storage in this design operate 210V, than in order for energy storage to proved the same power to run the train, energy storage in each A car should be capable to discharge current as high as 2040A(680×3).

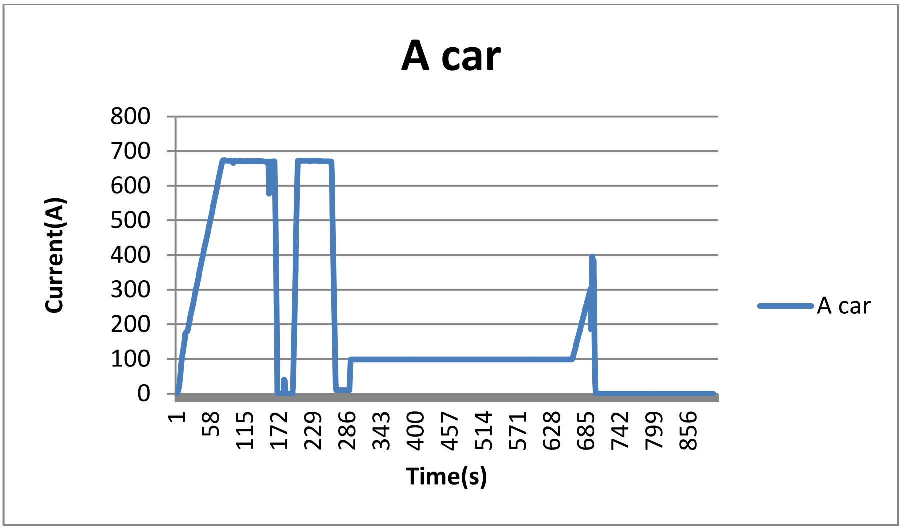

Figure 51Current required by each A cars during the journey of platform Brixton to platform Stockwell

Figure 52 also shows current required by each D and C cars during the same journey, as it illustrated this time maximum current required by train is 1360A. Therefore energy storage in D and C cars should be capable to discharge current as high as 4080A.

As results 4 group of energy storage required by this train, two for A cars and two C and D cars.

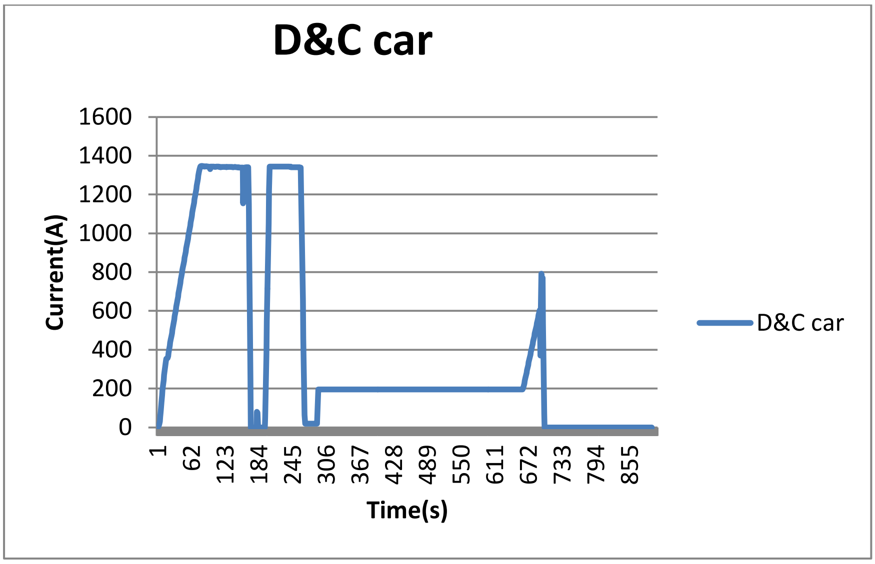

Figure 52 Current required by each D and C cars during the journey of platform Brixton to platform Stockwell

4.2.2 Energy Storage Design and Discussion

In this part of project different batteries and super capacitors has been considered, in order to design the best possibility of energy storage for the train to pass the gaps in London underground -Victoria line, without loosening any the performance.

4.2.2.1 Batteries design for London underground gaps

Different type of batteries has been considered. There are two different designs of batteries required for this specific train. Since there are two different types of cars (A and C&D), the capacity and discharge current required by those cars are different. In order to pass the gaps by designing the battery pack for the 2009 Tube Stock, there are some requirements that have to be taken into account. The first thing that needs to be considered is the output voltage of the batteries; this is important why the number of batteries that need to be in series must be calculated. In this design total voltage should be reach to 210V, as mention earlier interleaved bidirectional DC-DC converter with the ratio of three is used to convert the voltage of batteries to 630V.

Another important parameter in this design is to find out the maximum discharge current by the batteries. By connecting the batteries in parallel, the total discharge current required by the train can be achieved.

Capacity of batteries also need to be considered and should be big enough to supply enough energy to the train while the train is passing the gap. In order to increase the life cycle of batteries, it is better to choose a bigger capacity so each time when the train is passing the gaps, battery will discharge by the smaller percentage of their total capacity. The relation between the cycle life and the depth of discharge appears to be logarithmic as shown in the graph 53. In other words, the number of cycles yielded by a battery goes up exponentially the shallower the DOD. This holds for most cell chemistries. (Technologies, 2005)

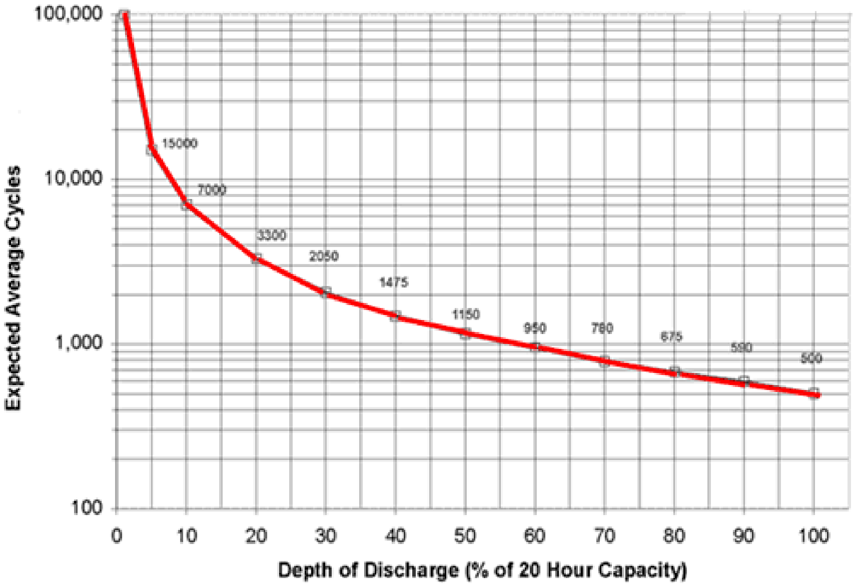

Figure 53 Depth of Discharge vs Life Cycle (Technologies, 2005)

In order to compare different types of batteries, same capacity for all type of batteries should be considered.

Weight of batteries are also important, since onboard energy storage is being used it is important to choose a lighter weight battery for this specific design. Life cycle of batteries also is important because if it is too short, then batteries need to be replacing more often, with significant increase of the maintenance costs, it is important to mention that in battery design energy of batteries is not really important but power is important. Table 3 compare different types of batteries designs which can use them as energy storage system for A cars.

Table 6 Different type of batteries design, in order to use them as energy storage system for A cars

CAR A				
Battery model	Lithium ion (model 9535)	Lithium ion (model 9522)	Lead-Acid (model 689-5854)	Nickel-metal hydride(model 10-340)
Output voltage(V)	72	28.8	12	12
Max discharge current(I)	250	125	1000	200
Weight of each battery(kg)	21.73	11.34	32.3	9
Number of battery in series for each motored car	3	8	18	18
Number of battery set in parallel for each motored car	12	16	4	30
Capacity of each battery(Ah)	34	25	100	12
Total capacity of batteries(Ah)	374	400	400	360
Total capacity of batteries(kWh)	78.54	84	84	75.6
Total weight of batteries(kg)	717.09	1451.52	2325	4860
Life cycle at 100% DOD	800	800	800	10000
Life cycle depends to number of gap	100000	100000	100000	1250000

As it demonstrated in the table above Lithium ion (model 9535) with output voltage of 72V and max discharge current of 250A with the 21.73 Kg is a suitable battery for this design. Therefore in order to get the voltage required, three of these batteries need to be connected in series. Furthermore in order to get the same capacity as other types of batteries that mentioned above and high discharge current, 12 set of this batteries need to be connected to each other in parallel. Therefore this set of batteries has a total capacity of 374 Ah and total weight of this set of batteries is 717.09 kg which is much lighter than other types of batteries for this design. Life cycle is another advantage of this type of design of batteries. Each time the train pass the gaps this set of batteries will discharge by 1.5 %(1.15/78.54=1.5). As results Lithium ion (model 9535) in this design are capable to power the train for about 100000 gaps. Total length of Victoria line is 21 km and between each 5 to 4 km conductor rail gaps are located. Therefore approximately there are 5 gaps in the Victoria line; each train in one day 100 times passing these gaps, as a result battery life Lithium ion (model 9535) in order to use it for Victoria line trains is about 3 years.

Each Lithium ion (model 9535) battery cost £368.96, therefore batteries for this design will cost car £13282.56 for each A cars which is excluded the cost of DC-DC converter and electrical connection. DC-DC converter for this propose is cost about £250 therefore the total cost of this energy storage with electrical connection is about £14000.

Table 4 compares the different batteries designs that can be used as energy storage system for C&D cars. Lithium ion (model 9535) is the most suitable type of battery for A cars as well as for C&D cars. They are the most suitable type of battery for C&D cars, since they have same benefits as they have been mentioned in the previous paragraph. As the number of batteries increases, the cost of batteries will increase too, therefore the total cost of batteries will be £23244.48 for each C&D cars and the total cost is about £24000.

Table 7 Different type of batteries design, in order to use them as energy storage system for C cars and D cars

CAR C&D				
Battery model	Lithium ion (model 9535)	Lithium ion (model 9522)	Lead-Acid (model 689-5854)	Nickel-metal hydride(model 10-340)
Output voltage(V)	72	28.8	12	12
Max discharge current(I)	250	125	1000	200
Weight of battery(kg)	21.73	11.34	32.3	9
Number of battery in series each motored car	3	8	18	18
Number of battery set in parallel for each motored car	21	29	7	58
Capacity of each battery(Ah)	34	25	100	12
total capacity of battery(Ah)	714	725	700	696
Total capacity of battery(kWh)	149.94	147	147	146.16
Total weight of battery(kg)	1369	2630.88	4069.8	9396
Life cycle at 100% DOD	800	800	800	10000
Life cycle depends to number of gap	100000	100000	100000	1250000

4.2.2.2 Super-capacitors design for London underground gaps

The main difference between batteries and super-capacitors is the fact that the super-capacitors are capable of discharging high current in short time. Therefore this is beneficial to use them as a power supply to the train during the conductor rail gaps. Super-capacitors have small capacity; however it has relatively a high number of life cycles, hence in this design there is no need to increase the number of cells set in parallel for each motored car as they already have a high number of life cycles and they are capable of discharging high current in short time.

Various numbers of super-capacitors has been considered in this part of project, in order to discover the best option for London underground conductor rail gaps.

In order to compare different super-capacitors for this application, first of all total capacity for different super-capacitors should be chosen at same rate. It has been shown on table 5, the life cycles of all capacitors are high, and consequently to choose the best super-capacitors, total weight of cells must be considered. Therefore table 5 illustrated super-capacitors model BMOD0165 P048 BXX has a smaller amount of weight than other types. As a result this type could be an option in designing energy storage for London underground conductor rail gaps (this type of super-capacitor has previously been used for some railway application). All the super-capacitors in this table are capable of high max discharge current, therefore the design of super-capacitors as energy storage will be the same for all A cars and C&D cars.

Table 8 Different type of super capacitors design, in order to use them as energy storage system for this application

super capacitor	BMOD0063 P125 B04/B08	BMOD0094 P075 B02	BMOD0130	BMOD0165 P048 BXX	BM0D0500 B02
Output voltage(V)	125	75	56	48	16
Max discharge current(I)	1800	1600	1800	1900	2000
Weight (kg)	60.5	25	18	13.5	5.51
Number of cells in series each motored car	5	9	12	13	40
Number of cells set in parallel for each motored car	3	3	3	3	3
Total weight of cells(kg)	907.5	675	648	526	661.2
Life cycle depends to number of gap	1000000	1000000	1000000	1000000	1000000
Total capacity (kWh)	1.313	1.25	1.273	1.39	1.39

Due to same information in terms of number of gap for Victoria line in London underground all the super capacitors which are explained in table 8, in order to use them for Victoria line trains will have life cycle of about 30 years.

Super-capacitors are more costly than batteries. Therefore each super-capacitors model BMOD0165 P048 BXX will cost £1209.66. Total cost of these super-capacitors for this design will be £47176.74 for each A and C&D cars. This design has lower weight compare to other type to super-capacitors which are introduced in above table but is not the cheapest one.

As it shows in table 8, BMOD0063 P125 B04/B08 capacitor is the cheapest super-capacitor for this design but it is heavier than other super-capacitors.

Table 9 Total cost of super-capacitors for this design

Type of Super-capacitors	Total cost for this design
BMOD0063 P125 B04/B08	£23325.00
BMOD0094 P075 B02	£53961.12
BMOD0130	£42537.96
BMOD0165 P048 BXX	£47176.74
BM0D0500 B02	£28862.40

4.3 Summary and Discussion

To summarize the founding in this chapter based on calculation and real traction data from London underground, a number of batteries and super-capacitors have been investigated to use them as energy storage system for London underground for the period of when trains are passing the conductor rail gaps. For choosing the best type and model of energy storage, weight, volume, max discharge current, capacity, life cycle and price of them has been compared. As results in batteries types, Lithium ion model 9553HV was the best choice for this design and in super-capacitors type, model BMOD0165 P048 BXX was the best choice. Finally by compare the batteries and super-capacitors, it can be seen super-capacitors are more expansive and they need higher capital cost but they have longer life cycle and they can be run in this design for 30 years and batteries only can be use for 3 years in this application, therefore after 3 years batteries are required to replaced, which is cost a lot. Consequently is not worth to use the batteries for this application.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The equivalent circuit mathematical model for the discharging progress of a lead-acid battery has been developed for this purpose and is implemented under Excel Microsoft software environment. The model involves most of the important concepts of a battery to reflect the dynamic response of terminal voltage when discharging.

A series of experimental tests have been carried out during the project for the model validation and the study of the state of charge. And battery model implemented under MATLAB/SIMULINK software environment. This battery model which has been made could help to select right battery for different DC railway application.

After that the integrated model of DC railway with two substations and moving train power system that has been developed in this project by using MATLAB/ SIMULINK program to better understanding of how DC railway is working. DC railway power supply has some gaps which disconnect the power supply to the train, therefore conductor rail gaps has been designed and simulated to shows what happened to train when passing the gaps. As results train was losing their performance over the gaps. consequently, in order to keep the train performance remain the same during the gaps, different type of energy storage such as batteries and super capacitor has been designed to find the suitable solution for power up the train though the gaps. As results of investigation, super capacitors are more suitable for this issue. Because of high current need to be discharged in short period of time, so super capacitors have batter capability compare to the batteries for discharging the high current. and most important things about the super capacitor is the life cycle of them, as result super capacitors for this application have 10 times longer life cycle.

5.2 Future Work

For using batteries in railway application, batteries are required to have high rate of charge and discharge to cope with the high current flows. As results, it is essential to consider the batteries life issue. Therefore life cycle of battery must be considered.

Generally, the number of cycle which is specified on batteries data sheet is just for one condition, which is tested in the laboratory. However, railways have different conditions and life cycle of batteries should be estimated for all routes under different conditions. Therefore, it is necessary to build up new tool for testing batteries to finding the life cycle of batteries for different uses in the railways and also to characterize the batteries. This could be future work area in this project.

References

(STIB), F.-O. D., 2011. *Overview of braking energy recovery technologies ,* s.l.: s.n.

Anon., n.d. *Nuenergy technologies.* [Online]
Available at: http://www.nuenergytech.com/product-development/kinmo-flywheel-energy-storage/
[Accessed 15 02 2013].

Arendarik, S., 2012. Active Cell Balancing in Battery. *Freescale Semiconductor.*

Beeching, R., 1963. *The Reshaping of British Railways - Part 1,* s.l.: Her Majesty's Stationery Office.

Berndt, 1993. *Maintenance-Free Batteries. A Handbook of Battery.* s.l.:Research Studies Press Ltd.

Blog, T. E., 2006. *The Energy Blog.* [Online]
Available at: http://thefraserdomain.typepad.com/energy/2006/01/sodiumsulfur_na.html
[Accessed 22 02 2013].

Brain, M., 2006. *How stuff works.* [Online]
Available at: http://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery1.htm
[Accessed 22 02 2013].

Buchmann, I., January 2004. Discharge methods.

Bullock, K. R., 1994. Lead/acid batteries. *Journal of Power Sources,* Volume 51, pp. 1-17.

Conway, B. E., 1999. *Electrochemical Supercapacitors: Scientific Fundamentals and Technological Applications.* Ottawa: s.n.

David Linden, T. B. R., 2002. *Handbook of Batteries.* 3 ed. s.l.:McGraw Hill Professional.

Dr. Michael Steiner, M. K., n.d. *Energy Storage System with UltraCaps on Board of Railway Vehicles,* s.l.: s.n.

Gholam-Abbas Nazri, G. P., 2003. *Lithium Batteries: Science and Technology.* s.l.:s.n.

Hanmin Lee*, G. K. C. L., n.d. *Analysis for EDLC Application on Electric,* s.l.: s.n.

Jih-Sheng (Jason) Lai, F. I. a. D. J. N., 2007. Energy Management Power Converters in Hybrid Electric and Fuel Cell Vehicles. *IEEE,* Volume 95.

Kadhim, R., 2009. *Energy Storage Systems for Railway Applications,* London: RSSB.

Lee, J., 2007. Li-ion battery SOC estimation method based on the reduced order extended Kalman filtering. pp. 9-15.

Lee, Y.-S., 2006. Quasi-Resonant Zero-Current-Switching. *IEEE TRANSACTIONS ON POWER ELECTRONICS,* Volume 21.

ltd, S. p., 2012. *SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES).* [Online]
Available at: http://www.superpower-inc.com/content/superconducting-magnetic-energy-storage-

smes
[Accessed 15 05 2014].

LUC FRUCHTER, G. C. a. A. L. M., 1986. BATTERIES, IDENTIFIED FRACTAL OBJECTS. *Journal of Power Sources,,* p. 51.

Michael Steiner, J. S. H. S. a. T. J., 2008. Energy Storage Systems for Improved Efficiency of Railway Vehicles.

Namisnyk, A. M., 2003. *A SURVEY OF ELECTROCHEMICAL ,* s.l.: s.n.

Okoshi, T. Y. K. H. T. a. E. A., 2006. Battery condition monitoring. *Journal of Power Sources,* Issue 2, p. 158.

Oura, Y., 1998. Railway Technology today 3. 16 june.

Parfomak, P. W., 2012. Energy Storage for Power Grids and Electric Transportation: A Technology Assessment. *Congressional Research Service.*

Perla B. Balbuena, Y. W., 2004. *Lithium-Ion Batteries: Solid-Electrolyte Interphase.* s.l.:Imperial College .

R Barrero1∗, X. T. a. J. v., 2009. Stationary or onboard energy storage systems for energy. *Rail and Rapid Transit.*

Rail, B., 2007. *rail.co.uk.* [Online]
Available at: http://www.rail.co.uk/british-railway-history/british-rail/
[Accessed 23 01 2013].

Rail, N., 2009. *Electrification,* London: Network Rail.

Rashid, M. H., 2004. *"Power Electronics Circuits, Drives and Applications,. "* 3rd Edition. ed. s.l.:Pearson/Prentice Hall.

REUK, 2006. *REUK.co.uk.* [Online]
Available at: http://www.reuk.co.uk/Lead-Acid-Batteries.htm
[Accessed 22 02 2013].

Rosch, W., 2001. *psmac.com.* [Online]
Available at: http://www.pcmag.com/article2/0,2817,1155271,00.asp
[Accessed 22 02 2013].

Schoenung, S. M. &. H., 2002. Long- vs Short-Term Energy Storage Technology Analysis.

Schramm, D. J., 2013. *Maxwell Technolgies.* [Online]
Available at: http://www.maxwell.com/products/ultracapacitors/products/k2-series
[Accessed 17 06 2013].

Steiner, D. M. D. J. S., 2005. Energy Storage on board of railway vehicles. *IEEE.*

Stock, L. U. 2., 2009. s.l.: s.n.

Technologies, B. a. E., 2005. *Battery Life (and Death).* [Online]
Available at: http://www.mpoweruk.com/life.htm
[Accessed 21 09 2013].

THOMAS, J., 2007. Storing Sunshine Using Flow Batteries.

Underground, L., 2009. *London Underground 2009 Stock.* london: London Underground.

Vazquez, S., 2010. Energy Storage Systems for Transport and Grid Applications. *IEEE,* Volume 57.

Vironment, A., 1998. *Remote Operation System 4.0 Manual,* California: s.n.

Whittingham, M. S., 2008. Electrical Energy Storage Using Flywheels. *Harnessing Materials for Energy,* Volume 33, p. 419.

Appendix1 Risk assessment

The following is a risk assessment for Operating the battery cycler with the aim of charging and discharging 14.4 volt batteries by using predefined current profiles.

Purpose

Aim of task is to determine resistance of battery in different states of charge and also calculate the resistance of battery with different current.

Action plan

1. The access to the lab must be restricted to personnel involved in test. Nobody is allowed in to the room when test are in progress. This is because people in the lab could accidentally touch and be subjected to undesired contact voltages.
2. Put the battery on floor next to battery cycler.bur make sure not in walkway. Way to emergency door must be clear.
3. Check all fuses in protection box to make sure they are working.
4. Connect with cable of appropriate cross section the protection box between the battery cycler and battery pack. Section of the cable is selected to according point 3.
5. Tighten securely all the connections.
6. Connect the computer to the battery cycler via RS232 AND set the programABC150 ready to run.
7. Now power on the battery cycler by closing the disconnected switch.
8. Set maximum current and voltage of the DC side using the front panel. Ensure this limits are within the range admitted to particular battery connected.

Ones all of these actions have been properly executed there are two task to complete;

Task 1)

1. Discharge the battery pack with constant current equal to the nominal current from 100% to 0% of the state of charge.

2. Control of the current through RS232 and recording data in a logging file.

Task 2)

1. Charge the battery pack with constant current equal to nominal current from 0% to10 % of state of charge, and calculate the resistance of battery.
2. Repeat action 1 with increments of 10% of state of charge, till battery is fully charged.
3. Repeat action number 1 and 2 with current equal to 25%, 50 % and 75%nominal current.

The University Personnel will be:

1. Siavash Hajiabady
2. Pietro Tricoli

Anticipated Tasks:

- battery cycler for charge and discharge battery
- battery for testing
- wire connection
- protection box
- fuses for safety
- computer to program battery cycler

Final copies to;

Andy Dunn NB6

RRC staff Room

Hazard and Risk Assessment

Assessment of Hazard and Risk Assuming No Controls																Existing Control Measures		
HAZARD (List only significant hazards capable of causing serious harm under foreseeable conditions)	PERSONS AT RISK (Indicate number)							PERSONAL HARM?			LIKELIHOOD				RISK LEVEL	CONTROLS/PRACTICE	INFORMATION/INSTRUCTION	CONTROL OK
	Ug	Pg	S	C	V	Pa	Pu	F	Mj	Mn	Y	Pr	Po	R	*			Y/N?
High dc voltage and dc current output		X	X						X				X			Must not be able to touch and must be covered.	High dc voltage and dc current output is very dangers and it could be cause of death. Therefore, when the power is on, we should not be able to touch the live conductors.	Y
Poor training		X							X				X			Staff should be present until adequate training of the postgraduate student is achieved.	The user first of all should read all safety and healthy document. If using the battery cycler for the first time, an experienced member of staff should be in the lab to explain all part of machine to user and he needs to make sure everything is right. And member of staff should stay till user working with the battery cycler. For the second time of using the battery cycler, supervisor should in lab to check if everything is right and he need to make sure user is ready to work with battery cycler for next time without him. When supervisor deemed user has competent to use the battery cycler, supervisor does not have to supervise directly user's work, but at least one member of staff should be in lab to help in case there are problems with the machine.	Y

Fire		X	X						X				X			Check everything carefully before powering on the equipment. For example when we want to connect battery to battery cycler in case of any fault happened, we will use some fuses in between of connection. By doing that if anything goes wrong just fuses will be broken.	Fuses must be used to connect the battery to the battery cycle. If anything goes wrong it might cause of fire in the battery. Batteries get warm when charged and we must be sure that the temperature does not reach critical value. This is ensured by the control of the current under the limit given by the battery manufacturer.	Y
Explosion or other damaged of 14.4V battery.		X	X						X				X			Battery could be damaged if the cell voltage is higher than that admissible.	In order to keep away from this problem, we have to make sure, voltage going to be use in turn of charging the battery is in the appropriate range (14.4 V for lead-acid battery, but different value for NiMh batteries). The machine can’t power on without setting the voltage limit to a value admissible for the battery.	Y
Unclean batteries		X	X						X				X			If battery allowed to be unclean (e.g. from dried spilled acid), it is possible for charge to slowly escape along the resulting electrically conductive discharge path.	The barterer’s exterior should therefore be kept clean especially around the terminals to ensure that no discharge path exists.	Y

Site area		X	X					X					X			Site area need to be restricted access during tests. Therefore we can put a notice behind the lab door warning people that lab will have restricted for the duration of the tests.	Site should be restricted because when we working in lab, equipment will be live and if everyone can come to the lab it will be dangers and they might touch the equipment.	Y
Connection of the battery and battery cycler		X	X				X						X			Use a protection box between the battery and the DC-side of the machine. Make sure protection box has no damaged or broken fuses. If it has any broken fuses, they should be replaced before connection.	Protection box has been made from some fuses in order to don't let the equipment damage.	Y
Wet hands		X	X					X					X			During the testing we should not work with wet hands	This is very dangers because this might reduce further the protection against electric shocks.	Y
Connect battery to the protection box		X	X					X					X			Verify the effectiveness of the connection and the absence of exposed live conductors.	If this is not, provide better insulation of the connection.	Y
Imagine if there is any person close to the equipment that could accidentally touch any live conductors		X	X				X						X			In order to make sure this does not happen, must cover live conductor and harm people around that test on the machine are in progress.	If a people do suffer accidentally from electric shock, make sure that the machine is powered off before helping him. Call immediately the 999 for an emergency intervention.	Y

Turn on the battery cycler		X	X				X						X			Turn on the battery cycler by closing the disconnect or switch and the circuit breaker. Check that the machine is in stand-by. If not, press the emergency stop (red button);		Y
CCTV camera		X	X					X						X		When we are working in the lab. Make sure CCTV camera is on.	CCTV camera should be on. During the test we are not in the room, So if anything goes wrong, we should be able to see and be able to stop the test.	Y
Eating or Drinking		X		X					X					X		When we are working in lab, we should not eat or drink.	Food waste creates mess in the lab. Drinks spilled on electrical equipment could be dangerous due to the possibility of creating short circuits and, hence, fire.	

EXAMPLES OF HAZARDS				
Poor instruction, information, training	Slipping/tripping hazards	Electricity	Pressure systems	Biohazards
Inadequate systems or procedures	Noise	Chemicals/substances	Fall of object from height	Radiation Hazards
Inadequate maintenance or monitoring	Lifting heavy objects	Dust	Drowning	Confined Spaces
Unsuitable workstation or equipment	Fall of person from height	Fume	Excavation work	Hand tools
Low temperature	Fire	Moving parts of machinery	Explosion (chemical/dust)	Stacking
Poor lighting	Vehicles	Ejection of material	Mechanical lifting	Compressed Gas

Key	PERSONS AT RISK		PERSONAL HARM?		LIKELIHOOD
Ug	Undergraduate	F	Fatality	Y	Yes/ Very High
Pg	Postgraduate	Mj	Major Injury	Pr	Probable
S	Staff	Mn	Minor Injury	Po	Possible
C	Contractor			R	Remote
V	Visitor				
Pa	Patient				
Pu	General Public				

* Risk/Action Matrix

	Y	Pr	Po	R
F	1	2	2	3
Mj	2	2	3	3
Mn	3	3	3	4

KEY

	Priority Action	
1	1st Priority Action	(Immediate Action)
2	2nd Priority Action	(As soon as possible)
3	3rd Priority Action	
4	Risk OK, no action	

Major Injury: Loss of or broken limb
Loss of or damaged eye
Loss of consciousness
Acute illness needing Medical treatment
Permanent ill health or disability

For safety reason the label below has been design and was installed on safety box.

WHEN YOU SWITCH OFF THE EQUIPMENT, WAIT AT LEAST FIVE MINUTES BEFORE OPENING THE BOX

Figure 54 Safety notice

Appendix2

Battery charging code

```
/* Battery Pack Model with SOC Dependence*/
/* Written by  S Hajiabady 25 Jan 2013*/
#request SG
main ()
{
        float Vth    = 14.4;    /* Fully charged voltage */
        float Istart = 25;      /* Charging current start value */
        float Istop  = 1;       /* Stop charging at this current */
        float Ic     = Istart;  /* Charching current at each time */
        float Vc;               /* charging voltage */
        float timer;            /* a time keeper variable */
        float timer2;           /* a time keeper variable */
        float Iold;             /* Previous recorded battery current */
        float Rw     = 0.06;    /* Wire resistance */
        int   StopIt = 0;
        /* Set Limits For ABC-170  */
        ABCVmin =  9.6;
        ABCVmax = 15.5;
        ABCImin = -6.0;
        ABCImax =  25.0;
        ABCPmin = -1.0;
        ABCPmax =  1.0;
        ChangeLimits();
        ABCCommandMode  = 1; /*Current Mode*/
        ABCCommandValue = Ic;
        /* LogMessage */
```

```
LogNumberMessage("Start charging with current=", Ic);
timer = TestTime;
while (TestTime-timer < 1.0) {} /* wait for 1 second */
LogNumberMessage("The battery voltage is:", ABCVoltage);


Vc    = Vth + (ABCCurrent * Rw); /* Find charging voltage based on battery current*/
while (ABCVoltage < Vc) /* wait until the battery reaches the voltage specified above*/
{
  Vc = Vth + (ABCCurrent * Rw); /* Find charging voltage based on battery current*/
        timer2=TestTime;
        while (TestTime-timer2 < 10.0) {} /* wait for 10 second */
}
Vc    = Vth + (ABCCurrent * Rw); /* calculate new charging voltage based on new current*/
LogNumberMessage("The battery voltage reached:", ABCVoltage);
LogMessage("Switch to voltage mode charging.");
ABCCommandMode  = 0; /* Switch to Voltage Mode*/
ABCCommandValue = Vc; /* Charging voltage*/
timer=TestTime;
while (TestTime-timer < 10.0) {} /* wait for 1 second */
timer = TestTime; /*save the current time*/
Iold = ABCCurrent; /*save the battery current at the present*/
/* wait until current is bigger than current */
while ((ABCCurrent >= Istop) && (StopIt !=1))
{
        if (((TestTime-timer)>3600) && ( abs(ABCCurrent - Istop) < 0.2)) /* if current is at minimum current wait for one hours*/
        {
                        StopIt=1; /* set the flag to stop waiting */
```

```
                LogNumberMessage("Battery is charging for two hours at current :", Iold);
                LogMessage("Decision has been made to stop charging.");
            }
            if (ABCCurrent != Iold) /* if the current changed calculate new charging voltage */
            {
                Vc = Vth + (ABCCurrent * Rw);
                ABCCommandValue = Vc; /* Set new charging voltage*/
                timer2=TestTime;
                while (TestTime-timer2 < 10.0) {} /* wait for 10 second */
            }
        }
        LogMessage("Stop charging...");
        LogNumberMessage("Last Charging Voltage was:", Vc);
        LogNumberMessage("Last Charging Current was:", Iold);
        ABCCommandMode  = 3; /*Standby the system*/
        LogMessage("Charging completed!");
}
```

By running this script, result of charging which are shows current behaviour and voltage behaviour and downloaded from battery cycler software are as below.

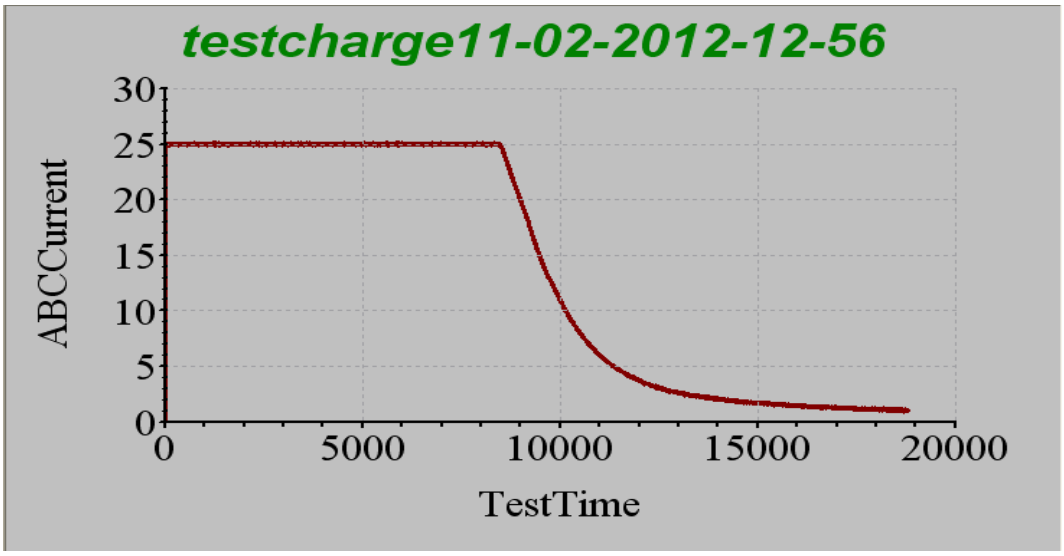

Figure 55 Charging current process

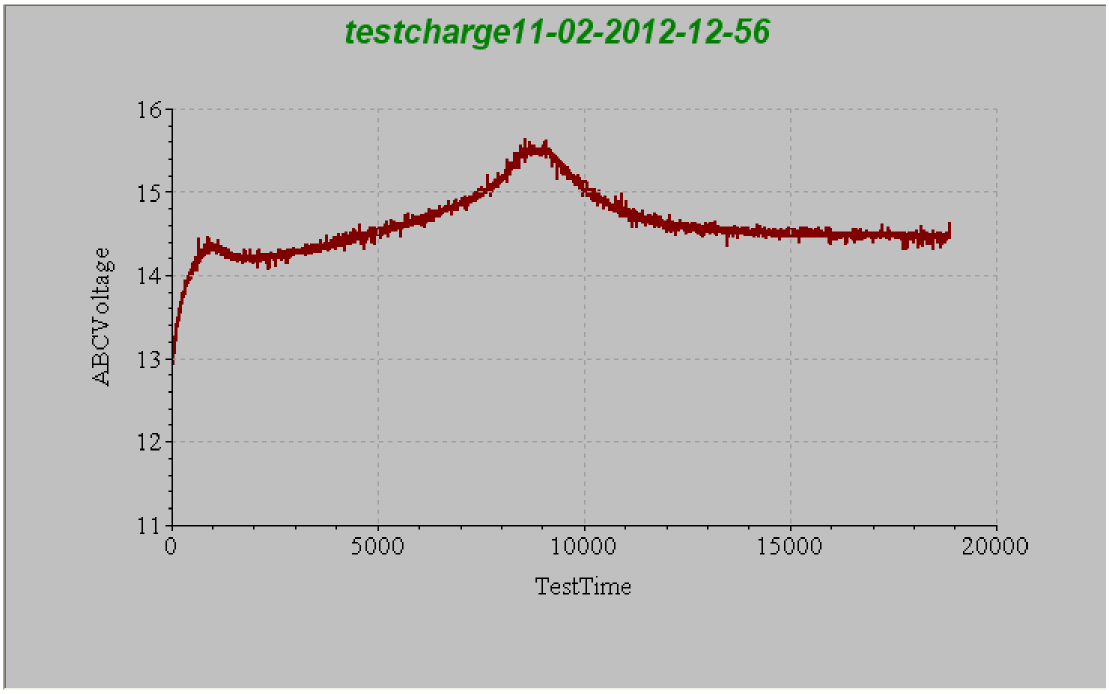

Figure 56 Voltage of battery during charging

For discharging operation voltage of battery demonstrated as below.

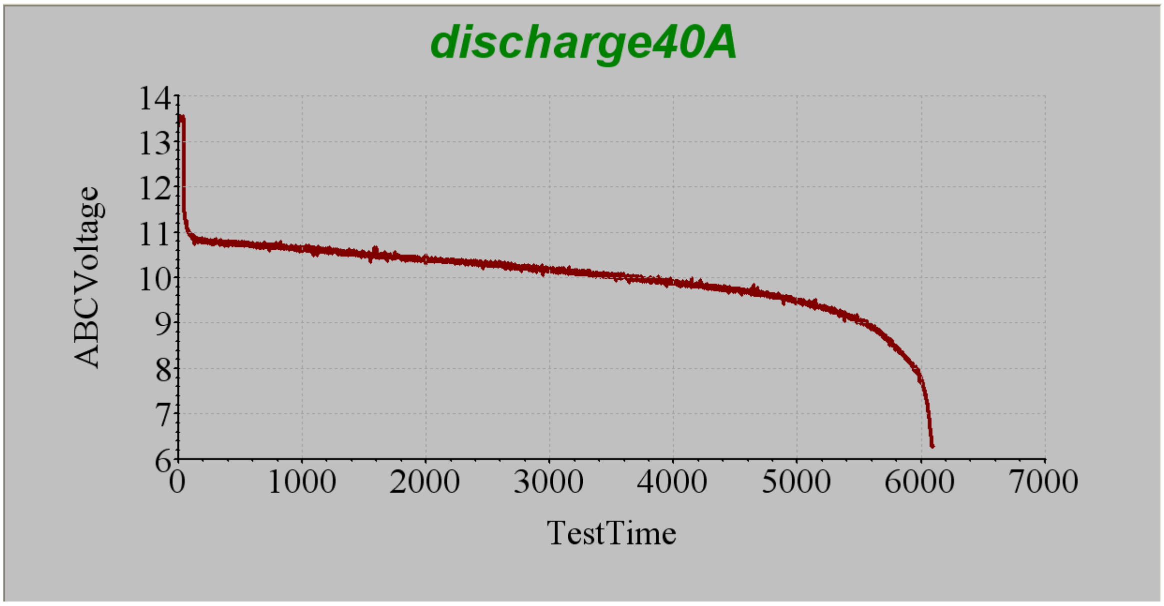

Figure 57 Battery discharge voltage

A lot of data was collected from battery cycler. Table below just shows small amount of this data.

ABCAh	Charging Current	ABCImax	ABCPower	ABCVmax	ABCVmin	ABCVoltage	TimeOfDay
0	0	25	0	15.5	9.6	11.1	46636
0	24.98	25	0.31	15.5	9.6	12.58	46637
0.01	25.06	25	0.32	15.5	9.6	12.64	46638
0.02	25	25	0.32	15.5	9.6	12.64	46639
0.02	24.96	25	0.32	15.5	9.6	12.72	46640
0.03	25	25	0.32	15.5	9.6	12.72	46641
0.04	25	25	0.32	15.5	9.6	12.72	46642
0.04	25.02	25	0.32	15.5	9.6	12.78	46643
0.05	25	25	0.32	15.5	9.6	12.76	46644
0.06	25	25	0.32	15.5	9.6	12.66	46645
0.07	24.98	25	0.32	15.5	9.6	12.78	46646
0.07	24.98	25	0.32	15.5	9.6	12.8	46647
0.08	25.02	25	0.32	15.5	9.6	12.82	46648
0.09	24.98	25	0.32	15.5	9.6	12.84	46649
0.09	24.96	25	0.32	15.5	9.6	12.86	46650
0.1	24.98	25	0.32	15.5	9.6	12.84	46651
0.11	25	25	0.32	15.5	9.6	12.86	46652
0.11	25.04	25	0.32	15.5	9.6	12.92	46653
0.12	25.04	25	0.32	15.5	9.6	12.86	46654
0.13	24.94	25	0.32	15.5	9.6	12.88	46655
0.14	25.04	25	0.32	15.5	9.6	12.86	46656
0.14	25	25	0.32	15.5	9.6	12.9	46657
0.15	25	25	0.32	15.5	9.6	12.9	46658
0.16	25.02	25	0.32	15.5	9.6	12.9	46659
0.16	24.92	25	0.32	15.5	9.6	12.9	46660

Battery discharging code

In this project manual mode has been used but if want used the automatic mode for discharge the code below is prepared.

```
/* Battery discharging model */

/* Written by  S Hajiabady 25 Jan 2013 */

#request SG

main ()

{

        /* Discharging the battery */
```

```
float Id     = -6;   /* Discharging current */
float Vstop  = 9.6;  /* Stopping condition for discharging */
/* Set Limits For ABC-170  */
ABCVmin=9.6;
ABCVmax=14.4;
ABCImin=-6.0;
ABCImax=6.0;
ABCPmin=-1.0;
ABCPmax=1.0;
ChangeLimits();
LogNumberMessage("Start discharging with current=", Id);
ABCCommandMode  = 1; /*Current Mode*/
ABCCommandValue = Id;
while (ABCVoltage > Vstop) {}  /* wait as long as the battery voltage it higher than Vstop*/
ABCCommandMode  = 3; /*Standby the system*/
LogMessage("Discharging completed!");
}
```

Appendix3

Battery model code

```
% X = Discharge Current
% Y = SOC
% Z = Voltage of the battery
Xresolution = 1; %currect
Yresolution = 0.01; %soc
%X=10:10:60;  % Original X values (10 20 30 ... 60)
%Y=100:-10:0; % Original X values (100 90 80 ... 0)
Z = xlsread('matrix.xlsx'); %read the data from excel file
[Ydim Xdim] = size(Z); %get the size of read data
X = linspace(10,60,Xdim); % from 10 to 60 divide by the size of our data
Y = linspace(100,0,Ydim);
Xfine = 10:Xresolution:60;   % Fine X values (10 11 12 ... 60)
Yfine = 100:-Yresolution:0;  % Fine Y values (100 99 98 ... 0)
[Xfmesh Yfmesh] = meshgrid(Xfine,Yfine); % Create a fine mesh to be used by Interpol
function
Zf = interp2(X,Y,Z,Xfmesh,Yfmesh); % calculate interpol values of Z based on new X and Y
hndl = figure;
%mesh(Xfine,Yfine,Zf);
if Yresolution < 1
   surf(Xfine,Yfine,Zf, 'linestyle', 'none');
else
   surf(Xfine,Yfine,Zf);
end
Xlabel('Discharge Current');
Ylabel('SOC');
Zlabel('Battery Voltage');
title('Model of the battery');
dcm = datacursormode(hndl);
set(dcm,'Enable','on','UpdateFcn',@xyzchange);
function output_txt = xyzchange(obj,event_obj)
% Display the position of the data cursor
```

```
% obj          Currently not used (empty)
% event_obj    Handle to event object
% output_txt   Data cursor text string (string or cell array of strings).

pos = get(event_obj,'Position');
output_txt = {['Discharge Current: ',num2str(pos(1),4)],...
    ['SOC: ',num2str(pos(2),4)]};

% If there is a Z-coordinate in the position, display it as well
if length(pos) > 2
    output_txt{end+1} = ['Battery Voltage: ',num2str(pos(3),4)];
end
```

Figure below also shows another model of battery which is show battery voltage in deferent SOC for different discharge current.

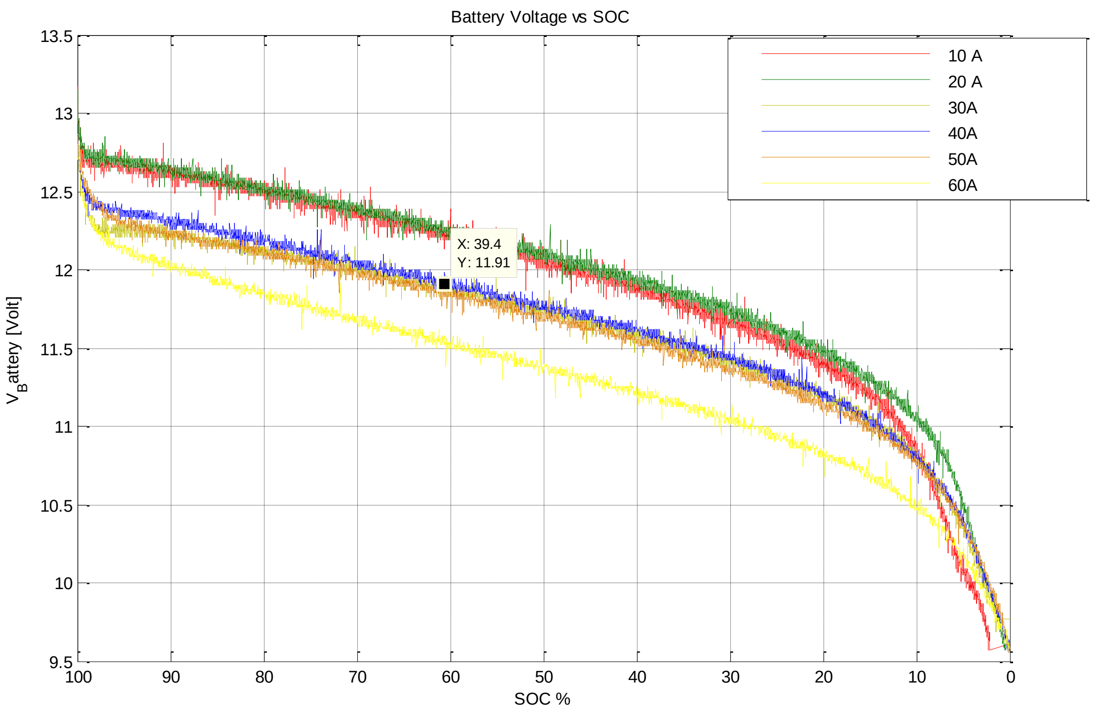

Figure 58 Battery voltage in deferent SOC for different discharge current

Appendix 4

In this project first different method has been used to model the DC railway as shown below. In this method induction motor was used instead of train and vector control was used to control the speed.

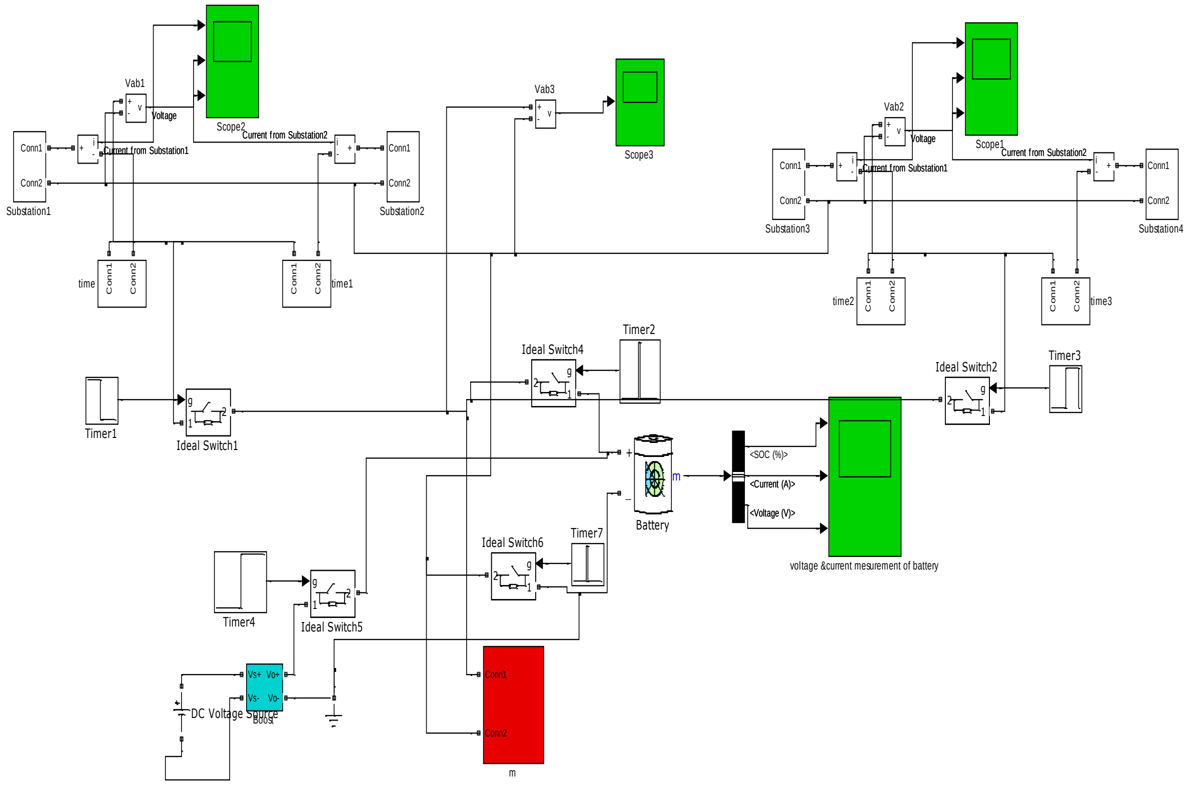

Figure 59 DC model of railway in SIMULINK

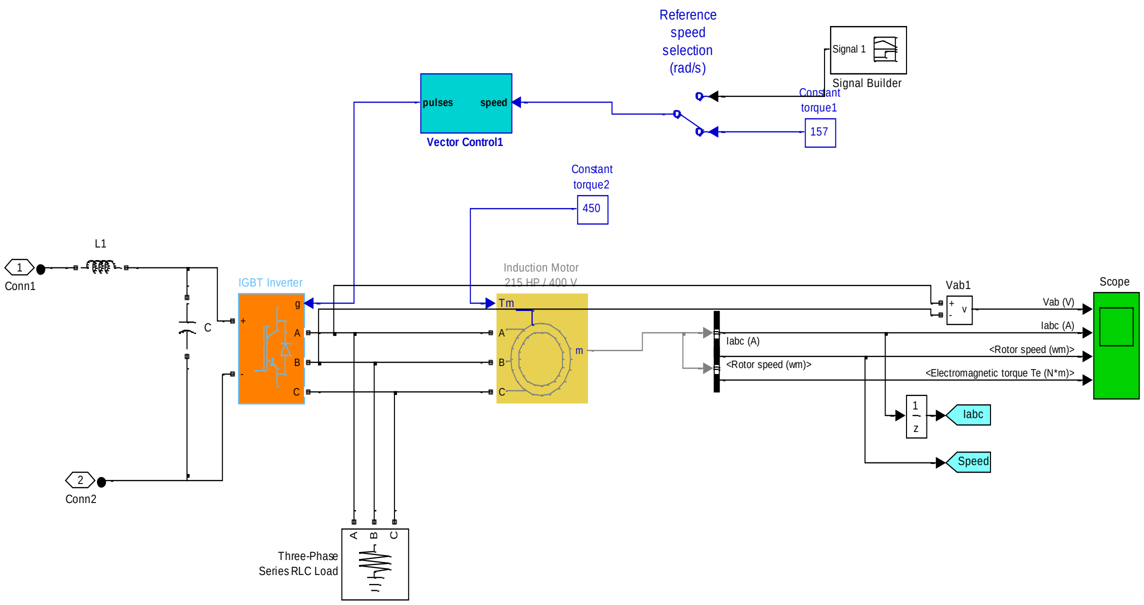

Figure 60 Induction motor model in SIMULINK

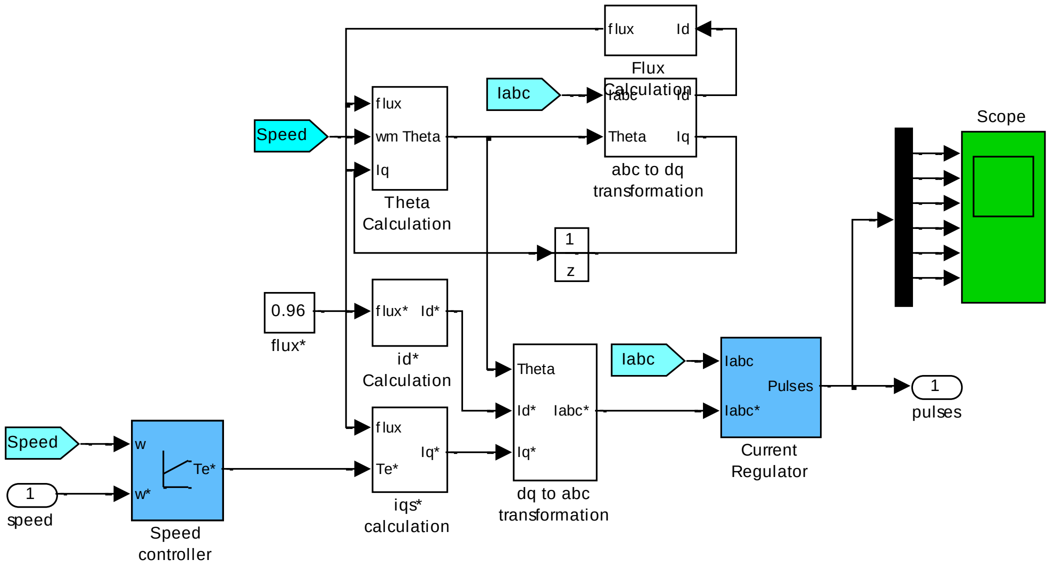

Figure 61 Vector control model

Appendix 5

MATLAB Function for simulation in the figure 41

Block 1

```
function V = fcn(x,v)
   if (x>5000 && x<5015)
Vo=v;
a=-0.7;
xo=5000;
V=sqrt((Vo^2)+2*a*(x-xo));
else
 V=v;
   end
end
```

Block 2

```
function G1 = fcn(x)
G1=1;
   if (x>5000)
G1=0;
   else
G1=1;
   end
end
```

Block 3

```
function G2 = fcn(x)
G2=0;
   if (x>5015)
G2=1;
   else
G2=0;
   end
end
```