ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

AFRICAN RAILWAY CENTER OF EXCELLENCE

APPLICATION OF ENERGY STORAGE SYSTEMS FOR ELECTRIC RAILWAYS CASE STUDY OF ADDIS ABABA LIGHT RAIL TRANSIT

A Thesis in Railway Engineering (Traction and Train control)

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UNDERTAKING

I certify that research work titled "**Application of Energy Storage System for Electric Railway Case-study of Addis Ababa Light Rail Transit**" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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ABSTRACT

Today's innovative technologies for Railway Electrification and Rolling Stock enable an energy-efficient operation of railway vehicles supplied by the overhead contact line. In case there is no possibility to recover the braking energy, an onboard energy storage unit allows absorption of this energy for later use. Therefore the energy consumption and the Greenhouse gases (CO_2) emission can be reduced significantly and the operation of such rail vehicles equipped with onboard EES on tracks without overhead contact lines is possible. However, the energy storage system's capability of powering the train during normal power supply system failure has been evaluated. East-West line of Addis Ababa Light Rail has been considered in modelling and simulation. The energy consumption has been calculated for the whole line for proper sizing of the onboard energy storage.

The analysis of different storage technologies considering their storage capacities charge and discharge capability has been reviewed and Lithium-ion battery has been modeled with a capacity of 76.5kWh. For the supercapacitor, it is difficult to be used alone due to a higher weight to be added on the train since onboard energy storage is preferred in the design. Thus, the combination of batteries and Supercapacitor modules has been modelled. The supercapacitor is used for quick exchange of power between the supply and the train (power efficiency) while Lithium-ion battery is used for energy efficiency. A power conversion system using bidirectional DC-DC converter for the charge and discharge and energy management system is used for the realisation of catenary free system.

The simulation results from Matlab Simulink show that to supply the train with the traction energy of 10.325kWh, the battery state of charge fall down to 99.9% from fully charged capacity. On the other hand the state of charge of the supercapacitor technology is 92% and recharged to 99%. The ESS supplies 640kW of power for acceleration time in the simulation. Energy storage technologies are effective solution to recover the regenerated energy and power the train during an emergency. The energy storage system is recharged during stops at stations and by the use of available braking energy.

Key words: Energy Storage System, Rail Power Supply System, Light Rail Trains.

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TABLE OF CONTENTS

UNDERTAKING III
ABSTRACT IV
ACKNOWLEDGMENTS V
TABLE OF CONTENTS VI
LIST OF TABLES IX
LIST OF FIGURES X
ABBREVIATIONS AND ACRONYMS XI
1. INTRODUCTION 1
  1.1 Background 1
  1.2 Problem Statement 2
  1.3 Objectives 3
    1.3.1 General Objectives 3
    1.3.2 Specific Objectives 3
  1.4 Methodology 3
  1.5 Scope 3
  1.6 Overview of Addis Ababa Light Rail Transit 4
    1.6.1 Traction Power Supply System Overview 4
    1.6.2 Main Power Supply for Addis Ababa Light Rail Transit 5
    1.6.3 Auxiliary power supply system 6
    1.6.4 Electric Traction System for AA-LRT 6
  1.7 Thesis Layout 7
2. LITERATURE REVIEW 8
  2.1 Background 8
  2.2 Literature Review 8
  2.3. Current Transportation Systems Powered by Energy Storage Technologies 10
  2.4 Review of Energy Storage System 11
    2.4.1 Energy storage selection criteria for railway application 12
    2.4.2 Different Types of Energy Storage 13
    2.4.3 Battery Based Energy Storage Systems 14
    2.4.4 Supercapacitor ESS 16

2.4.5 Flywheels Energy Storage System 16
2.4.6 Superconducting Magnetic Energy Storage System (SMESS) 17
2.4.7 Combination of Supercapacitors and Batteries ESS 18
2.4.8 Trackside or Stationary Energy Storage Applications 19
2.4.9 Onboard or Mobile Energy Storage Application 20
2.4.10 Power Converters in Railway Application 21
3. MATHEMATICAL MODELLING AND SIMULATION 23
3.1. Train Motion and Energy Consumption Modelling 23
3.1.1. Force required to overcome resistance due to acceleration (Fa) 23
3.1.2. Force required to overcome the train resistance (Fr) 24
3.1.3. The force required to overcome the gradient resistance (Fg) 25
3.1.4. The Power Output from the driving axles 26
3.1.5. The Energy Output from the driving axles 26
3.1.6. Determination of Energy Output from simplified Speed-Time Curve 26
3.1.7. The Energy required for accelerating the train (Ea) 28
3.1.8. The Energy required for overcoming gradient (E_g) 28
3.1.9. The Energy required to overcome resistance (E_r) 28
3.1.10. Train Energy Consumption 29
3.1.11. Regenerative Braking Energy Modeling 30
3.2. Energy Storage Modelling and Sizing 32
3.2.1. Modelling Overview 32
3.2.2. Design of Energy Storage Systems 33
3.2.3. Battery design for East-West line of AA-LRT 33
3.4.4. Supercapacitors design for Addis Ababa Light Rail Transit 35
3.2.5. Combination of Battery and Supercapacitor (Hybrid ESS) 39
4. SIMULATION RESULTS AND DISCUSSION 43
4.1. Traction Power and Energy Consumption simulation results 43
4.2. Hybrid EES charging and discharging operation 46
4.3. Energy consumption calculation results on East-West line of AA-LRT 47

4.4. Regenerative Braking Energy calculation results 50
4.5. Battery charging and discharging control simulation 51
4.6. Cost Benefit Analysis 52
5. CONCLUSIONS AND RECCOMENDATIONS 54
5.1. Conclusion 54
5.2. Recommendations 55
REFERENCEES 56
APPENDIX A: TRAIN DATA CHARACTERISTICS FOR AALRT 60
APPENDIX B: BATTERY RATINGS AND CHARACTERISTICS 64
APPENDIX C: MATLAB FUNCTION FOR SPEED PROFILE GENERATION . 67

LIST OF TABLES

Table 2-1 Energy storage comparison in terms of energy density 13

Table 2-2 Summary of Energy Storage Technologies [32] 17

Table 3-1 Main characteristics of Li-ion Battery model 9535 and 9522 35

Table 3-2 Characteristics of BMOD0063P125 B04/B08 SC Module [50] 37

Table 3-3 Bidirectional dc-dc converter specification... 41

Table 4-1 Energy consumption calculation results on East-West Line 48

Table 4-2 Regenerated Energy for both direction of East-West line................................ 50

LIST OF FIGURES

Figure 1-1 Schematic diagram DC power supply network for urban rail systems [5]. 5
Figure 1-2 Traction power supply arrangement [7]. 6
Figure 1-3 Illustration of main circuit of traction system of AA-LRT [4]. 7
Figure 2-1 Ragone plot of energy storage devices [20]. 13
Figure 2-2 Charge and Discharge comparison of Batteries and Supercapacitors [27]. 18
Figure 2-3 Parallel connection of Battery and Supercapacitor ESS 18
Figure 2-4 Schematic of Wayside ESSs operation in urban rail [34]. 19
Figure 2-5 Schematic of Onboard ESSs operation in urban rail [34]. 20
Figure 2-6 Bidirectional DC-DC converter interfaced with Supercapacitor [42]. 22
Figure 3-1 Resistance due to gradient 25
Figure 3-2 Trapezoidal speed–time curve 27
Figure 3-3 Onboard Energy Storage for Electric Rail Vehicle Power flow 32
Figure 3-4 Supercapacitor Model for Electric Rail System application 36
Figure 3-5 Example of a MAXWELL 63 F SC module [47] 38
Figure 3-6 Parallel connection of Battery and Supercapacitor Model design 40
Figure 3-7 Bidirectional dc-dc converter modelling 41
Figure 3-8 Normal Traction power supply model interfaced with ESS 42
Figure 4-1 Tractive Force, Power and Traction Energy simulation model 43
Figure 4-2 Train Speed Profile simulation graph for Lideta-Cola-cola 44
Figure 4-3 Traction force simulation graph for Lideta-Coca-Cola 44
Figure 4-4 Traction Power simulation graph for Lideta-Coca-Cola 45
Figure 4-5 Traction Energy and traction power simulation graph 45
Figure 4-6 Supercapacitor charging and discharging operation 46
Figure 4-7 Energy consumption of East-West forward direction of AA-LRT.................49
Figure 4-8 Energy consumption of West-East line Return direction [AA-LRT] 49
Figure 4-9 Battery Charging and Discharging simulation graphs 51

ABBREVIATIONS AND ACRONYMS

Term	Explanation / Meaning
AA-LRT	Addis Ababa Light Rail Transit
AC	Alternating Current
AIS	Air Insulated Substation
APM	Automated People Mover
APS	Alimentation Par le Sol (in French)
DC	Direct Current
DMU	Diesel Multiple Unit
DOD	Depth Of Discharge
EAPS	Electric Auxiliary Power supply
ERC	Ethiopian Railway Corporation
ESS	Energy Storage System
FBES	Flow Battery Energy storage
FES	Flywheel Energy storage
GIS	Gas Insulated Substation
HEVs	Hybrid Electric Vehicles
HVAC	Heating Ventilation and Air Conditioning
HVCB	High Voltage Circuit Breaker
IGBT	Insulated Gate Bipolar Transistor
JNR	Japan Network Rail
KWh	Kilowatt hour
LRT	Light Rail Transit
LRV	Light Rail Vehicle
MHI	Mitsubishi Heavy Industries
Ni-Cd	Nickel Cadmium
Ni-MH	Nickel Metal Hydride
OCL	Overhead Contact Line
OESS	Onboard Energy Storage System
OHL	Over Head Line
SMES	Superconducting Magnet Energy Storage
SOC	State Of Charge
TCU	Traction Controller Unit

Term	**Explanation / Meaning**
TMS	Train Monitoring System
TPS	Traction Power Substation
TPS	Train Performance Simulator
UPS	Uninterruptable Power Supply
VVVF	Variable Voltage Variable Frequency
WESS	Wayside Energy Storage System

1. INTRODUCTION

1.1 Background

Rail transport is a means of transporting passengers and goods by using vehicles running on rails, also known as tracks. It is commonly referred to as train transport.
Urban rail transport is among the rail transport type that plays an important role in the sustainable development of metropolitan areas due to its high transport capacity, frequency of service, energy efficiency and environmentally friendly. It comprises four basic modes such as tramway, light rail transit, rapid rail transport (more commonly known as metro) and regional or commuter rail transport [1]. These categories offer different levels of service and they are electrically powered and commonly characterised by the shorter distance between stations.

The technology of the railway system is advancing and the improvements concerning energy saving with an adequate power supply are also improving. The use of energy storage systems (ESS) has been considered as the main tool to improve energy efficiency in urban rail transport. The installation of energy storage devices either onboard or at the traction substation or along the track improves the performance of the power supply network system in terms of energy-saving and comfort. Storage technologies and their control strategies are constantly being developed under the influence of hybrid and pure electric vehicles. This leads to the new possibilities in the railway sector [2].

Moreover, the fast and outstanding development of power electronic converters has enabled ESS to become an optimal alternative for the re-use of the regenerated braking energy in urban rail systems. With the development of modern technologies in industry and transport, many mobile devices appear, that is the reason why the problem of energy storage becomes crucial [3].

Nowadays, Storages systems can guarantee higher values of specific energy, specific power, longer life cycles, reduced environmental impact, costs, and better dynamic performances. The energy storage system advantages are not only in energy consumption reduction and power peak demand, but also in voltage regulation, energy and power compensation, and the possibility for light rail vehicles to be independent of an external power supply which is the aim of this research. Some locations on the rail track cannot be electrified for aesthetic reasons, such as city centers, square, or tracks passing in historical areas, or where it is difficult to install overhead lines, such as on bridges, underground sections, and in tunnels, or in places where the safety of other infrastructures and passengers is at risks [2].

1.2 Problem Statement

The advancement of technology changes the lives of people and is trying to fulfill the unlimited interest of human being. Public transport is a major characteristic which shows the development of the metropolitan area by contributing to the improvement of living conditions. However, the rapid growth of population and industrialization is associated with energy availability. Rising demand is forecast in developing countries due to industrialization which highly requires access to electricity supplies. When the demand is greater than the supply, energy shortage occurs and causes different problems threatening the supply in many countries including Ethiopia and due to energy shortage, power blackouts are frequent.

Electric rail transportation (Addis Ababa Light Rail Trains) is among the big energy consumers. This does not only imply the cost but also the power instability to other customers. Naturally, the urban rail braking period is accompanied by the production of energy from the regenerative braking process when acts as service brake. For AA-LRT trains, regenerative braking energy is supplied back to the overhead catenary and to protect the system in overvoltage, the overhead contact system is closely monitored to keep its voltage under 1000V.

As mentioned above increased demand for electricity causes blackout most of the time. Therefore alternative power source to the train is required. This is the reason why this thesis has been carried out by suggesting energy storage systems to supply the train during this period of blackout using the regenerated energy together with the energy from the grid network charged during stops at station. The great consideration has been given to the energy storages that presents a good command in supplying the rail vehicle to equality of normal traction substation composed of rectifiers and silicon transformers after compiling data related to different types of storage available on the market. When the designed system output is implemented, electricity bill together with customer satisfaction for AA-LRT and system stability will be improved.

1.3 Objectives

1.3.1 General Objectives

The main objective of this project is to study the energy storage system capacity and reliability to supply the rail transit system during emergency and peak power demand conditions in the existing rail power supply infrastructure.

1.3.2 Specific Objectives

- Explore the power supply network of AA-LRT
- Evaluate performance of Energy Storage System on the trains during emergency
- Design and analyze energy storage system which are capable to drive the traction system during emergency and during power peak demand condition
- Simulate the system using MATLAB/SIMULINK software.

1.4 Methodology

To achieve the highlighted objectives, the following methods have been used:

- Data collection from AA-LRT power supply system department on existing power supply system, train specifications and other related parameter
- Literature review on energy storage system, and selection of the appropriate type of energy storage system according to the objective of the project
- Model the Energy Storage System for traction power supply
- Simulate the system using MATLAB/SIMULINK software
- Draw conclusion and recommendation from the results obtained

1.5 Scope

This research is limited to the examination of the current power supply network of Addis Ababa Light Rail Transit and evaluation of the use of energy storage system to boost its power supply system during power peak demand in the network, and also their application as main power supply source for emergency case.

1.6 Overview of Addis Ababa Light Rail Transit

AA-LRT is an urban rail transportation system operating on two lines (East-West and North-South) in Addis Ababa City with a total number of 39 passenger stations. The East-West line is 17.4km long stretching from Ayat to Torhailoch, while the North-South line is about 16.9km long from the terminal station Menelik II Square to Kality Depot. Both lines have a common track section of 2.7km from Stadium to St. Lideta [4]. The minimum distance between stations is 435m while the longest is 2362m which results in an average distance of 1398.5m between passenger stations. The network has an underground section of 0.655km. It is a standard gauge rail (1.435mm) running trains at a maximum operational speed of 70km/h. The AA-LRT starts its operations with 41 trains on its two lines and each train is designed to have a capacity of 254 passengers [4].

1.6.1 Traction Power Supply System Overview

Unlike diesel traction, where the energy required for train operation is generated within the vehicle itself, electric traction requires an external power supply system. In general, these kinds of electric systems can either work with direct current (DC) or alternating current (AC). But most urban rail systems worldwide are DC-powered either at 600V, 750V, 1500V or 3000V [5]. Regardless of the type of electrification, railway power supply networks essentially consist of the following subsystems:

i. **Traction Power Substations** are usually located at predetermined places along the track. They include step-down transformers to condition the power from the distribution network, which can be the public grid or a distribution network within the system itself. In the case of DC electrification, substations are additionally equipped with a rectifier assembly to convert AC into DC.
ii. **Traction power distribution system**: it conveys the electric power from the substations to the rail vehicles. It typically consists of an overhead line (catenary), though a conductor rail (third rail) can be also found in some metro systems with heavy traffic loads and/or reduced space inside tunnels.
iii. **Traction power return system:** it returns the electric power to the substations, typically through the running rails or an extra conductor rail (fourth rail).

Rail vehicles traction motors are directly fed from the power distribution system (catenary) using pantographs. For the rolling stock itself, electricity is used to drive both the traction equipment and the auxiliary systems. The auxiliaries consist of all the equipment assuring the operation of the vehicle such as traction cooling systems, compressors, air conditioning (HVAC), lighting and passenger information systems. In turn, the propulsion system comprises the electric traction drive, including its associated equipment (converter and control system) and the torque transmission system [5].

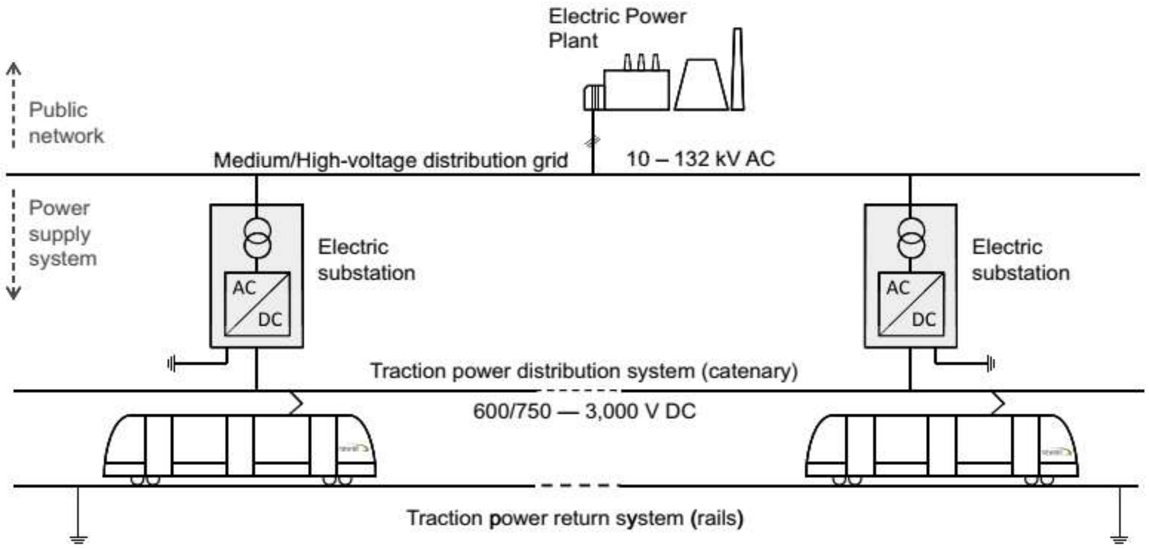

Figure 1-1 Schematic diagram DC power supply network for urban rail systems [5].

As for the type of traction motors, DC machines have traditionally been the most widely used in urban rail. However, as a result of the outstanding advances experienced by power electronics in the last decades, AC (usually asynchronous induction) motors have been widely introduced, as they typically require less maintenance work, offer lighter weight per output torque and present higher efficiency [6].

1.6.2 Main Power Supply for Addis Ababa Light Rail Transit

The main power supply network of AA-LRT starts from the Gas Insulated Substation (GIS) where the national grid power of 132kV high voltage is stepped-down to 15kV of distributed power. The 15kV is feed to Air Insulated Substation (AIS) for metering and protection purpose before being directed to the power transformer which steps down the 15kV to 590V. The 12-pulse full-wave rectifier is connected at the secondary of the transformer. The rectifier outputs DC750V which is used to feed the traction catenary. The traction feeding mode is DC750V overhead contact system and line feed track return current mode. The train roof houses a traction control unit (TCU) that is used to condition the power for traction motor requirements [7].

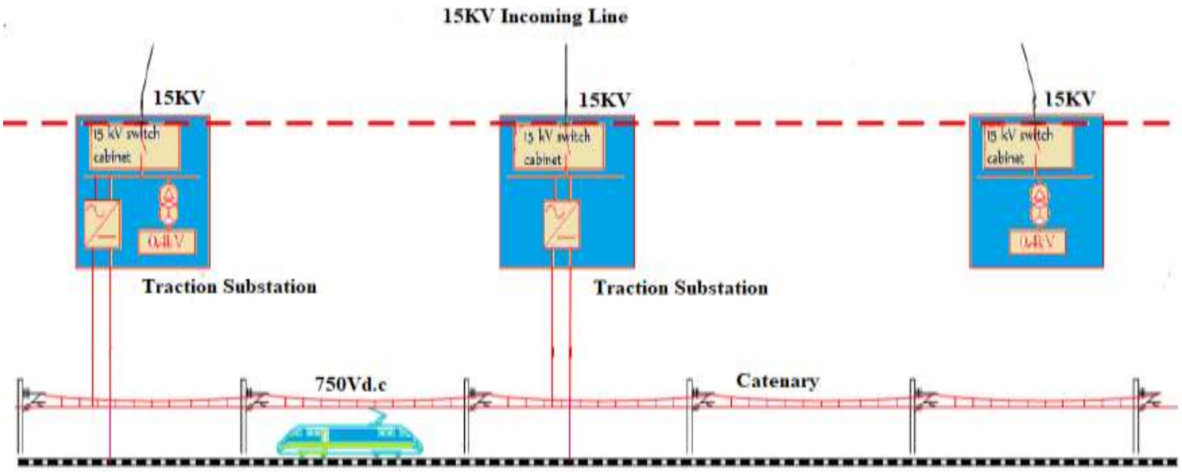

Figure 1-2 Traction power supply arrangement [7].

1.6.3 Auxiliary power supply system

Electrical Auxiliary Power Supply (EAPS) system equipment converts the train's main power supply input voltage to voltages required for the train's auxiliary systems, such as climate control system, train control and lighting circuits, door opening etc. The battery system covers the equipment that stores and provides emergency power to maintain power to essential auxiliary systems when the main power supply is not available. Auxiliary power supply system supplies AC 380V and DC 24V to the train and charges the batteries.

1.6.4 Electric Traction System for AA-LRT

The traction system of AA-LRT is mainly composed of pantograph, main circuit breaker (HSCB), surge arrestor, traction inverter, brake resistor and traction motors. The train uses the sliding Z-shaped pantograph to continuously collect power from the catenary of DC 750V which is connected to the traction inverter via high speed circuit breaker (HSCB) [4]. Each car is equipped with a traction inverter for supplying power to the two traction motors on local bogie. The control of Electric traction system is variable voltage variable frequency (VVVF) controlled AC transmission system. Vector control is used for the torque control of traction motor. The power element of VVVF inverter is IGBT, a heavy-duty power electronic element. Traction motor is subject to axle control [4].

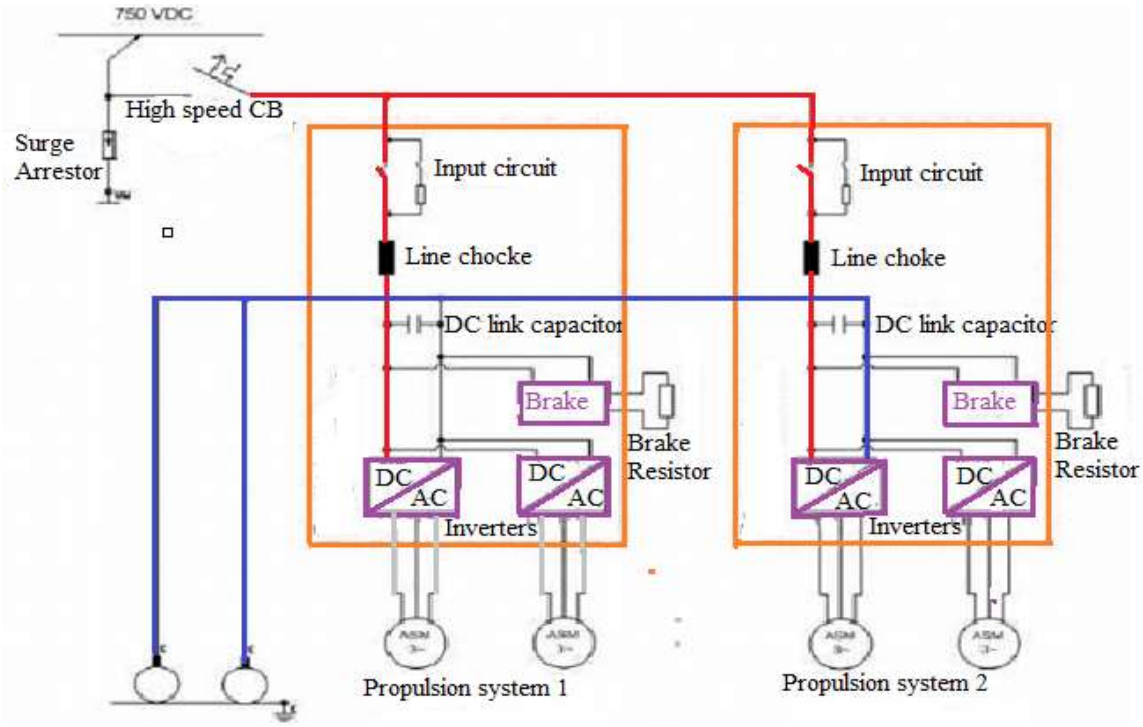

Figure 1-3 Illustration of main circuit of traction system of AA-LRT [4].

1.7 Thesis Layout

This thesis work is organized as follows:

Chapter one consists of introduction, motivation of the research project, problem explanation, methodology used; the objectives and scope of the thesis work. Theoretical fundamentals of rail power supply system and brief overview of AA-LRT.

Chapter two is about literature review and background on energy storage systems, their capacity and capability to serve as traction system, their comparison for selecting the best energy storage technologies for railway application, regenerative braking system for urban rail vehicles and related literature.

Chapter three consists of methodology and approaches in more detail starting from train energy consumption and regenerative braking energy modelling followed by energy storage system design and selection of the suitable one for recapturing the regenerated energy and provide enough power to rail vehicles during emergency condition at least to run the train to next station.

Chapter four presents the Simulation results and analysis of different mitigation alternatives, cost and worth of reliability of the chosen storage.

Chapter five: Conclusion and recommendation for further research in this field.

2. LITERATURE REVIEW

2.1 Background

The energy storage system was first introduced as a wayside installation, and the expectation was to reduce line voltage fluctuations and other losses. But regular maintenance was required for the flywheel ESS, very short battery life also was observed for the lead-acid battery system due to frequent charge-discharge cycles [8].

But with improved development in batteries and capacitor technologies, it has been shown that the problems observed will not be an issue anymore. Higher charge and discharge efficiency and longer life cycle show that these systems will save energy as expected and made the system effective and reliable transport system, and will require only limited maintenance for years just like the existing power feeding substations which use silicon rectifiers [8].

The introduction of the Energy Storage System based on a new electrical connection to the common power supply voltage offers extended possibilities of the operation mode of driving train without overhead contact line. Consequently, increasingly arising requirement of customers due to aesthetical, environmental or operational reasons can be satisfied by the technology of onboard energy storage units [9].

The different types of railway operation, calls for different methods of power supply also with energy optimization. While the improvement of vehicle technology has high cost and takes time in general, the greatest effects will arise from a systematic and operational approach of the railway system based on sophisticated train control and management systems. In particular, intelligent control and management of auxiliary component can result in a drastic reduction of energy consumption during catenary-free operation of the LRV [6].

Although the state of the project is limited to the evaluation of energy storage system for emergency power supply, application of energy storage system to dc railway has a great potential interest in storing the braking regenerated energy.

2.2 Literature Review

Currently, several studies related to ESSs application have been carried out [10], especially in storing the regenerative braking energy of railway vehicle [11]. In the aspect of energy loss, researches show that the onboard storage system has a better performance. They can eliminate the thermal loss generated when the regenerative current is transmitted between vehicle and substation [12]. However, considering the investment cost together with the energy conversion system and maintenance cost, substation-installed energy storage system is more economic [13].

The author in [2] verified that Li-ion Supercapacitor is able to reach overall energy saving up to 16.5% of the regenerated energy. But the storages get charged also when the train is stopping at stations. The stored energy is used by the train for acceleration and overcoming gradient. The author stated that the energy to be discharged may vary according to the control mechanism of the energy management system.

For London underground line [14], to keep the train performance remain the same when trains are passing over the gaps, a different type of energy storage such as batteries and supercapacitor has been tested for powering up the train over the gaps. Because of the high current needed to be discharged in a short time, supercapacitors have been compared with batteries for this reason. The life cycle of supercapacitors has been evaluated and found to be 10 times that of batteries. But the charging is from the grid network during stopping at stations. In the recommendation, the author stated that the use of hybrid ESS is more efficient than a single storage unit. In practical experiments to absorb the regenerated energy with Li-ion battery and supercapacitor ESS [9], the author concludes that the supercapacitor efficiently absorbs 97% of the regenerated energy, whereas only 57% were observed for the battery.

The concept of combining the supercapacitor and battery EES shows a great advantage of providing high power to the train to cover a long distance during operation without external power supply than running only under supercapacitor storage. The charging of both storage units is done during braking and if necessary by the stationary charging units along the track or at the train passenger stations. These charging stations are ideally fitted with stationary energy storage systems to realize quick exchanges of energy on the vehicle without peak loads within the feeding power supply.

A further advantage of the hybrid concept is the intrinsic possibility to be able to move the vehicle because of the energy content of the traction battery even in case of a blackout of mobile (e.g. Pantograph) or stationary components of power supply (e.g. OCL, charging unit or substation) or at maintenance works at the traction power supply on the track [9].

Thus for this thesis the energy storage system is suggested to be used to cover the power supply interruption problems which occur in the transmission line most of the time, to maximize the passenger wishes of reaching to their destination accordingly.

2.3. Current Transportation Systems Powered by Energy Storage Technologies

Many research organizations and vehicle manufacturers have been studying battery-powered transportation systems. The first example is Mitsubishi Heavy Industries**.** Their work focused on developing rail vehicle powered by lithium-ion batteries as the main power source. The example of these rail vehicle produced by MHI includes light rail transit (LRT) systems and automated people mover (APM). They are developed to solve traffic problems like congestion, noise, and various other environmental issues. The MHI work made the world major cities to welcome these APMs and LRT as a means of people-friendly transportation that are also environmentally-friendly [15].

APMs are used between terminals in an airport or within a metropolitan area and are equipped with rubber tires for noise and vibration reduction [15]. LRT vehicles, on the other hand, are a new generation of the street-car with high performance and stylish appearance. Their barrier-free design with extremely low floor levels makes them easily accessible to all. These features contribute to LRT’s favourable acceptance as an effective means of public transit. MHI put on the market these two types of vehicle equipped with energy storage systems as their traction power supply after testing them on the rail track having charging stations at every 6km on the line in Japan [15].

Bombardier has also developed the Primemove system that enables it's flexity tram to operate catenary-free over varying distances including on contactless power transfer buried in the ground. Its electric supply components are invisible, hidden under the vehicle and beneath the track. The Primemove system uses the MITRAC energy saver that stores the energy released each time a vehicle brakes and improves the efficiency of operational energy consumption with the ultra-capacitor-based storage unit. The Primemove system also provides energy management control system that integrates energy awareness, efficiency and carbon control into an operator’s business [16]**.**

Bombardier’s MITRAC Pulse traction batteries are an innovative solution for environmentally-friendly mobility and can be applied to various trains, from APMs to commuter and regional to high speed. With battery technology, trains can operate catenary free for distances up to 100 kilometres. One of their earliest battery projects was for the Chinese city of Nanjing in 2013. In partnership with Chinese joint ventures, they delivered 15 catenary free low floor trams and by now Nanjing trams equipped with MITRAC traction batteries can operate without OCL on 90 per cent of its lines. Note that recharging occurs seamlessly during regular passenger station [16].

Alstom has applied a ground-level power-supply system (APS), a third rail embedded among the tracks, for their Citadis trams. The APS allows trams to travel without overhead catenaries, and integrate harmoniously into the urban landscape [17]. In Nice, France, the Alstom Citadis trams utilize battery power alone to cross a distance of 500m across the city’s historical place such as Masséna and Garibaldi squares. The roof-mounted SAFT Ni-MH batteries allow the trams to run for 1km at 30km/h. Ansaldo STS in Italy is currently offering similar ground power supply technology for light rail applications [17].

Therefore, light rail transit systems as tramways, urban and subway metro-systems and trolleybuses are complex electrical systems characterized by continuous load changing. Because of their attractive characteristics in terms of costs, environmental pollution reduction and energy efficiency, they will be exploited more and more in the next future. Their foreseeable expansion and the increasing of both power requested and the vehicle frequency; require exploring the possibility tendered by the new advanced technologies.

Storage technologies devices, which may be onboard or located in both the substations or along the track, are very interesting means for enhancing energy saving, energy efficiency, pantograph voltage stabilization and peak power levelling and the possibility of catenary free sections.

2.4 Review of Energy Storage System

The introduction of the energy storage system has great potential in improving the power system stability, quality of supply, reliability and efficiency. For railway application, they are used to manage the surplus of electricity which would have been wasted and in some emergency power supply. Their benefits cover energy saving as well as improved system performance, together with possible reductions of greenhouse gas emission. With the growing concern about the environmental impact of the energy sector, energy storage technologies, performance and markets are developing quite rapidly. The worldwide storage capacity is about 90GW roughly 2.6% of the total generation capacity which was 3400GW in 2007 [18].

ESS in commercial use today can be broadly categorized as mechanical, electrical, chemical, biological and thermal. In particular electrical energy storage refers to a process of converting electrical energy from a power network into another form that can be stored for converting back to electrical energy when needed [19].

Three major parameters define an electrical ESS:

i. **Energy storage capacity**, which is determined by the size and energy density of the storage technology.
ii. **Power rating**, which is directly related to the maximum current that can be transmitted between the main supply and the storage device.
iii. **Load cycles**, or how many charging and discharging cycles can the storage system handle over its lifetime

The need for electrical ESS can occur in the following cases:

- It is necessary to supply power to electrical loads when the main or primary power source is unavailable due to faults or maintenance work (backup power);
- A requirement of the immediate availability of energy onboard vehicles with electric propulsion, even partial;
- There is a compelling need for early availability of additional power which cannot be supplied by existing infrastructure;
- Energy is available in a useful and advantageous form but cannot be used instantly as there is no demand.

The choice of the ESS for any application mainly depends on its power, energy ratings, response time, lifecycle, weight, volume and operating temperature [19].

2.4.1 Energy storage selection criteria for railway application

The main parameters to consider while selecting the EES application for railway transportation are power density, energy density and rate of charge/discharge. Then, other parameter can be checked such as; environmental impact, cost, technology maturity and fitness with existing infrastructures. The investment cost is high but it can be regained in average time (5-8years). One measure to characterise a storage system is to determine the energy to weight ratio (Wh/kg) and energy to volume ratio (Wh/L) [3].

Table 2-1 Energy storage comparison in terms of energy density

Type of storage	**Wh/kg**	**Wh/L**
Lead acid battery	30	70
NiMH battery	95	350
Lithium Ion Battery	120	250
Supercapacitor	5	6.5
Conventional Flywheel	3	2

The Ragone diagram can also guide while selecting storage technology by taking into consideration power and energy densities.

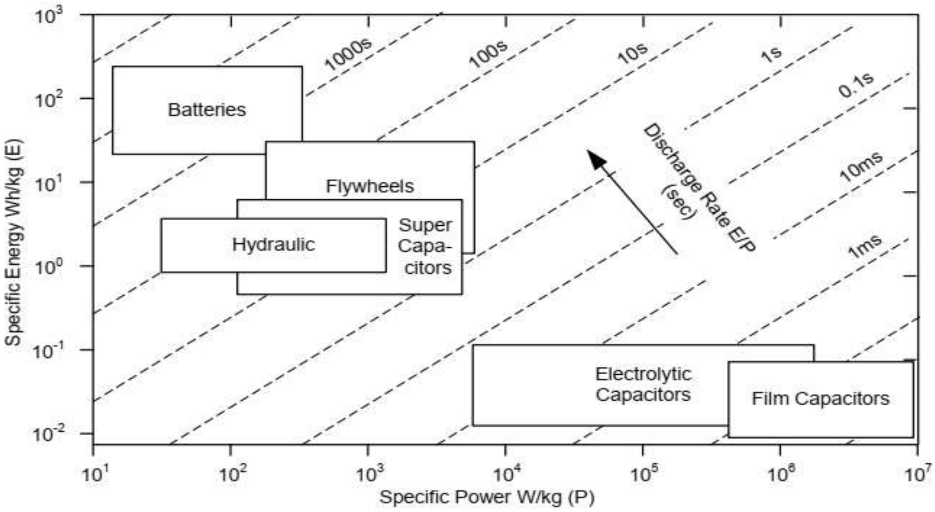

Figure 2-1 Ragone plot of energy storage devices [20].

The ratio of energy density to power density corresponds to the time required to charge or discharge the storage technology. The diagonal lines represent the minimum time in which the energy can be extracted from a fully charged storage device [21].

2.4.2 Different Types of Energy Storage

Many energy storage technologies have been designed according to the type of application. For railway application; batteries, supercapacitors and flywheel are given consideration. Each will be introduced and explained. However Superconducting Magnetic Energy Storage also can be considered for the railway industry, but currently, this type of energy storage has not been used for many railway applications [22].

2.4.3 Battery Based Energy Storage Systems

A battery is a device composed of one or more electrochemical cells, which normally consists of anode, cathode, and electrolyte; all these equipment 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 compile more details information on batteries. In addition, for railway application, it is necessary to know the characteristics of trains, such as input voltage, maximum power, maximum current, and characteristic of the electrification system [23].

Then, the battery pack should be chosen on the basis of voltage and power required by the train. In assessing the suitability of battery systems for traction applications, it is more important to focus on the terminal characteristics rather than the chemical processes involved. In the typical operating conditions of a railway system, the key parameters of a battery that need to be considered are operating temperature, rate of charge and the level of depth of discharge (DOD). There are many types of batteries that are currently being used or being developed for Rail vehicles application. For this thesis paper, those batteries which are suitable for rail application are explained in the next section [5].

2.4.3.1. Nickel Cadmium (Ni-Cd)

A Ni-Cd battery uses nickel hydroxide and metallic cadmium as the two electrodes and an aqueous alkaline solution as the electrolyte. It is characterised by high robust reliabilities and low maintenance requirements. Ni-Cd battery is considered to be very reliable due to its long-life, a low self-discharge and high sturdiness. It can also withstand a high temperature operating condition. This property related to weather condition makes them fit for heavy-duty applications. Drawbacks include memory-effect and the fact that cadmium and nickel are toxic metals, resulting in environmental hazards, meaning that the final disposal of these batteries is a major issue [24].

2.4.3.2. Lead-Acid Batteries

The lead-acid battery is among the oldest rechargeable electrochemical batteries [25]. The cathode is made of PbO_2, the anode is made of Plomb (Pb), and the electrolyte is sulfuric acid. These batteries are used as standard starting-lighting-ignition (SLI) in conventional cars. Their main characteristics include fast response time, low self-discharging rates (<0.3%) per day, relatively high cycle efficiency (63-90%) and a relatively low capital costs (50-600 $/kWh) [25]. Lead-acid batteries area of application includes a back-up power supply for data and telecommunication systems equipment and energy management. They are also used as power sources for hybrid or fully electric vehicles [19].

However, the limitations of Lead-Acid battery are low cycling times (up to 2000), energy density 100 Wh/L and specific energy (35-50Wh/kg) [26]. Lead-acid batteries are typically characterised at a C/20 discharge rate, where C is the capacity of the battery in Ah. In addition, they may perform poorly at low temperatures so a thermal management system is normally required, which increases the cost.

2.4.3.3. Nickel-Metal Hydride (Ni-MH) Batteries

A nickel-metal hydride battery is one of the rechargeable battery types. It uses a chemical composition of either lithium-nickel or titanium-nickel alloy; it also makes use of potassium hydroxide electrolyte to reform the NiMH cell. Nickel metal hydride batteries have a high capacity, but its cell potential is only 1.35V. Nickel-metal have a higher energy density and longer life cycle than lead-acid batteries. The specific energy is approximately 95Wh/kg and the energy density is roughly 350Wh/L [27].

The main limitations for Ni-MH batteries include the overcharging which overheats the battery and can release hydrogen which posing a serious fire hazard, and therefore, it requires the use of complex charging circuitry. Furthermore, when discharged at high-current levels, as it happens with heavy transportation applications, its lifetime is reduced significantly (200-300 cycles) [28].

2.4.3.4. Lithium-Ion (Li-Ion) Battery

Recent researches show that the Lithium-Ion (Li-Ion) battery is suitable for electric rail transportation and is growing in popularity for military and aerospace applications. It has a high cell voltage, high energy density, long shelf and cycle life with no memory effect, and no environmental issues like in Ni-Cd and Ni-MH technologies [28]. Its larger energy density made this battery very appropriate for hybrid vehicle applications.

2.4.3.5. 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). It has a solid electrolyte membrane between the anode and cathode. Positive Sodium ions flow through the circuit of the battery during the discharging process, producing about 2Volts. This process is reversible when current is supplied from an external source. Its main characteristics are high energy density, high efficiency of charge/discharge (89-92%), and a long cycle life resulting in low cost of the battery [25].

2.4.4 Supercapacitor ESS

The energy is stored in the form of static charge on the surfaces between the electrolyte and the two-conductor electrodes. The supercapacitors with high-performance are based on nanomaterial to increase the electrode surface area for enhancing the capacitance. Supercapacitors are used in applications requiring many rapid charges and discharge cycles rather than long term compact energy storage: within cars, buses, trains, cranes and elevators, where they are used for regenerative braking, short term energy storage or burst-mode power delivery [27]. Supercapacitors, in terms of a lifetime (8-10years), depth of discharge, operating temperature range, and power specific ratios are better than batteries. But, they don't have good specific energy compared with batteries [27].

Like all typical capacitors, Supercapacitors are restricted by the level of discharge allowed to maintain life, and they have an internal resistance that can limit their power transfer. A typical capacitor is deemed to have reached the end-of-life if the capacitance drops to 80% of the initial value, or if the internal resistance doubles from the initial value [21].

2.4.5 Flywheels Energy Storage System

Generally, flywheels store rotational kinetic energy in the form of a spinning cylinder or disc, and then use this kinetic energy to regenerate electricity at a later time. The amount of energy stored in a flywheel depends directly on the dimensions of the flywheel and its mass, and on the square of its rotational speed at which it spins. Consequently, its State of Charge can be easily measured as a function of angular speed. Their specific energy is around 130Wh/kg while their specific power is about 500W/kg [29]. Flywheel has typical capacities starting from 1kWh 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 [29].

2.4.6 Superconducting Magnetic Energy Storage System (SMESS)

These devices store energy in the form of a magnetic field. By applying a DC to a coil, a magnetic field is created, storing magnetic energy. When the DC potential is removed, the energy is released. By using low loss superconducting coils, high amounts of energy can be stored in the magnetic field. SMESS are used to improve power quality in distribution networks [30]. The superconducting material of nearly zero resistance is generally made in Niobium Titanium (Nb-Ti) filaments that operate at very low temperature (-270^{0}C). The current increases or decreases during charge and discharge respectively. The merits of SMESS are their high efficiency (95%) and their ability to discharge the totality of the stored energy [19].

The main advantages of SMES systems are their great energy storage efficiency and very fast responses. Additionally, they can be almost completely discharged and present a very high life cycle. Their major drawbacks include their high investment and operational costs mainly due to the cooling system. This technology has installed capacities of up to about 10MW and their most common area of application is power quality improvement [18].

Some specifications of energy storage technologies are summarized in Table 2-2.

Table 2-2 Summary of Energy Storage Technologies [31].

Technology		Typical nominal power	Discharge time	Response time	Efficiency	Lifetime
Battery	Flow battery	25kW-10MW	1-8h	30-100ms	65-85%	2-10 years
	Lithium battery	10kW-10MW	10min-1h		85-90%	
	Lead acid	30kW-30MW	15min-4h		70-80%	
	Sodium sulfur	50kW-30MW	1-8h		75-90%	
Supercapacitors		10kW-1MW	1s-1min	5-10ms	85-95%	40 years
Superconducting magnetic energy storage		1MW-100MW	1s-1min	5-10ms	85-95%	30-40 years
Flywheels		10kW-20MW	1s-1h	5-10ms	85-95%	20 years

2.4.7 Combination of Supercapacitors and Batteries ESS

The combination of Supercapacitors and Batteries is a common architecture in many applications that utilises the energy storage capacity of a battery and provides the ability to deliver peak power during motoring or capture regenerative power during braking when using a supercapacitor. During charging and discharging, the terminal voltage of the two devices is not the same, as is shown in Figure 2-2 [27].

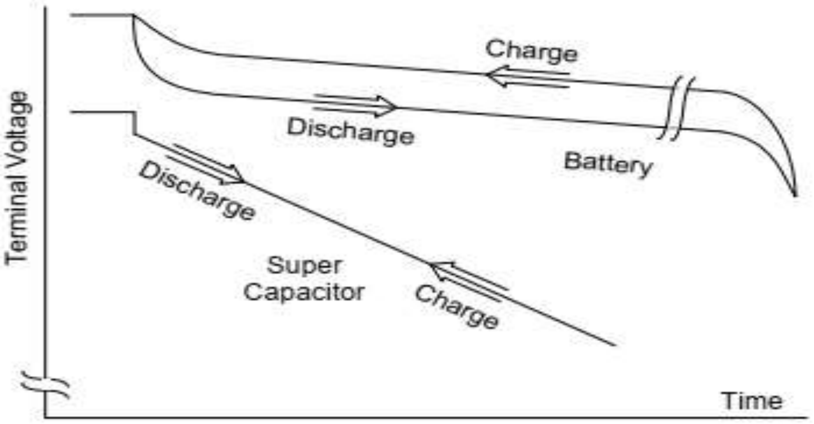

Figure 2-2 Charge and Discharge comparison of Batteries and Supercapacitors [27].

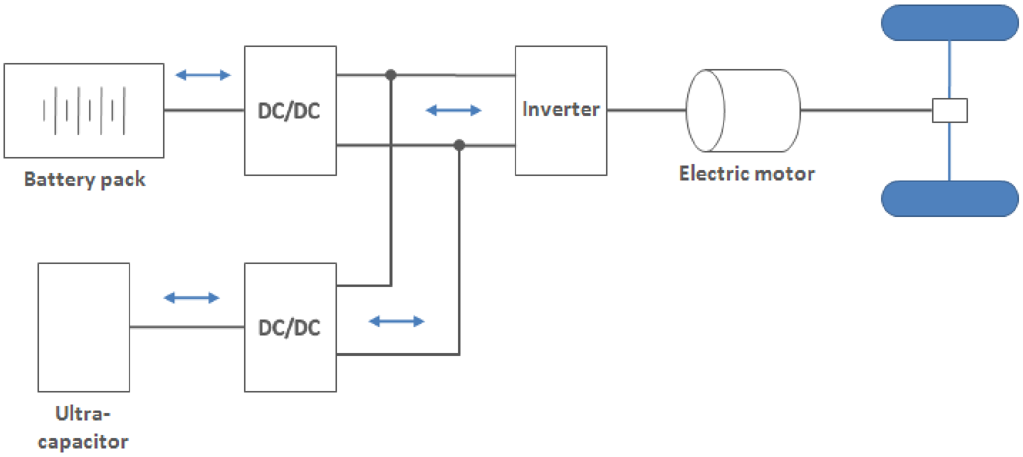

Figure 2-3 Parallel connection of Battery and Supercapacitor ESS

However, the advancement of storage technology for high specific energy and high specific power batteries, such as lithium-ion, would provide the required characteristics for energy and power simultaneously, particularly if the battery is used for emergency application. Just this case we preferred batteries combined with supercapacitor due to the increased weight of supercapacitor when used alone for catenary free operation of the train.

2.4.8 Trackside or Stationary Energy Storage Applications

Trackside or stationary ESSs essential work is to capture the regenerative braking energy that cannot be used simultaneously in the system and release it when required for the acceleration of any vehicle running in the same electric section, Figure 2-4. The charge and discharge processes require an electronic controller that generally operates as a function of the voltage on the line [32]. When an overvoltage takes place as a result of any braking process, ESSs operate in charging mode absorbing the excess of regenerated energy on the line; in turn, when a voltage drop is detected, ESSs deliver the stored energy in order to keep the threshold value on the network.

Wayside ESSs are usually installed in existing substations or in specific places where the contact line voltage variations are more significant, for instance near to stations. Stationary ESSs can be used to reduce the energy demand of the whole system, but also to stabilise the network voltage at weak points of the network, which is a major advantage over reversible substations. Wayside ESSs might eliminate the need for additional feeding substations to compensate the voltage drops typically associated with the end of the line [33].

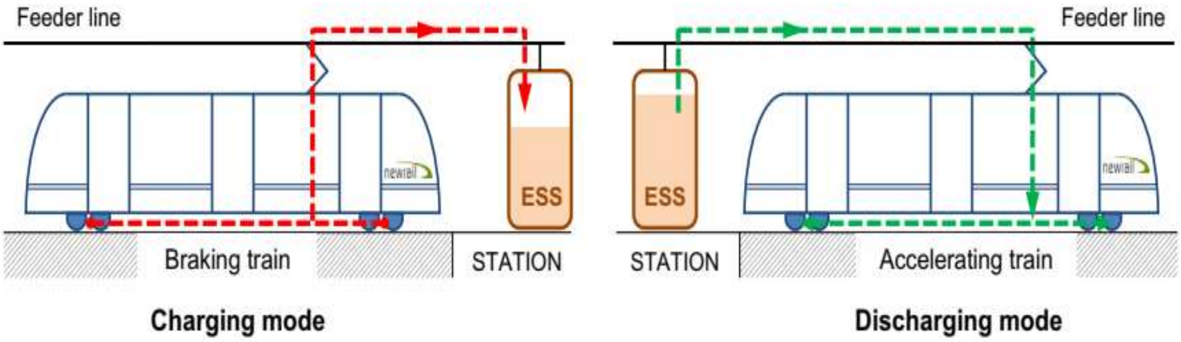

Figure 2-4 Schematic of Wayside ESSs operation in urban rail [34].

Similarly to onboard ESSs, stationary devices can greatly contribute to shaving peaks of energy consumption during acceleration of vehicles, which in many cases imply considerable cost savings for operators. Besides, they might enable trains to reach the nearest station in case of failure of the power supply, increasing the system security. When compared with onboard devices, wayside systems present the advantage of having fewer restrictions in terms of weight and required space.

Moreover, stationary systems can recover energy from several braking vehicles at the same time and their implementation and maintenance do not affect operations. On the contrary, they are generally less efficient due to transmission losses taking place in the network. This fact is directly related to the distance between the braking vehicles and the ESS [35].

2.4.9 Onboard or Mobile Energy Storage Application

Onboard ESSs can considerably contribute to energy savings in urban transit systems since the energy recovered and stored during the braking process can be used to power the vehicle itself during the next acceleration, see Figure 2-5. Moreover, from the installation of onboard ESSs the following advantages can be expected:

- Shaving of power peaks demanded during acceleration of vehicles, which leads to reduced energy cost and minimum resistive losses in the supply line.
- Limitation of voltage drops in the network, which might eventually allow for a higher traffic density without further modification in the existing infrastructure.
- Certain power autonomy, for instance in emergencies, depot operations or in free-catenary applications such as lines going through historical city centres with visual impact restrictions [34].

In comparison with the wayside storage system, onboard ESSs have the advantage of operating with higher efficiency due to the absence of line losses. Besides, the management of the recovered energy is simpler since the control is independent of traffic conditions [36]. In contrast, onboard ESSs typically require large space on the vehicle and introduce a significant increase in weight. Some studies have assessed that the additional mass due to onboard ESSs increases the traction energy consumption by 1-2% [36].

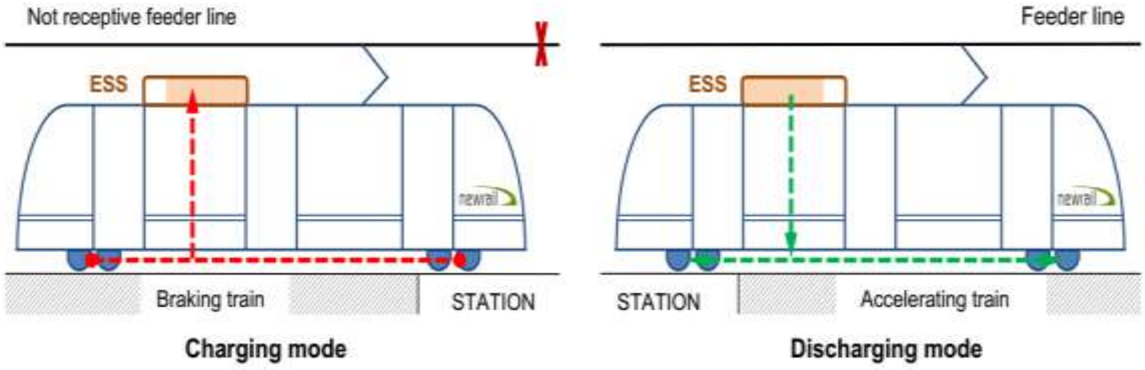

Figure 2-5 Schematic of Onboard ESSs operation in urban rail [34].

A fine-tuned analysis is required to achieve an optimal design of onboard ESSs. Oversizing might unnecessarily increase the mass and volume of the system, whereas under-sizing might lead to considerable energy waste. The sizing method for mobile ESSs depends upon their main function; that is, the design requirements will be different when aiming at maximizing the energy savings, reducing the voltage drops at the line or running the vehicles in free-catenary mode. A general criterion for energy-saving purposes is that the ESS must absorb the maximum amount of braking energy that can be recovered in sudden braking, assuming that no energy can be returned to the network [37].

However, since vehicle speeds and occupancy rates are variable, a careful analysis considering weights and costs must be carried out to determine the optimum capacity [38]. Designing mobile ESSs for voltage stabilisation applications requires the consideration of the operational characteristics of the whole line, for instance, the distance between substations and trains timetables [12].

Lastly, if the main purpose of the ESS is to enable free-catenary operation, the system has to be sized to fully drive both traction and vehicle auxiliary systems in the sections without overhead contact line (OCL). In that case, it is also common practice to optimize the driving style to minimise the size of the mobile ESS [39]. Whichever is the main function of an onboard ESS, they are normally installed together with braking resistors that protect the system when the recovery energy exceeds the storage capacity.

As for the control of onboard ESSs, different parameters such as vehicle speed, State of Charge, requested traction power and network voltage must be considered. Generally speaking, control systems have to ensure that ESSs are charged enough to power the vehicle during accelerations and that they remain completely discharged at high vehicle speeds to accept the highest amount of energy during braking or charging from the network during stopping time at stations.

2.4.10 Power Converters in Railway Application

The main function of power converters is to transform electrical power from one form to another. To use energy storage technologies for railways, power converters are essential. Bidirectional DC/DC or DC/AC converters have both features of step-down and step-up the input voltage [14]. Railway voltage supply demands that a large number of storage cells are connected in series; case of battery. 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. Theoretically, the imbalances of storage cell voltage are typically caused by the differences among cell residual capacities, internal resistances, degradation, and the ambient temperature gradient during charging or discharging [40]. Each cell in a battery has fairly different capacity and maybe at the different State of Charge, therefore causing the entire battery to have an unbalanced voltage [41].

Hence power converters play a vital role in applying the storage system in the railway industry. 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 storages [40].

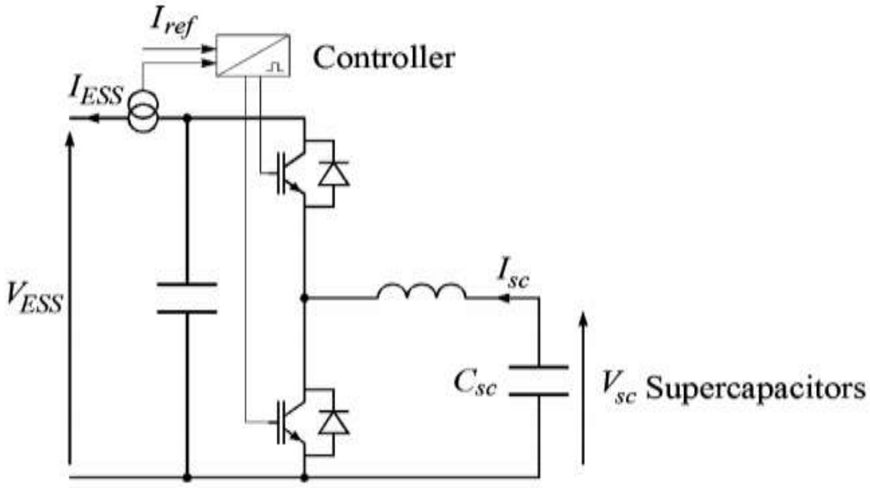

Figure 2-6 Bidirectional DC-DC converter interfaced with Supercapacitor [42].

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 storage, so control of charge and discharge cycles is assured.

3. MATHEMATICAL MODELLING AND SIMULATION

3.1. Train Motion and Energy Consumption Modelling

To determine the power and energy requirements for a train operating on a defined track, the standard equations of motion are applied. To apply these equations, the forces acting against the train movement must be considered. These resistances opposing the train motion includes resistance due to aerodynamic drag, rolling resistance, resistance due to acceleration and resistance due to gradient. For simplicity, in this model, we will consider three opposing forces such as acceleration force, train motion resistance and resistance due to the gradient.

The tactive effort required for train propulsion is:

$$F_t = F_a + F_g + F_r \qquad (3.1)$$

Where

F_a: the force required for giving linear acceleration to the train

F_g: the force required to overcome the gravity

F_r: the force required to overcome train resistance

3.1.1. Force required to overcome resistance due to acceleration (Fa)

According to the Newton second of the motion, the force required to accelerate the train in motion is given by Force = Mass × acceleration,

$$F_a = M\alpha \qquad (3.2)$$

The fact that the train has rotating parts such as motor armature, wheels, axels, and gear system, its mass including the mass rotating parts is known as effective mass or accelerating mass (Me) and is much higher (about 8–15%) than its stationary mass (M) [43]. Hence, these parts need to be given angular acceleration at the same time as the whole train is accelerated in a linear direction. Thus the equation (3-2) becomes

$$F_a = M_e\alpha \text{ [Newton]} \qquad (3.3)$$

When $M_e$is the train effective mass expressed in kg and α acceleration expressed in m/s^2 the above equation becomes

$$F_a = 1000M_e\left(\frac{1000}{3600}\right)\alpha \text{ [kg-m/s}^2\text{]} \qquad (3.4)$$

Therefore, the force required for a linear and angular acceleration is:

$$F_a = 277.8\ M_e \alpha\ [N] \qquad (3.5)$$

Where M_e = 1.1M tones = 1.1 * 59.24 = 65.164 tones
Acceleration = 1 m/s^2 = 3.6 km/hr.

$$F_a = 277.8 \times 65.164 \times 3.6 = 65169.21312\ [N]$$

3.1.2. Force required to overcome the train resistance (Fr)

When the train is running at uniform speed on a level track, it has to overcome the opposing forces due to the surface friction, i.e., the friction at various parts of the rolling stock, the fraction at the track, and also due to the wind resistance. The magnitude of the frictional resistance depends upon the shape, size, and condition of the track and the velocity of the train, etc. considering “r” as specific resistance, the force required to overcome this resistance is:

$$F_r = Mr \qquad (3.6)$$

The total resistance against the train movement is given by Davis equation:

$$R = 1.3W + 29N + b * W * V + c * A * V^2 \qquad (3.7)$$

Where

R: total resistance in lbs; (1lbs $= 4.45N$)
W: train weight in tones
N: number of train axles;
V: train speed in miles/hour
b: experimental friction coefficient (for passenger car $b = 0.03$)
c: drag coefficient (for passenger car $c = 0.00034$)
A: cross section of train frontal area (square feet);

At maximum speed (70km/h equivalent to 112 mph)

$$R = 1.3 * 59.24 + 29 * 6 + 0.03 * 59.24 * 112 + 0.00034 * 107.639 * 112^2 = 909.134\text{lbs}$$
$$R = 4045.648\ \text{N}$$

Therefore at maximum speed, Specific Resistance is $R = \frac{4045.648}{59.24} = 68.29\ \text{N/tonne}$

At average speed (24km/h equivalent to 38.4mph)

$$R = 1.3 * 59.24 + 29 * 6 + 0.03 * 59.24 * 112 + 0.00034 * 107.639 * 38.4^2 = 311\text{lbs}$$
$$R = 1384\ \text{N}$$

So that at average speed, Specific Resistance $R = \frac{1384}{59.24} = 23.36\text{N/tonne}$

Thus, $F_r = 59.24 * 68.29 = 4045.4996$ N at maximum speed and

$F_r = 59.24 * 23.36 = 1383.8464$ N at average speed

3.1.3. The force required to overcome the gradient resistance (Fg)

When the train is moving on up gradient as shown in Figure 3-1, the gravity component of the dead mass opposes the motion of the train in an upward direction. In order to prevent this opposition, the force should be acting in an upward direction.

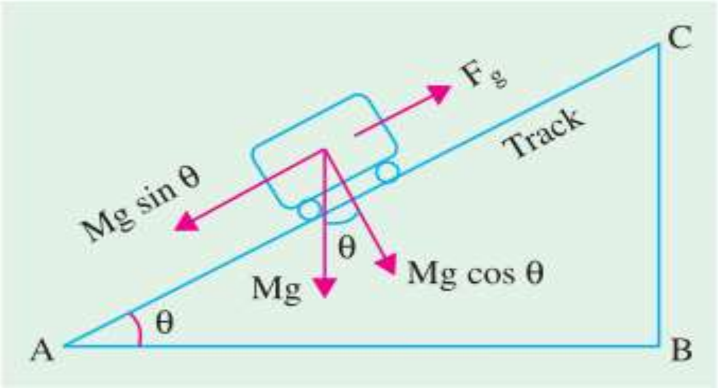

Figure 3-1 Resistance due to gradient

Considering an upward motion of the train, the forces acting on the train are:

- The weight of the train (Mg), which acts downwards (perpendicular to AB)
- Normal pressure $N = MgCos\ \theta$ on the rail track which acts perpendicular to AC
- The resistance which acts parallel to AC, in the opposite direction to motion

The force required to overcome the resistance due to gravity is:

$$F_g = M\, g \sin\theta \tag{3.8}$$

In railway practice, the gradient is expressed as the rise (in meters) a track distance of 100m and is called "percentage gradient".

$$\%G = \frac{BC}{AC/100} = 100 * \frac{BC}{AC} = 100\sin\theta$$

Substituting the value of Sin θ, the equation becomes:

$$F_g = Mg\frac{G}{100} \tag{3.9}$$

When the mass is expressed in kg, the force to overcome gradient becomes:

$$F_g = 9.81 * 10^{-2}(1000MG) = 98.1MG\ [\text{Newton}] \tag{3.10}$$

This force is when the train is moving up on gradient, but while going down the gradient the same force will be added to the total tractive effort.

Taking an example from the interstation percentage gradient in appendix B. Lideta-Coca-Cola for example (3.92), then $\mathrm{F_g} = 9.81 * 59.24 * 3.92 = 22780.861$ N

The total tractive effort required for the propulsion of train becomes $F_t = F_a \pm F_g + F_r$

$$\mathrm{F_t} = 277.8\mathrm{M_e}\alpha + \mathrm{Mr} \pm 98.1\mathrm{MG} \text{ [Newtons]} \tag{3.11}$$

$$\mathrm{F_t} = 65169.21312 + 4045.4996 + 22780.861 = 91995.57372 \text{ N}$$

3.1.4. The Power Output from the driving axles

Knowing that Ft is the tractive effort in Newton and *v* the speed of the train in km/h, then

$$\mathrm{P_{out}} = \mathrm{F_t} \times \mathrm{V} \tag{3.12}$$

When $\mathrm{F_t}$ is expressed in newton and v is in m/s, the equation becomes

$$\mathrm{P_{out}} = \mathrm{F_t} \times \left(\frac{1000}{3600}\right) \mathrm{V} \text{ [watt]} = \frac{\mathrm{F_t V}}{3600} \mathrm{kW} \tag{3.13}$$

If 'η' is the efficiency of the gear transmission, then the power output of motors becomes

$$\mathrm{P_{out}} = \frac{\mathrm{F_t V}}{\eta} \text{ [w]} \tag{3.14}$$

$$\mathrm{P_{out}} = \frac{\mathrm{F_t V}}{3600\eta} \text{ [kW]} \tag{3.15}$$

$$\mathrm{P_{out}} = \frac{91995.57372 * 19.4}{3600 * 0.96} = 516.41\mathrm{kW}$$

3.1.5. The Energy Output from the driving axles

Energy (like work) is given by the product of power and time

$$\mathrm{E} = (\mathrm{F_t} * \mathrm{V}) * \mathrm{t} = \mathrm{F_t} * \mathrm{V} * \mathrm{t} = \mathrm{F_t} * \mathrm{D} \tag{3.16}$$

Where D is the distance travelled in the direction of tractive force

3.1.6. Determination of Energy Output from simplified Speed-Time Curve

Speed time curve shows how station to station speed trajectory and help in determining the time taken for acceleration, constant speed and deceleration Figure 3-2. This is mainly for accelerating the train from the rest to velocity 'Vm', this is the energy required to overcome the gradient and track resistance to motion.

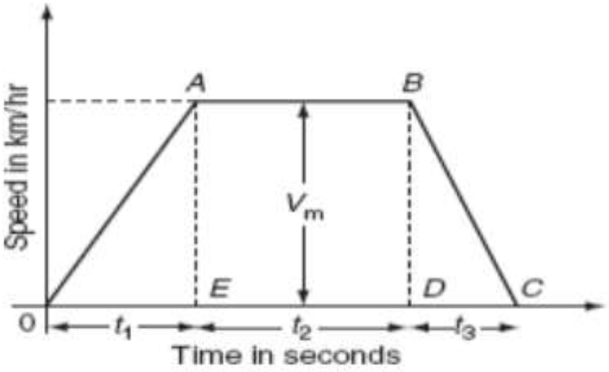

Figure 3-2 Trapezoidal speed–time curve

The total energy output from driving axles for the run is E= Energy during acceleration + Energy during free run. From the above figure,

$$E = F_t * \text{Area OAE} + F_t' * \text{Area ABDE} = F_t \frac{1}{2} V_m t_1 + F_t' V_m t_2 \qquad (3.17)$$

where

F_t is the tractive effort during the acceleration period,

$F_t{}'$ is a tractive force during the free running period.

Note that F_t consists of the three components of the tractive force expression as in equation (3.1) while F'_t consists of gradient and resistance component of tractive force.

The value of t_1, t_2 and t_3 and the corresponding distance covered are calculated as follows:

$$t_1 = V_m/a\,, \quad t_3 = -V_m/\beta\,, \quad D_1 = 0.5\left(\frac{V_m{}^2}{a}\right), \quad D_3 = -0.5\left(\frac{V_m{}^2}{\beta}\right), \qquad (3.18)$$

$$D_2 = D - (D_1 + D_3)\,, \quad t_2 = D_2/V_m\,, \quad t = t_1 + t_2 + t_3\,, \qquad (3.19)$$

where

t_1 is the time for acceleration,

t_3 is the time for deceleration,

$t_2$is time for running at constant speed (free running),

t is the actual running time of the train from starting station to the next station,

D1 is distance travelled during acceleration,

D2 distance travelled during deceleration,

D3 distance travelled during free-running (constant),

D is the total distance between two consecutive stations,

β is the deceleration,

V_m is the maximum /constant running/ speed.

For the chosen interstation (Lideta-Coca-Cola) the distance is 0.7286km.

Therefore, the time the train uses from Lideta to Coca-Cola is 1.1022 minutes or 66.132 seconds.

3.1.7. The Energy required for accelerating the train (Ea)

From Figure 3-2; it can be seen that the energy required to overcome the acceleration is

$$\mathrm{E_a} = \mathrm{F_a} * \mathrm{Area\ OAE} = 277.8 * \alpha * \mathrm{M_e} * \frac{1}{2} * \mathrm{V_m} * \mathrm{t_1}. \tag{3.20}$$

$$\mathrm{E_a} = 277.8\alpha\mathrm{M_e} \times \frac{1}{2}\mathrm{V_m} \times \frac{\mathrm{V_m}}{\alpha}. \tag{3.21}$$

$$\mathrm{E_a} = 277.8\alpha\mathrm{M_e} \times \left(\frac{1}{2}\frac{1000}{3600}\mathrm{V_m} \times \frac{\mathrm{V_m}}{\alpha}\right) [\,\mathrm{Joules}]. \tag{3.22}$$

The same expression in watt-hour (Wh) while the speed is in km/h becomes:

$$\mathrm{E_a} = 277.8\alpha\mathrm{M_e} \times \left(\frac{1}{2}\frac{1000}{3600}\mathrm{V_m} \times \frac{\mathrm{V_m}}{\alpha}\right). \tag{3.23}$$

$$\mathrm{E_a} = 277.8\alpha\mathrm{M_e} \times \left(\frac{1}{2}\frac{\mathrm{V_m}}{3600} \times 1000\frac{\mathrm{V_m}}{\alpha}\right). \tag{3.24}$$

$$\mathrm{E_a} = 0.01072\mathrm{V_m}^2\mathrm{M_e}\,. \tag{3.25}$$

3.1.8. The Energy required for overcoming gradient (E_g)

If we look at Figure 3-2, it can be seen that the force required to overcome gradient resistance force is

$$\mathrm{E_g} = \mathrm{F_g} * \mathrm{D'}. \tag{3.26}$$

Where $\mathrm{D'}$ is the total distance over which power remains ON. Its maximum value equals the distance represented by the area OABD as shown in figure 3-2, the energy required to overcome gradient is given by:

$\mathrm{E_g} = 98.1\mathrm{MG} * (1000\mathrm{D'}) = 98100\mathrm{MGD'}$[Joules] where D' is expressed in km

When Eg is expressed in watt-hour, it becomes

$$\mathrm{E_g} = 98100\mathrm{MGD'}\frac{1}{3600}\mathrm{Wh} = 27.25\mathrm{MGD'}. \tag{3.27}$$

3.1.9. The Energy required to overcome resistance (E_r)

The energy required to overcome train resistance is also calculated by considering the travelled distance when the power is ON; like the energy required to overcome gradient has been calculated.

$$\mathrm{E_r = F_r * D' = MR(1000D')\ [Joules]} \tag{3.28}$$

$$\mathrm{E_r = \frac{1000M_rD'}{3600} = 0.2778M_rD'\ [Wh]} \tag{3.29}$$

The total energy output from driving axles becomes:

$$\mathrm{E_t = E_a + E_g + E_r} \tag{3.30}$$

$$\mathrm{E_t = 0.01072V_m^2M_e + 27.25MGD' + 0.2778MRD'\ [Wh]} \tag{3.31}$$

3.1.10. Train Energy Consumption

The energy input to the traction motors is called energy consumption. This is the energy consumed by various parts of the train for its propulsion. The energy drawn from the distribution system should be equal to the energy consumed by the various parts of the train and the quantity of the energy required for lighting, heating, control, and braking [43].

The train energy consumption calculation requires detailed train running states outputted from train performance simulator (TPS) or speed profile generator, including train speed, running time, corresponding tactive effort and braking force. The model employs a numerical integration method to estimate the overall energy consumption of a single train operation. It can be found by dividing the energy output of the driving axles with the combined efficiency of transmission gear and motor.

$$\left.\begin{matrix}\text{Energy}\\ \text{consumption}\end{matrix}\right\} = \frac{\text{energy output from the driving axles}}{\eta_{\text{motor}}\eta_{\text{gear}}}\,[\text{Wh}]$$

By considering the efficiency of the traction inverter, we have

$$\left.\begin{matrix}\text{Energy}\\ \text{consumption}\end{matrix}\right\} = \frac{\text{energy output from the driving axles}}{\eta_{\text{inv}}\eta_{\text{motor}}\eta_{\text{gear}}}\ [\text{Wh}]$$

$$\text{Energy consumption}\,\} = \frac{\mathrm{0.01072V_m^2M_e + 27.25MGD' + 0.2778MrD'}}{\eta_{\text{inv}}\eta_{\text{motor}}\eta_{\text{gear}}}\ [\text{Wh}] \tag{3.32}$$

Where V_m is expressed in km/h; M and Me in tones and r is expressed in N/tone.

By applying the basic motion equations, outlined above, it is possible to determine the train power, energy, speed, etc. Determining these parameters will enable quantifying the size and type of the energy storage system to fit the purpose required.

3.1.11. Regenerative Braking Energy Modeling

Modern electric trains are usually equipped with regenerative braking. During the braking period, electric power is generated from the kinetic energy of the train. Note that the braking force of the train is composed of friction braking force and motor braking force which is the force the motor used to generate electricity. Thus, the product of the motor braking force, velocity and regenerative efficiency yield the electric power produced by the regenerative braking. It's expression is as follows [44]:

$$\mathrm{P_{reg} = F_b \times V \times \eta_{reg}} \tag{3.33}$$

where

$\mathrm{P_{reg}}$ is the electric power regenerated from braking (kW)

$\mathrm{F_b}$ is the regenerative braking force (kN)

V is the speed of the train (m/s)

η_{reg} is the efficiency of regeneration system

The power consumed during braking and regenerated power can be estimated based on the traction braking force which acts to decelerate and stop the train. Its expression is

$$\mathrm{M_{tot}}\beta = -(\mathrm{F_B + F_g + F_r}) \tag{3.34}$$

$$-\mathrm{F_B} = \mathrm{M_{tot}}\beta + \mathrm{F_g + F_r} \tag{3.35}$$

where $\mathrm{F_B}$: is the braking force in N

β: Deceleration ($\mathrm{m/s^2}$)

3.1.11.1. Power consumed during braking and Power Regenerated

The consumed power to halt the motion is equal to the product of braking force $\mathrm{F_B}$, and the change in velocity gives the power to be provided for braking [45]:

$$\mathrm{P_{cons} = F_B \times \Delta V} \tag{3.36}$$

Where Pcons is the power consumed during braking and ΔV is the change of speed during braking to stop. It is possible to calculate the regenerated power for a break at stations [45]:

$$\mathrm{P_{reg} = P_{cons} \times \eta_{reg}} \tag{3.37}$$

$$\eta_{\mathrm{reg}} = 1/\left(e^{\frac{\alpha}{|a|}}\right) \tag{3.38}$$

where

$\boldsymbol{\alpha}$ is the Optimum model parameter (commonly used 0.65 for Asynchronous motor-driven machines) [45],

a is the maximum deceleration of the vehicle.

3.1.11.2. Regenerative braking Energy

Regenerated energy is calculated by integrating the power over the braking time [45]

$$\mathrm{E_{reg}} = \int \mathrm{P_{reg}}\, \mathrm{dt} \tag{3.39}$$

Form the above equations; it is clear that the magnitude of regenerated energy depends on a combination of many factors including efficiency of regeneration, braking time, deceleration, train mass, maximum operational speed, and all resistive forces**.**

In order to decide on the adoption of regenerative braking system on a rail line, energy consumed between stations is estimated followed by the calculation of regenerative braking energy at each station.

In the analysis of comparison of energy consumed and energy regenerated, each interstation spanning is investigated for estimating the consumed energy based on traction motor requirements. Also at each passenger station, regenerated energy is computed based on the station gradient and train dynamics principles. The calculated results are presented in Table 4-2.

3.2. Energy Storage Modelling and Sizing

3.2.1. Modelling Overview

Today onboard storage devices are being introduced for self-powering the train. However, this thesis shall consider the onboard energy storage system to power the train. Onboard energy storage presents little losses compared to trackside energy storage. Trains with onboard energy storage technologies can run on a free catenary section of the track. The dc-link is used to interface the traction inverter, auxiliary load, and the storage device. The storage device is connected through a bidirectional dc-dc converter. Power can flow in both directions for the main traction power supply and the storage device except the auxiliary load.

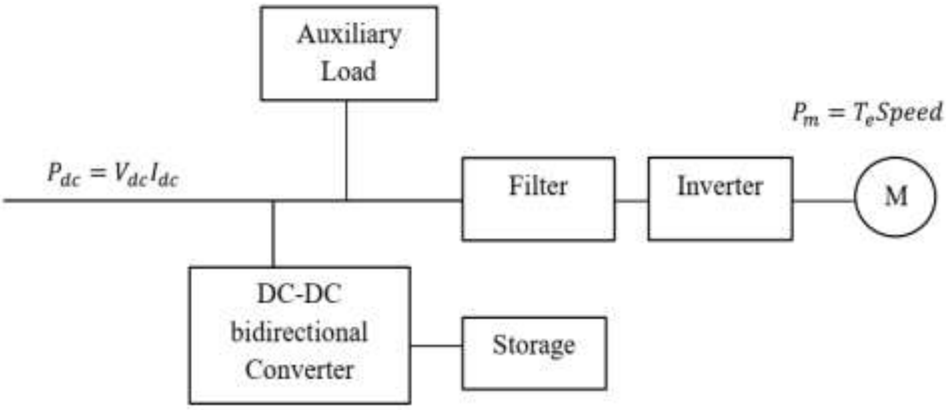

Figure 3-3 Onboard Energy Storage for Electric Rail Vehicle Power flow

During regenerative braking, power is fed to the dc link. This power is shared between the auxiliary loads and charge the storage device (if required), with the excess power fed back into the overhead line. Charging and discharging of the storage device is governed by the energy management system which balances all factors involved in the operation.

Power losses can happen in every transfer in all directions. The traction losses are in the inverter filter, inverter switching and through conversion from electrical to mechanical power in the traction motors. Other losses occur in the power supply (from the overhead line). All these losses appear in both directions of power flow. For the storage device, the losses occur during the charge/discharge process resulting in a combined round efficiency. There are also losses due to leakages within the storage device, but these are small when compared with the charging and discharging losses.

3.2.2. Design of Energy Storage Systems

Energy storage designed shall provide the same DC voltage as output voltage from the traction substation. Since the train requires high DC voltage, it could become an expensive solution to use the energy storage alone to provide such voltage, because a big number of energy storage cells (i.e battery cells) would be required which results in a bigger and heavier and requires more space on the train. Therefore a bidirectional dc-dc converter shall be included in the model to increase the voltage provided by the energy storage cells to the preferable amount required by the train. This bidirectional dc-dc converter will also be used to control the charge and discharging of the storage.

3.2.3. Battery design for East-West line of AA-LRT

As the main objective of this research is to use energy storage system to provide power to train when excess power is required in addition to the grid, and to supply power for the traction when the normal power supply is not available, the chosen energy storage must have the capacity to supply the train during emergency so that the train can run at least to the next station. Therefore, the largest traction track line requiring more energy in East-West line of AA-LRT is Lideta to Coca-Cola. On this block, the train consumes energy of 10.325 kWh to move from Lideta to Coca-Cola station. If the storage can be used to supply the train over this track section length, it can also be used to supply the train over the remaining interstation distances for the same case.

3.2.3.1. Battery Design Consideration

Addis Ababa light rail vehicles are 70% low floor modern trams with the maximum operating speed of 70km/h. To design battery storage for these vehicles, some requirements have to be taken into consideration.

1. **Battery Output voltage**: this condition will be attained by calculating the number of battery needed to be connected in series to get the required voltage of 750VDC. The total voltage of the batteries pack can be expressed as follow:

$$V_{bat} = n_{series} \times V_{cell} \tag{3.40}$$

2. **The maximum discharge current** of the batteries which can be achieved by parallel connection of the series branches.
3. **Battery capacity**: this represents the amount of the electrical charge available and it is often expressed in Ampere-hours (Ah). The capacity of a battery is not a fixed quantity. It

varies according to the discharge rate. Therefore, it is better to choose a bigger capacity to supply the train so that the batteries will be discharged with a small percentage of their total capacity.

According to Peukert's law [14]

$$C_P = I^k t \tag{3.41}$$

Where

C_P is the capacity at one-ampere discharge rate,

I is the discharge current (A),
k is Peukert's constant (ranging 1.1-1.3) and
t is the time of discharge (hour).

The energy of the battery is calculated using

$$E = C_P V \tag{3.42}$$

Where C_P is the battery capacity in Ah, and V is the voltage of battery.

4. **Battery weight**: since onboard energy storage is considered; it is important to choose a lighter weight battery.
5. **The life cycle of battery:** This criterion is of great importance for this design because when the battery life cycle is too short, then the battery needs to be replaced more often, which will result in increased maintenance costs. Note that in battery technology design the energy is not important, but power is important.

3.2.3.2. Battery selection

After comparing various types of rechargeable batteries and compiling data on their service life and other characteristics, Lithium-ion batteries are selected. Compared with supercapacitors and Ni-MH (nickel-metal hydride) batteries, Lithium-ion cells have higher energy and power densities and are smaller and much lighter. In short, Lithium-ion cells are superior to other equivalent secondary batteries, they are manufactured for applications demanding rapid frequent switching back and forth between charge and discharge, and they are ideal for accommodating loads of electrified railroads [46]. Considering the lithium-ion models available on the market, the two models shown in Table 3-3 are compared for a better selection of the battery storage to be applied in the model design.

Table 3-1 Main characteristics of Li-ion Battery model 9535 and 9522

Battery characteristics	Li-Ion model 9535	Li-Ion model 9522
Rated max. output Voltage (V)	72	28.8
Max. Discharge current (A)	250	125
Weight of battery(kg)	21.73	11.34
Capacity (Ah)	34	25

Lithium-ion model 9535 with output voltage of 72V, maximum discharge current of 250A and the weight of 21.73 kg is suitable for this design. To get the required output voltage and appropriate high discharge current, 6 batteries need to be connected in series to give the $(6 * 72) = 432$ V input to the dc-dc converter to be regulated and boosted with boosting ratio of 1.8 which gives 777.6 V which is in the range of working voltage of train [500V-900V] and 6 set parallel branches of these batteries need to be connected in parallel. Then total capacity is 204Ah and total weight of 782.28kg. Hence the total number of battery for this design is 36 batteries with the capacity of 76.5kWh which is enough to drive the train from the station to another considering the energy consumption on the longest track on the East-West line of AA-LRT.

3.4.4. Supercapacitors design for Addis Ababa Light Rail Transit

The main difference between supercapacitors and other storage technologies is the fact that supercapacitor has the advantages of rapid charge/discharge frequencies, a long life cycle and high power density. These behaviours of the supercapacitor match the characteristics of urban rail transit, such as short running time between stations, frequent accelerating and braking. Thus, it is beneficial to use them as a power supply to the train during normal power supply interruptions.

The supercapacitors energy storage consists of a bank of individual supercapacitor modules interconnected in series and parallel by a static bidirectional dc-dc converter. The series and parallel connection are required in order to obtain the desired values of voltage and current. [2]

The energy stored in a supercapacitor, as in a conventional capacitor, is

$$\mathrm{E} = \frac{1}{2}\mathrm{C_{SC}}\,\mathrm{V^2}_{\mathrm{SC}} \tag{3.43}$$

$$\mathrm{i_{sc}} = \mathrm{d}(\mathrm{C_{SC}} * \mathrm{U_{SC}})/\mathrm{d}(\mathrm{t}) \tag{3.44}$$

$$\mathrm{V_{SC}} = \mathrm{U_{SC}} - \mathrm{r_{SC}}\mathrm{i_{SC}} \tag{3.45}$$

$$\mathrm{U_{SC}}(0) = \mathrm{V_{SC,max}} \tag{3.46}$$

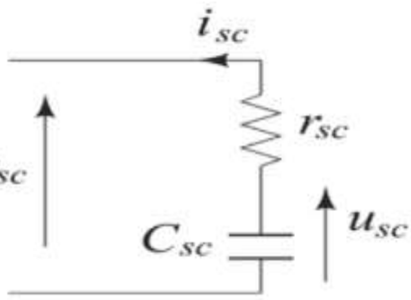

Figure 3-4 Supercapacitor Model for Electric Rail System application

The maximum energy stored in the supercapacitor storage depends on its equivalent capacitance. Thus, the expression for maximum energy storage is as follows:

$$\mathrm{E_{max}} = \frac{1}{2}\left(\mathrm{C_{eq}} * \mathrm{V_{SC,max}}^2\right) \tag{3.47}$$

$$\mathrm{E_{max}} = 0.5 \times 840 \times 375^2$$

Practically, it is not feasible to discharge all the stored energy; there is a fixed minimum allowable voltage that limits available energy. In supercapacitors as per the standard, the minimum voltage limit to be discharged is half of the maximum voltage limit of the cell/module.

Since the voltage constraint is determined to be $\mathrm{V_{min}} < \mathrm{V} < \mathrm{V_{max}}$, the usable energy to be supplied by the supercapacitor is:

$$\mathrm{E_{usable}} = \frac{1}{2}\mathrm{C_{eq}}\left(\mathrm{V_{max}}^2 - \mathrm{V_{min}}^2\right) \tag{3.48}$$

$$\frac{\mathrm{E_{usable}}}{\mathrm{E_{max}}} = 1 - \left(\frac{\mathrm{V_{min}}}{\mathrm{V_{max}}}\right)^2 \tag{3.49}$$

Where

$\mathrm{E_{usable}}$ is the useful energy of the supercapacitor,

$\mathrm{C_{eq}}$: Equivalent capacitance,

$\mathrm{V_{max}}$ Maximum voltage of the supercapacitor,

V_{min}: Minimum voltage of the supercapacitor,

$\mathrm{E_{max}}$: Maximum energy in the supercapacitor,

Usable energy stored in the supercapacitor in terms of the rate of discharge is expressed as:

$$\mathrm{E_{usable}} = \frac{\mathrm{E_{max}}}{[1-(\mathrm{d})^2]} \tag{3.50}$$

$$\mathrm{d} = \frac{\mathrm{V_{min}}}{\mathrm{V_{max}}} \tag{3.51}$$

From the characteristic of the supercapacitor $d = 0.5$, therefore the maximum energy of the supercapacitor which gives 10.325kWh usable energy to cover the distance from Lideta to Coca-Cola is:

$$\mathrm{E_{usable}} = \frac{\mathrm{E_{max}}}{[1-(\mathrm{d})^2]} = \frac{10.325}{1-(0.5)^2} = 13.7667\ \mathrm{kWh}$$

The maximum energy storage capacity of the supercapacitor should be ≥ 13.7667 kWh.

Table 3-2 Characteristics of BMOD0063P125 B04/B08 SC Module [47]

Parameters	Units	Value
Rated Capacitance	[F]	63
Maximum ESR DC, initial	[mΩ]	18
Rated Voltage	[V]	125
Absolute Maximum Voltage15	[V]	136
Maximum Continuous Current (ΔT = 15 °C)	[A]	140
Maximum Continuous Current (ΔT = 40 °C)	[A]	240
Maximum Peak Current, 1 second (non-repetitive)	[A]	1800
Leakage Current at 25 °C, maximum	[mA]	10
Maximum Series Voltage	[V]	1500
Capacitance of individual cells	[F]	3000
Number of cells	-	48
Operating Temperature range	[°C]	-40 to +65
Specific Power	[W/kg]	1.7
Specific Energy	[Wh/kg]	2.3
Storable Energy	[Wh]	140
Projected DC Life at 25 °C	-	10 years
Projected Cycle Life at 25 °C	-	10^6 cycles
Typical Mass	[kg]	61

The determination of the storage capacity allows defining the dimensions and weight of the storage device. Various numbers of supercapacitors have been considered in this part of the project, in order to discover the best option for supplying the trains of Addis Ababa Light Rail Train. Commercially there are modules suitable for transport or industrial applications, with working voltages from few volts to more than 300 V and with capacitances of a few hundreds or even thousands of farads. According to Maxwell products, 125V heavy transportation module Supercapacitors; MAXWELL BMOD0063P125 B04/B08 SC module is selected for this application considering its characteristics as shown in Table 3-2 [47].

Figure 3-5 Example of a MAXWELL 63 F SC module [47].

Note that the size of the storage shall match the choice of the dc-dc interfacing converter, in particular, the determination of the maximum and minimum input and output voltage levels and the maximum allowable current.

3.4.4.1. Determination of number of supercapacitor required

Based on the energy consumption on the track section selected (Lideta-Coca-Cola) 10.325 kWh and with required maximum voltage (750V) the number of supercapacitor modules required can be calculated. The dc-dc converter to be integrated with the module shall work with boosting ration of 2 and buck with duty ratio of 0.5. So, the voltage output from SC storage $750/2 = 375$ which is $3 * 125\mathrm{V}$ where 3 is the number of series connected supercapacitor

Considering the supercapacitor voltage

$$\mathrm{E_{max}} = \frac{1}{2}\left(\mathrm{C_{eq}} * \mathrm{V_{SC,max}}^2\right).$$

$\mathrm{C_{eq}} = 819.2\ \mathrm{F}$ (The rated Capacitance of the Supercapacitor module is 63F) and maximum allowable

$$\mathrm{C_{eq}} = \mathrm{C_{cell}} * \left(\mathrm{n_p}/\mathrm{n_s}\right).$$

where

$\mathrm{n_s}$ is the number of cells/modules in series,

$\mathrm{n_p}$ is the number of parallel branch,

$\mathrm{C_{cell}}$ is the capacitance of cell /module in Farad,

$\mathrm{C_{eqSC}} = 63(\mathrm{n_s}/3)$ and $\mathrm{n_s}$ =39.05,

Approximately 40 parallel branches are required with equivalent capacitance of 840F.

Then required number supercapacitor module is 120 modules (40 parallel branches with 3 modules in series) are used to get 16.4 kWh with the total weight of 7320kg. They can store

$$\mathrm{E_{max}} = 0.5 * 840 * 375^2 = 16.4\mathrm{kWh}.$$

Considering the weight and space on the train, the number of the supercapacitor required should be minimized. Therefore supercapacitor alone cannot be used to supply power to train due to unreasonable weight to be added on the train.

3.2.5. Combination of Battery and Supercapacitor (Hybrid ESS)

From the previous design of battery and supercapacitor as energy storage, it is difficult for the designed number of supercapacitor modules to be added on the train due to additional higher weight and the space required on the train. To adopt the use of supercapacitor as energy storage system; the required number of modules should be minimized. To do so, the combination of battery and supercapacitor is considered to provide the required energy and power to the train with a lighter weight Storage. As it has been determined early, the series modules are 3 with a total voltage of 375V connected to the low voltage side of the dc-dc converter to be boosted to 750V. For the number of parallel branches, it should have the capability to recapture regenerated energy, so the power is the determinant. Then to have enough power capability from the supercapacitor 8 parallel branches have been selected for this design.

$$\mathrm{C_{eq}} = 8 \times 163/3 = 168\mathrm{F}$$
$$\mathrm{E_{max}} = 0.5 \times \mathrm{C_{eq}} \times \mathrm{V}^2 = 3.28\ \mathrm{kWh}$$

From this calculated energy the usable is 2.46kWh energy. Thus 2kWh supercapacitor storage capacity is selected and the required number of SC is 24 modules with the mass of 1,464kg. Therefore, Total the hybrid ESS designed would have a weight of 1,464kg+782.28kg= 2,248kg and including the weight of the dc-dc converter 128kg+156kg=284kg, the total weight becomes 2,532kg to be added on the vehicle weight. The gross weight of the train with full load becomes 65,552kg is equal to 65.55tones. The total Energy Capacity of the ESS becomes 79.88kWh where the capacity of the Li-ion battery is 76.5kWh.

The following circuit illustrates a hybridization of a supercapacitor with a battery. The supercapacitor is connected to a buck/boost converter and the battery is connected to a boost converter. Power of the battery is limited by a rate limiter block; therefore the transient power is supplied by to the DC bus by the supercapacitor.

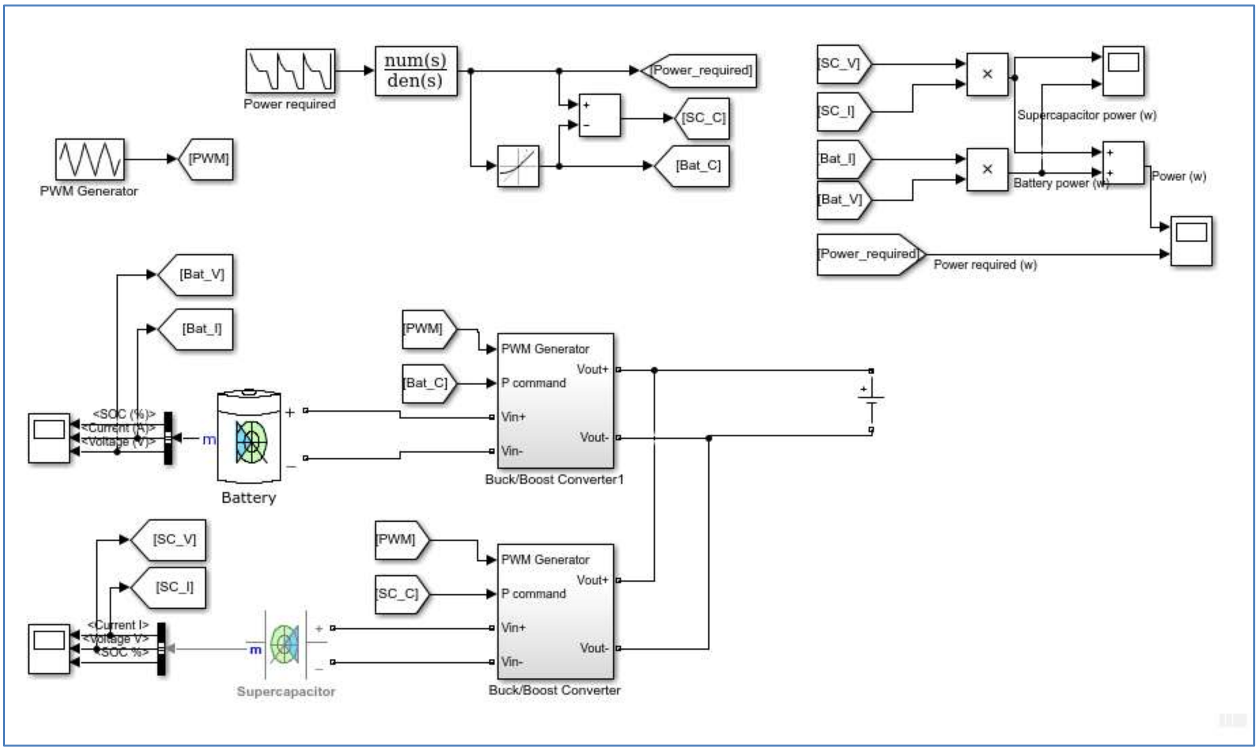

Figure 3-6 Parallel connection of Battery and Supercapacitor Model design

In this circuit, the bidirectional dc-dc converter has been used to connect the storage to the DC link. The bidirectional dc-dc converter is used for continuous charging power of 130kW required for the traction motors. As depicted in the Figure 3-6 above, the DC link is connected to the energy storage system through the bidirectional dc-dc converter.

During the charging phase of the onboard energy storage system, the nominal value of the high voltage side is 750V. The bidirectional dc-dc converter works in buck mode to control the recharge current of the energy storage system. While during the discharging phase of the onboard energy storage system, the value of the low voltage side is 375V. The dc-dc converter works in boost mode to regulate the voltage at the DC link.

Table 3-3 Bidirectional dc-dc converter specification

Parameters	**Units**	**Values**
High voltage side (DC-link)	[V]	750
Low Voltage side (energy storage)	[V]	375
Average output power	[KW]	150
Switching Frequency	[Hz]	1000
DC link side inductance, Lin	[mH]	0.5
Energy storage side inductance, Lout	[mH]	3
DC link capacitance	[mF]	3
DC link resistance	[Ω]	1000
Duty ratio	0.5	

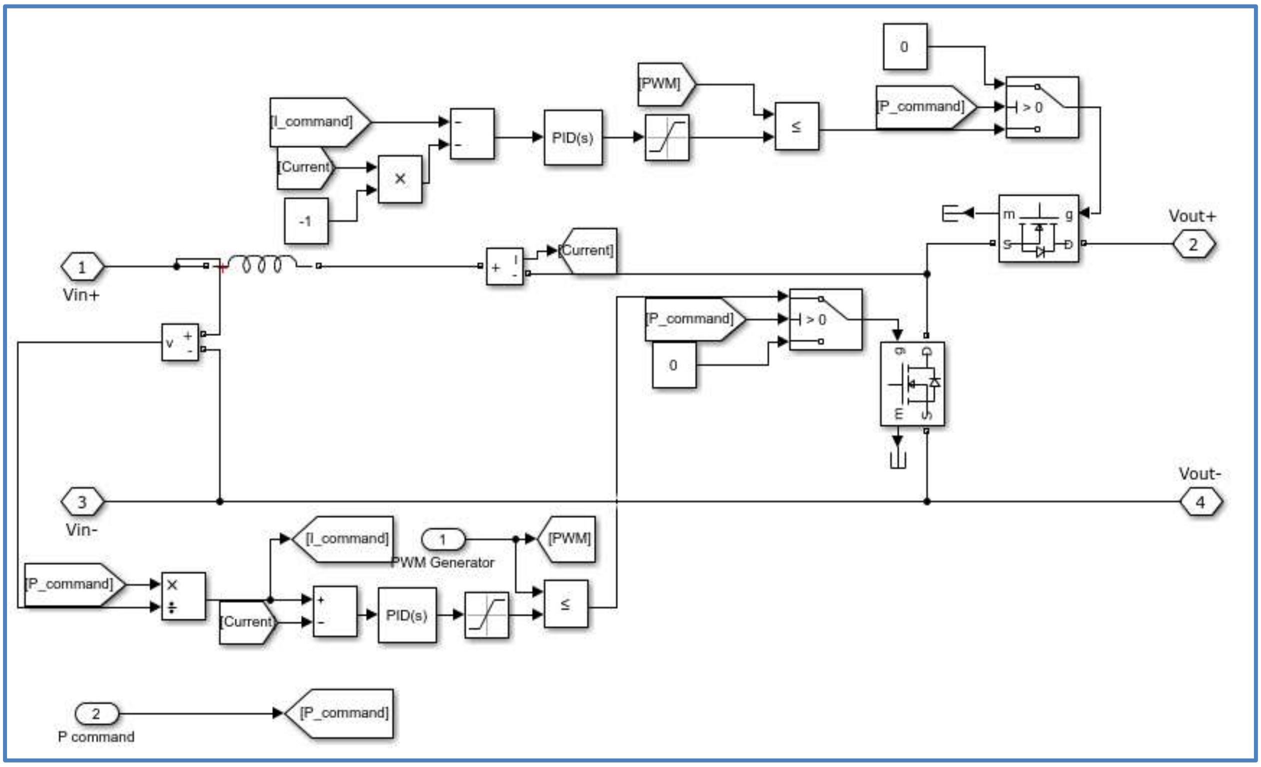

Figure 3-7 Bidirectional dc-dc converter modelling

The following ciruit illustrates the connection arrangement to the normal power supply interfaced with the storage technologies.

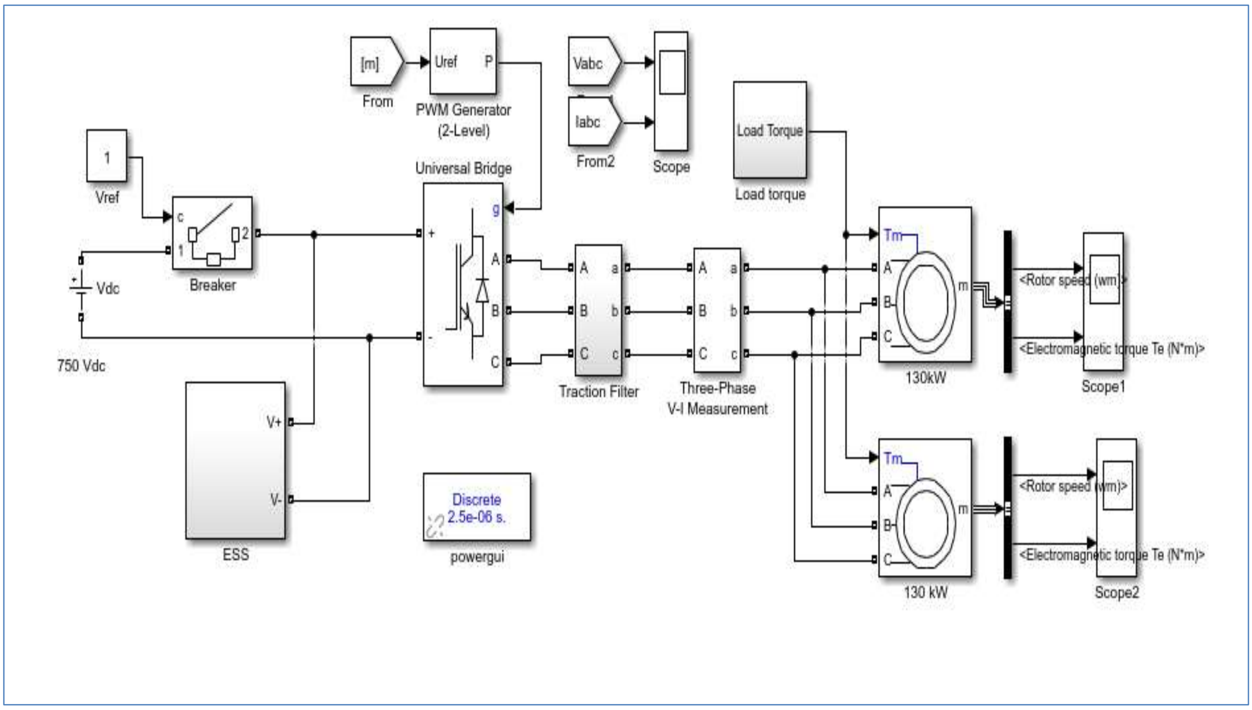

Figure 3-8 Normal Traction power supply model interfaced with ESS

The main elements of the block diagram are listed below.

- DC power supply 750V DC
- Energy storage system with DC/DC converter
- Inverter (Universal converter IGBT with diode for bidirectional)
- Inverter gate signal (voltage regulator based PWM)
- Motor torque (traction load torque)

4. SIMULATION RESULTS AND DISCUSSION

4.1. Traction Power and Energy Consumption simulation results

When the rail vehicle moves from one station to another, it does have acceleration, constant speed, coasting and deceleration states, and of course, the tractive force, power and energy applied varies according to those states. For urban service, coasting is excluded because of shorter distances between stops.

To be able to evaluate the train energy consumption during the simulation, a Matlab function to generate the speed profile for the train movement stages has been formulated as given in Appendix C. From simulation results it is clear that the train consumes a certain amount of energy corresponding to the states of motion, as it is moving on. The main components which can be seen in the traction profile simulation are the opposing forces and the Matlab function for generating the speed profile of the train by using known data from the ERC office.

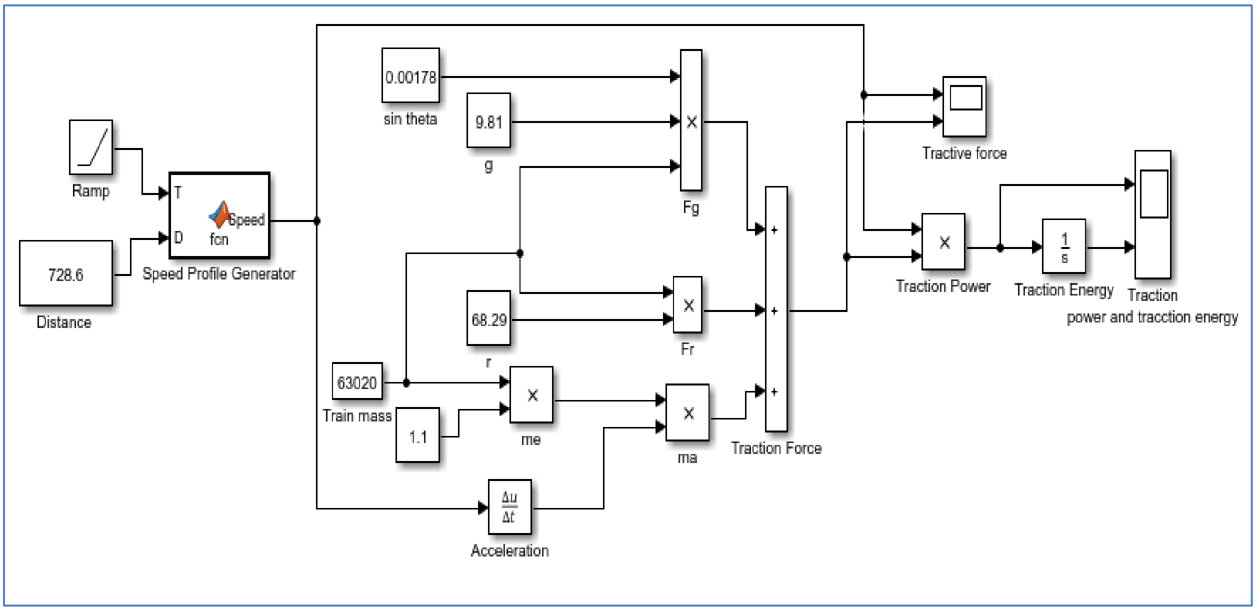

Figure 4-1 Tractive Force, Power and Traction Energy simulation model

The speed profile has been formulated corresponding to the distance between stations by using the general specification of AA-LRT such as acceleration 0.9m/s^2 with the accelerating speed (0-70km/hr), and the deceleration speed of (70– 0 km/hr) for -1m/ s^2.

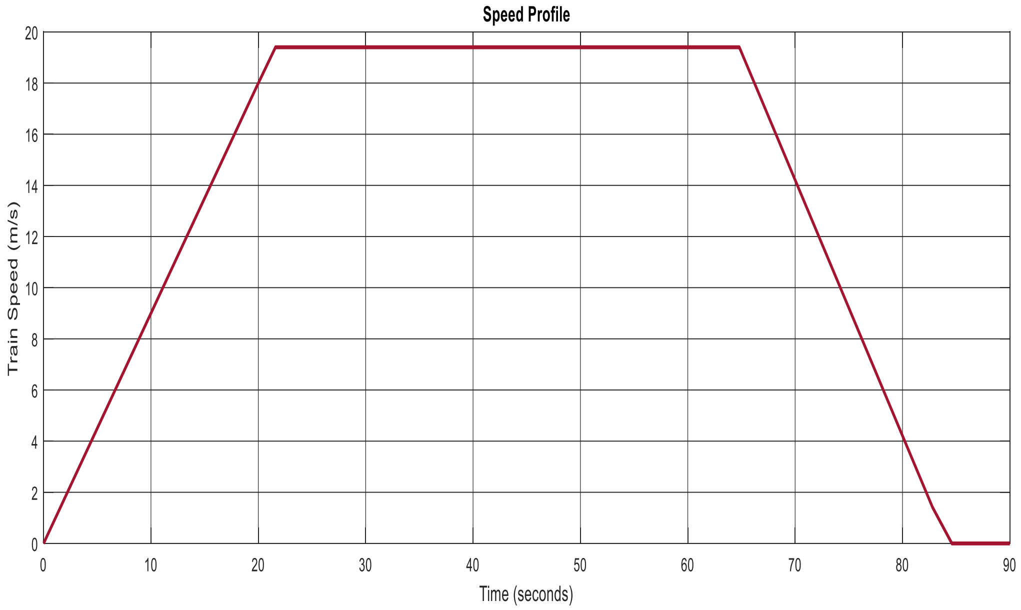

Figure 4-2 Train Speed Profile simulation graph for Lideta-Cola-cola

The force required to haul the train from a standstill to its maximum acceleration increases from zero to its maximum value during acceleration period. For constant speed (free running) the force applied is constant as shown in Figure 4-3. As describe in modelling, the power supplied to train remains ON during acceleration and constant speed periods. During the deceleration phase, the train keeps braking and generates energy called regenerative energy due to braking force applied. This force increases to its maximum negative point and brought the train to stop.

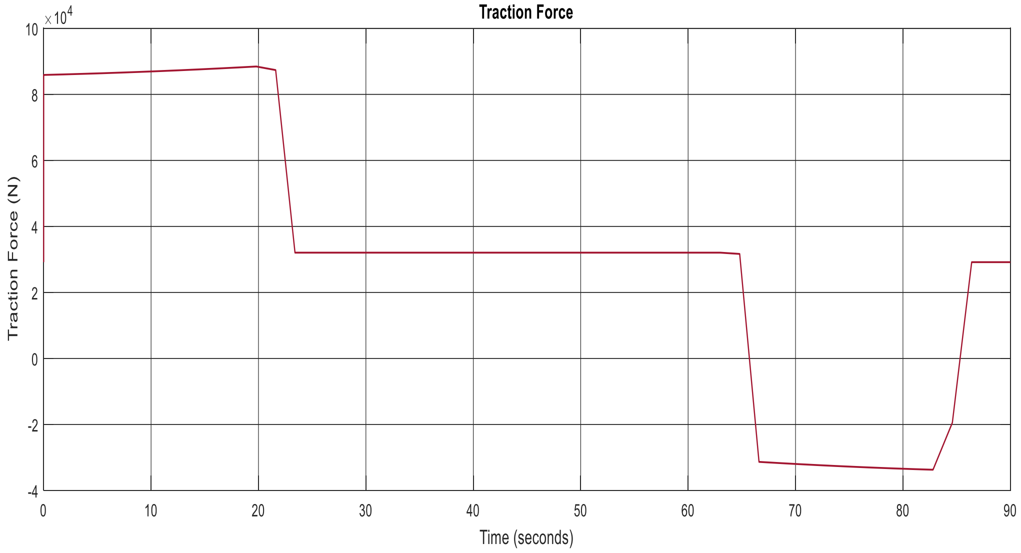

Figure 4-3 Traction force simulation graph for Lideta-Coca-Cola

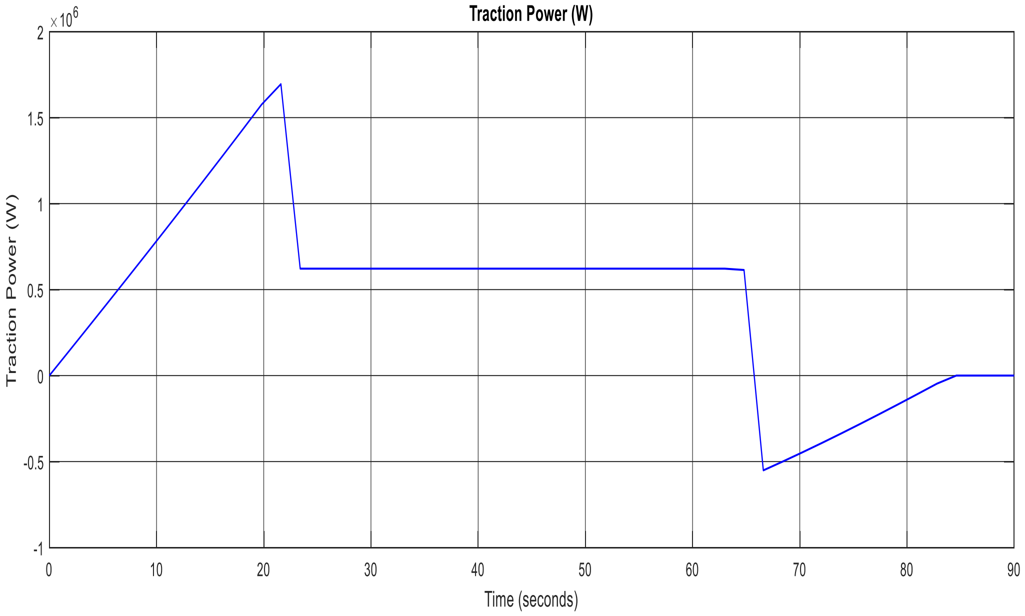

Figure 4-4 Traction Power simulation graph for Lideta-Coca-Cola

The traction power curve increases to its maximum value corresponding to the maximum force required to overcome the train resistances during the acceleration period. Then after that, the traction power falls to a lower value at the start of the free running period, since there is no power needed to accelerate the train. During the constant speed period the train keeps running with a constant power. Finally, in the deceleration phase, the traction force is at its maximum negative value. The power falls to its negative maximum peak value and returns with decelerating rate to zero. This is the maximum braking power required to decelerate the train from maximum speed to zero.

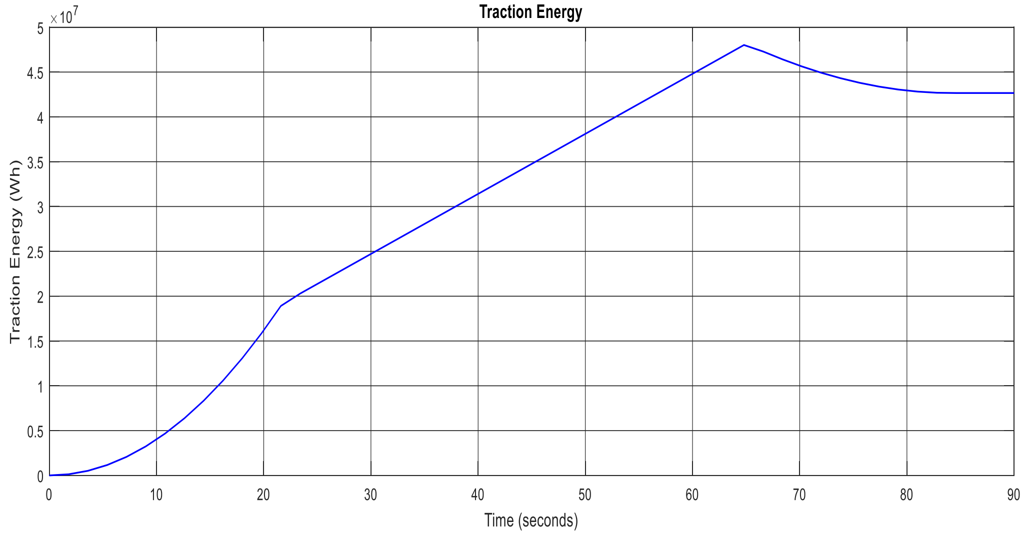

Figure 4-5 Traction Energy consumption simulation graph for Lideta-Coca-Cola

4.2. Hybrid EES charging and discharging operation

To accelerate the train from a standstill, it requires a higher power from the supply network. For this stage, the supercapacitor is the best power supply due to its characteristics of fast charging and discharging. Contrary to that, the battery energy storage is used during constant speed phase because it takes time to extract the energy stored and it has high energy capacity to supply the train over a long distance. During retardation, the energy regenerate is quickly stored in the supercapacitor and gets discharged during the next acceleration phase while batteries get charged with the excess regenerated energy or when the train stops at passenger station. Note that charging station shall be built separately from the normal power supply for better control of battery life and a designated amount of current it can tolerate.

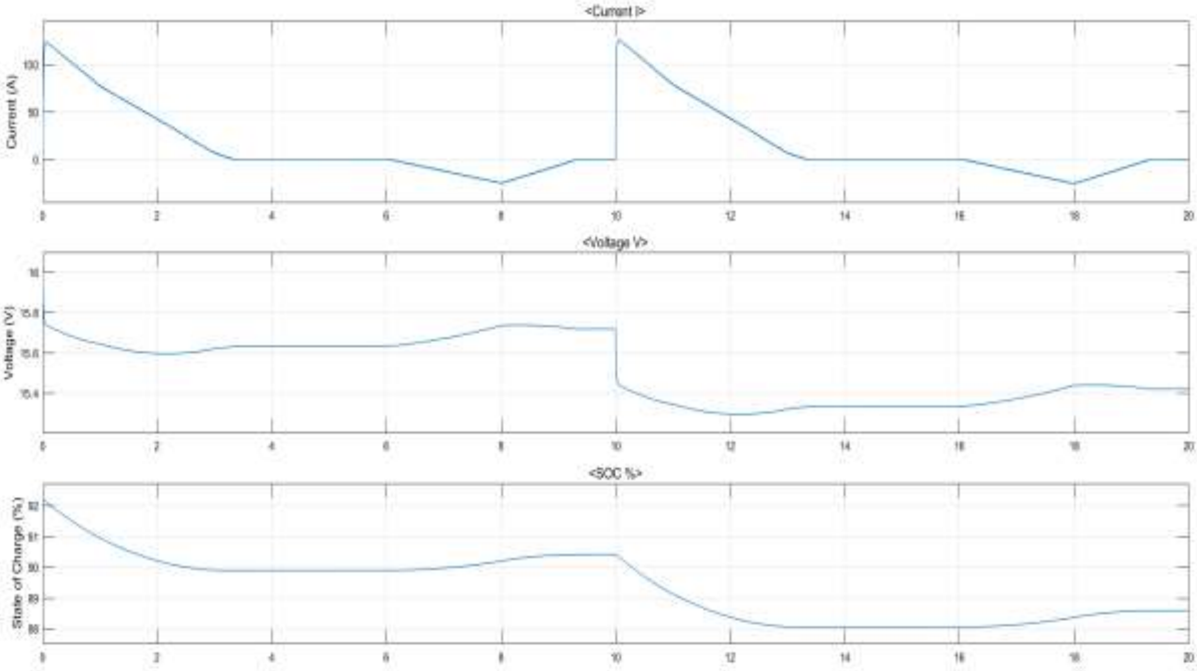

Figure 4-6 Supercapacitor charging and discharging operation

The single-use of supercapacitor energy storage units on urban rail transit is enough for the energy-efficient use of vehicles operated only with Overhead Contact Line because large power has to be transferred within short times at a high number of cycles. The operation without OCL can be realized up to certain track lengths via the energy content of today’s supercapacitor energy storage systems usually between 1kWh up to 2kWh. However, ambitious track topologies, wider station distances and demands to the running characteristic and the air-conditioning of the vehicles need more energy than what can be stored in the supercapacitor energy storage systems. At this point, the advantage of the higher energy content of the traction battery can be used.

The combination of both systems to a hybrid energy storage system offers unique advantages, which is the possibility to drive train on longer tracks without OCL. During the acceleration time, energy is taken within a short time out of the supercapacitor energy storage unit of 2kWh with high power. The energy content of the Supercapacitor ESS is sufficient to accelerate the train to the desired speed.

During the constant speed/free running while the supercapacitor energy storage unit reaches its lowest SOC the energy is provided by the traction battery, but with a considerably smaller power. During the dwell time at the passenger stations, the stationary charging units are used, which can charge the energy storage system within a short time.

Another advantage of this Hybrid Energy Storage system is the fact that at disturbances, unforeseeable stops or maintenance work on the track, the energy content of the traction battery can be used for further operation also at a higher depth of discharge.

A vacating of the track would be possible even in the case of damage to the supercapacitor energy storage unit over longer distances. Since such operation scenarios should not often happen, the lifetime of the traction battery will not suffer substantially. The use of traction batteries is only to be recommended at sole operation at the OCL if a sufficient operation of the vehicle is wanted during voltage blackout or maintenance at the traction power supply.

4.3. Energy consumption calculation results on East-West line of AA-LRT

The following section presents the calculated results of energy consumption which has been considered during the sizing of the storage system for generating the energy required for the train over the length of the East-West line of Addis Ababa.

The results have been computed using the data related to gradient and distance between passenger stations of West–East line of AA-LRT and the vehicles specifications as given in Appendix A (Table 01 and Table 02).

Table 4-1 Energy consumption calculation results on East-West Line

Stations		**Econs in Forward direction**		**Econs in Return direction**	
Departure Station	**Destination Station**	**Max. Speed(Kwh)**	**Aver. Speed (KWh)**	**Max. Speed(kWh)**	**Aver. Speed (kWh)**
Ayat	Meri	7.621	1.972	5.297	0.956
Meri	CMC	5.852	1.141	5.298	0.949
CMC	St.Michael	5.502	0.961	0.334	-5.236
St.Michael	C.S. College	5.51	0.982	5.191	0.915
C.S. College	Mgt. Institute	5.412	0.892	8.176	4.768
Mgt. Institute	Gurda shola1	5.63	1.015	6.61	3.572
Gurda shola1	Gurda shola2	5.79	1.212	0.649	-5.164
Gurda shola2	Megenagna	5.5	0.956	5.613	1.108
Megenagna	Lem Hotel	5.391	0.913	5.261	0.936
Lem Hotel	Hayahullet 1	5.382	0.912	5.651	1.149
Hayahullet 1	Hayahullet 2	4.312	-0.098	8.423	5.042
Hayahullet 2	St.Urael	0.811	-3.796	6.516	2.413
St.Urael	Bambis Hotel	5.298	0.842	5.422	1.03
Bambis Hotel	Estephanos	5.642	1.045	5.516	1.085
Estephanos	Stadium	5.156	0.809	5.755	1.173
Stadium	Leghar	7.384	3.16	5.622	1.097
Leghar	Mexico square	8.743	4.355	5.325	0.99
Mexico square	Tegbared	2.414	-1.956	5.464	1.034
Tegbared	Lideta	5.373	0.912	5.457	1.021
Lideta	Coca Cola	10.325	5.592	5.806	1.197
Coca Cola	Torhailoch	5.328	0.899	7.464	1.908
Total energy consummation		**118.673**	**22.612**	**114.85**	**21.88**

The train energy consumption depends on the magnitude of the gradient and the direction of travel. When the train is moving on descending a gradient (downward direction), the train does not consume a lot of energy, instead, it keeps on braking to safely run at permissible speed. And if the train uses regenerative braking system as service brakes, it produces energy instead of consuming it. The reason why there are negative values in the calculated energy consumption is that regenerated energy which flows from traction motor to the catenary is greater than the energy drawn from the catenary to overcome the acceleration and resistance.

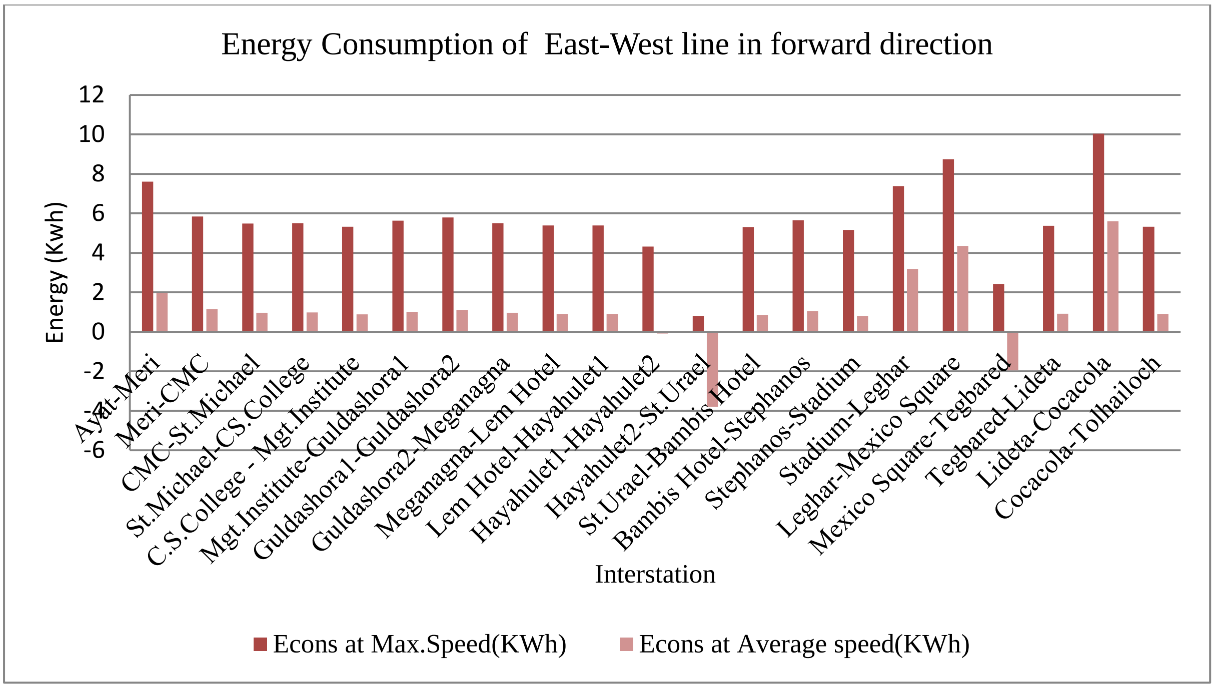

Figure 4-7 Energy consumption of East-West forward direction of AA-LRT

As state above, the energy consumed when ascending a gradient is different from the consumed energy when descending that gradient, reason why the calculated energy consumption was computed for both direction of the East-West line of AA-LRT. With these charts, it is easily to observe the track section with higher energy consumption which has been considered during the design of energy storage system required for the traction purpose.

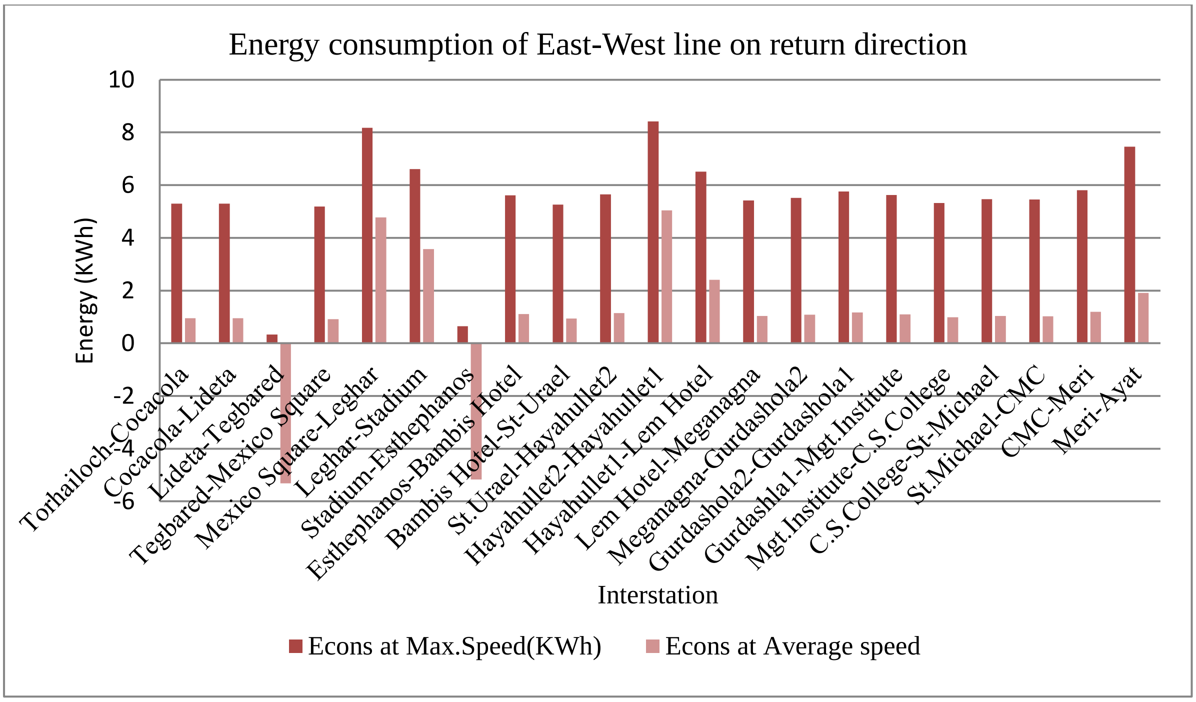

Figure 4-8 Energy consumption of West-East line Return direction [AA-LRT]

4.4. Regenerative Braking Energy calculation results

From these results presented in Table 4-2, when the train is running at the speed above the average speed, it results in generating a higher energy during braking period. Contrary to the energy consumption, the train consumes a bit higher energy when it is running at higher speed. While low energy consumption is observed for the speed below the average speed.

Table 4-2 Regenerated Energy for both direction of East-West line

Interstation	**Forward direction**		**Return direction**	
	E reg at Max. Speed(KWh)	**Ereg at Aver. speed(KWh)**	**Ereg at Max. Speed(KWh)**	**Ereg at Aver. speed(KWh)**
Torhailoch-Cocacola	1.73	0.198	2.401	0.276
Cocacola-Lideta	2.526	0.292	2.398	0.278
Lideta-Tegbared	2.529	0.292	2.401	0.277
Tegbared-Mexico Square	3.102	0.359	2.399	0.279
Mexico Square-Leghar	3.213	0.372	2.395	0.277
Leghar-Stadium	1.534	0.177	2.401	0.281
Stadium-Esthephanos	2.529	0.292	2.398	0.277
Esthephanos-Bambis Hotel	2.526	0.292	2.394	0.287
Bambis Hotel-St-Urael	2.533	0.293	2.396	0.267
St.Urael-Hayahullet2	3.12	0.361	2.221	0.257
Hayahullet2-Hayahullet1	2.706	0.313	1.807	0.208
Hayahullet1-Lem Hotel	2.53	0.293	2.394	0.277
Lem Hotel-Meganagna	2.517	0.293	2.401	0.277
Meganagna-Gurdashola2	2.529	0.292	2.398	0.277
Gurdashola2-Gurdashola1	2.526	0.292	3.393	0.393
Gurdashla1-Mgt.Institute	2.531	0.293	3.082	0.357
Mgt.Institute-C.S.College	2.528	0.292	1.825	0.211
C.S.College-St-Michael	2.526	0.292	2.398	0.277
St.Michael-CMC	2.529	0.292	2.401	0.278
CMC-Meri	2.526	0.292	3.206	0.371
Meri-Ayat	2.526	0.292	2.4	0.277
	53.317	**6.166**	**51.62**	**5.953**

4.5. Battery charging and discharging control simulation

In the study of battery energy storage system for electric railway application, charge and discharge control is a must to meet the desired output voltage and also to protect the battery. Therefore the next graph is a block diagram simulation showing the charging/discharging control of battery using a dc-dc converter. The charge and discharge processes require a proper controller that generally operates as a function of the line voltage: when an overvoltage takes place as a result of any braking process, the dc-dc converter works in buck mode and charges the ESS with the excess of regenerated energy on the line; conversely, when a voltage drop is detected, the ESS releases the stored energy in order to keep the threshold value on the network. This time the dc-dc converter works in boosting mode.

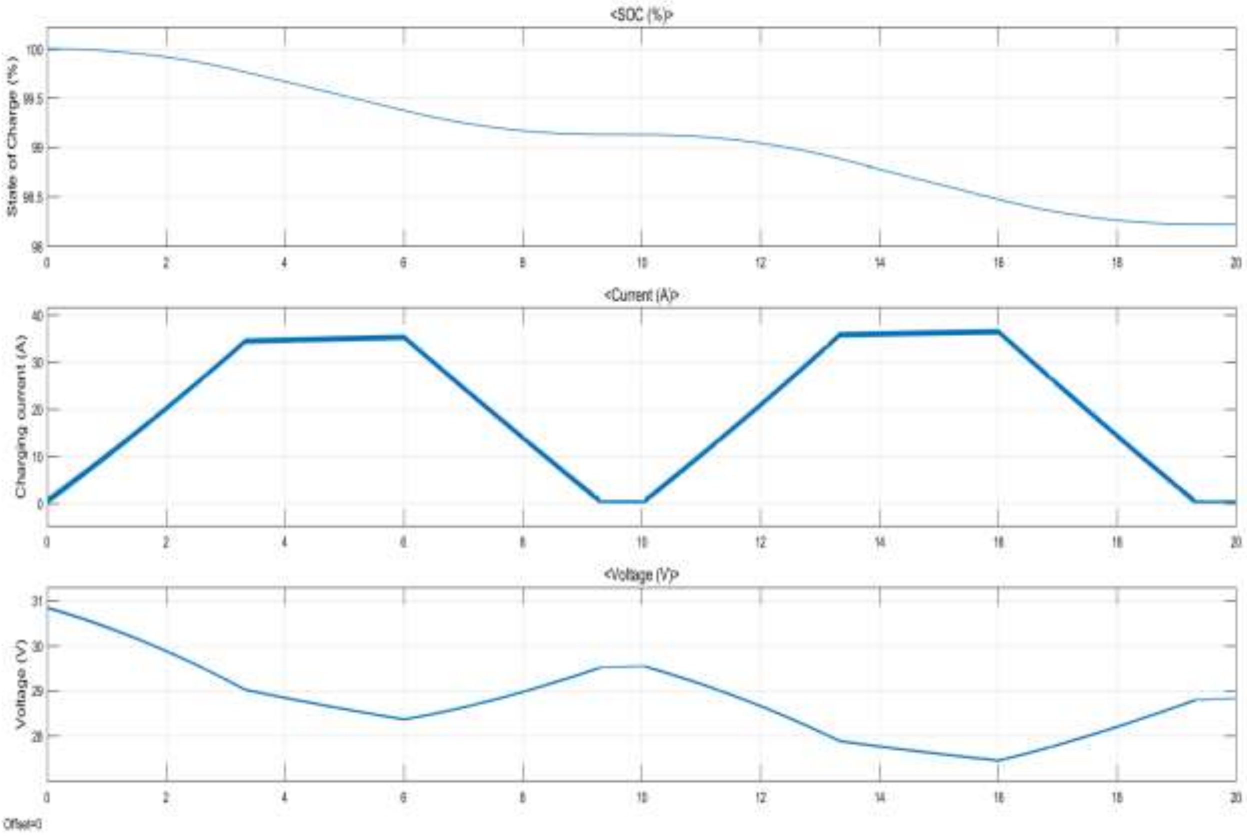

Figure 4-9 Battery Charging and Discharging simulation graphs

Figure 4-9 shows the Current, Voltage and state of charge of the Lithium-ion Battery in the hybrid ESS. From the graph, the battery discharging rate is shorter from 100% to 98.2% which means that the discharging rate is not falling below 98%. The battery voltage and current curves are balanced with the required power to be fed to the traction inverter to be transformed to ac current before being directed to the traction motors.

4.6. Cost Benefit Analysis

The investment cost of the ESS and their operating cost can be evaluated based on the current market price. Today the price of energy storage decreases due to the mass production considering the area of application. In this particular case of modern electric rail transit, the use of regenerative braking pushes railway operators to think about the price of electricity and the energy wasted during regenerative braking. Apart from regenerated energy, the failure of the power supply for one hour is also a loss considering the daily income of a properly working system and customer satisfaction.

Current prices are related to storage technologies ratings which define the fitness in a specific application. From the available price of supercapacitor storage available, MAXWELL BMOD0063P125 Supercapacitor module with rated voltage of 125V, 1800A of current and 63F of capacitance is 5854.55$ per module. Considering the number of modules needed including the price of the dc-dc converter (600/720Hz) total price will be 100,448.16$ per one vehicle. In line with the number of train in operation on East-West line of AA-LRT, the total cost will be 100,448.16$*16 trains = 1,607,170.56$.

For Lithium-Ion battery (model 9535) with output voltage of 72V, maximum discharge current 250A and the weight of 21.73kg the price is 648.96$. Therefore, total batteries cost will be 23362.56$. Maintaining the run time between the first station to the end station will decrease the headway and the number of passenger boarding a train will increase so the income. As the urban population is increasing rapidly, the cost of extending the line in terms of power supply (overhead line) will decrease due to storage available on the train.

From the objectives of this study, it is quite understandable that using energy storage system for emergency case only will take a long time to benefit from the additional power supply of the EES system. But if the designed storage systems have the capability of recuperating the regenerated energy, the benefit will increase and the investment cost will be accumulated in a short time.

From the primary data collected, the running time for a train in one way is 1589seconds. The available designed running timetable suggests 30seconds of duel time at every passenger station. Considering the number passenger station on East-West line (21passenger stations), the stopping time is 630 seconds. Therefore, the total time for a train round trip is 4438seconds (1.2hrs).

The operation starting time is 06:00 AM and the stopping time is 10:00PM resulting in 16hours of operation per day. Thus each train can make 13 round trips per day. The regenerated energy in forward direction of East-West line is 5.92kWh whilst the return direction (West to East) of the line regenerates 6.31kWh, resulting in 12.23kWh per round trip of one train. Considering the total 13 round trips, the total energy from regenerative braking is 158.99kWh/day/train.

On East-West line of Addis Ababa Light Rail Transit, 16 trains successively are spanned by 20seconds which means that 2543.84kWh are generated per day. The tariff of electricity in Ethiopia supposes 0.06$/kWh. This implies that the total amount of 151$ are gained for total energy generated per day in addition to transportation service tariff collection.

5. CONCLUSIONS AND RECCOMENDATIONS

5.1. Conclusion

This thesis presents the use and applications of energy storage devices in urban electrified railways, where light rail vehicles of Addis Ababa belong. Energy storage devices are essentially able to recover the regenerative braking energy and releasing it to support rail vehicles acceleration or the main electrical substations in the neighborhoods. They can actually improve energy efficiency and support the performance of urban electrified railways including the catenary free operation.

After a comprehensive overview of the currently available storage technologies for urban rail traction, and also pointing out the current commercially proven solutions, it has been identified that Lithium-Ion Battery storage and Supercapacitor technology are the most suitable technologies that match the performance requirements of the urban rail traction.

Lithium-ion is suitable for emergency and catenary free operation because of its response time and life cycle but frequent charge and discharge can reduce its life cycle. On the other hand the supercapacitor energy storage technology is the best technology for regenerative braking energy recuperation and releasing it when required due to its fast response on power system, but its fast discharging the stored energy is not good for catenary free operation or emergency condition which needs a timely based discharging state to supply train over a long distance.

Thus, for better efficiency mechanism, the combination of battery and supercapacitor energy storage was designed to combine the characteristics and use them according to different running state which needs a different amount of energy to be discharged. Thus, a hybrid energy storage system with the capacity of 79.88kWh and a weight of 2460kg is used. To power the train with the ESS, the stored energy of the supercapacitor is released during acceleration and the battery for free running with 92% and 98% state of discharge respectively.

As a result the combination was found suitable technology for catenary free operation and emergency conditions based on the designed storage capacity and the computed results for the normal power consumption of the line observed from the mathematical modelling. The designed storage contribute in the traction power supply during emergencies and the possibility of free catenary operation can been realized once this project is implemented.

5.2. Recommendations

After completion of this project work, the following recommendations are to be carefully taken care of:

- Due to lack of operational data, some assumptions have been made in the simulations. For future work, the actual operational data need to be collected by the corporation for correct modelling and design.
- For future work, control system like fuzzy logic control can be used for better observation of the behaviours of the control system designed.
- A further study on the application of wayside storage system can be conducted for comparison with the onboard type.

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APPENDIX A: TRAIN DATA CHARACTERISTICS FOR AALRT

Table 01-Data related to train movement

No	**Parameter**	**Value**
1	Track gauge	1435 mm
2	Vehicle weight (empty)	44,000 kg
3	Vehicle weight (fully loaded)	64,000 kg
4	Vehicle height (without pantograph)	5 m
5	Vehicle length	29.4 m
6	Vehicle width	2.65 m
7	Vehicle frontal area	10 m^2
8	Maximum operational speed	19.4 m/s
9	Average starting acceleration;	0.9 m/s^2
10	Max. acceleration;	1 m/s^2
11	Actual running acceleration	0.5 m/s^2
12	Service brake deceleration	1.1 m/s^2
13	Motor efficiency	87 %
14	Inverter efficiency	90 %
15	Gearbox efficiency	96 %
16	Acceleration due to gravity(g)	9.81
17	Air density	1.2 kg/m^3
18	Rolling resistance coefficient (C_R)	0.0071
19	Aerodynamic drag coefficient (C_w)	0.5
20	Track surface coefficient ($\mathrm{C_h}$)	1.2
21	Wind speed	15 m/s

Table 0-2 Data related to track section of East–West line direction

N^o	Station	Gradient	Interstation Spacing	Value(m)
1	Torhailoch	0.0054^0	Torhailoch–Coca cola	720.9
2	Coca Cola	0.00998^0	Coca Cola–Lideta	728.6
3	Lideta	2.247^0	Lideta–Tegbared	768.4
4	Tegbared	0.00102^0	Tegbared–Mexico Square	635.6
5	MexicoSquare	1.591^0	Mexico Square–Leghar	663.4
6	Leghar	1.901^0	Leghar–Stadium	412.1
7	Stadium	2.767^0	Stadium–Estifanos	607.3
8	St. Estifanos	0.00155^0	Estifanos–Bambis Hotel	950.2
9	Bambis Hotel	0.00849^0	Bambis Hotel–St.Urael	699.5
10	St. Urael	0.00989^0	St. Urael–Hayahulet 2	953.5
11	Hayahulet 2	1.641^0	Hayahulet2–Hayahulet1	685.1
12	Hayahulet 1	0.491^0	Hayahulet1–Lem Hotel	782.6
13	Lem Hotel	0.00358^0	Lem Hotel–Megenagna	799.2
14	Megenagna	0.00953^0	Maganagna–Gurd-Shola2	856.3
15	Gurd -Shola 2	0.00127^0	Gurd-Shola2–Gurd-Shola1	1054.9
16	Gurd -shola 1	0.0079^0	Gurd-Shola1–Mgt Institute	970.8
17	Mgt Institute	0.00632^0	Mgt.Institute -Civ.Service College	724.5
18	Civ. ServiceCollege	0.00458^0	Civil Service -St. Michael Church	845.2
19	St. Michael church	0.000958^0	St. Michael Church-CMC	849.1
20	CMC	0.00093^0	CMC-Meri	1092.2
21	Meri	0.00917^0	Meri-Ayat	2362.2
22	Ayat	0.00818^0		

Table 0-3 Recalculated data related to East-West line of AALRT

Passenger station	%G	Interstation spacing	Value of D' [km]
Ayat	0.014	Ayat-Meri	2.2
Meri	0.016	Meri-CMC	0.921
CMC	0.0016	CMC-St. Michael	0.678
St. Michael	0.0167	St. Michael-CS. College	0.674
Civil Service College	0.00799	CS. College - Mgt.Institute	0.553
Management Institute	-0.011	Mgt.Institute-Gurdashola1	0.8
Gurdashola1	0.0137	Gurdashola1-Gurdashola2	0.884
Gurdashola2	0.00221	Gurdashola2-Meganagna	0.686
Meganagna	-0.0166	Meganagna-Lem Hotel	0.628
Lem Hotel	-0.00624	Lem Hotel-Hayahullet1	0.611
Hayahullet1	-0.856	Hayahullet1-Hayahullet2	0.514
Hayahullet2	-2.86	Hayahullet2-St.Urael	0.782
St.Urael	-0.0172	St.Urael-Bambis Hotel	0.528
Bambis hotel	0.0148	Bambis Hotel-Estephanos	0.779
Estephanos	0.0027	Estephanos-Stadium	0.436
Stadium	4.8	Stadium-Leghar	0.2414
Leghar	3.31	Leghar-Mexico Square	0.493
Mexico square	-2.776	Mexico Square-Tegbared	0.465
Tegbared	0.00178	Tegbared-Lideta	0.597
Lideta	3.92	Lideta-Cocacola	0.5578
Coca Cola	0.0173	Cocacola-Torhailoch	0.55

Table 0-4 Vehicle Specifications of the AA-LRT

No.	Parameter	Value
1	Train car weight	44tone
2	Vehicle Car weight with full passenger 6persons/m^2	59.24tone
3	(With 8 persons/m^2)	(63.02tone)
4	Vehicle length (single vehicle)	29.7m
5	Car body width	2.65m
6	Maximum operation speed	70km/hr
7	Operation base speed	40km/hr
8	Acceleration under rated load (from 0-40km/hr)	1m/s^2
9	Acceleration under rated load (from 0-70km/hr)	0.5m/s^2
10	Average service brake deceleration:	1.1 m/s^2
11	Emergency brake deceleration:	2m/s2
12	Longitudinal vehicle jerk rate:	1.0 m/s3
13	Rated voltage supply	DC 750V
14	Voltage range	DC 500 – 900V
15	Rated power of traction motor	130kW (2×130Kw
16	Range of input voltage of control circuit:	DC 16.8→ 30V
17	Rated voltage of traction motor	AC 500V (3 phase)
18	Rated Current of traction motor	AC 210A
19	Rated working current of pantograph	1050A
20	Rated working voltage range of Pantograph	DC 500-1000V

APPENDIX B: BATTERY RATINGS AND CHARACTERISTICS

1. CAPACITY

The battery capacity is a measure of how much energy the battery can store. Batteries do not simply serve as a bucket into which one dumps electricity and later extracts it. The amount of energy that can be extracted from a fully charged battery, for instance, depends on the temperature, rate of discharge, battery age, and battery type. Consequently it is difficult to specify a battery's capacity using a single number. There are primarily three ratings that are used to specify the capacity of a battery:

i. **Ampere-hour:** The Ampere-hour (Ah) denotes the current at which a battery can discharge at a constant rate over a specified length of time. For SLI (starting-lighting-ignition) batteries that are commonly used in cars, the standard is to specify Ampere-hours for a 20 hours discharge. This standard is denoted by the nomenclature of C/20. A 60Ah C/20 battery will produce 60Ah for a 20 hour discharge. This means that the new and fully charged battery will produce 3Amps for 20hours - it doesn’t mean that the battery can produce 6 Amps for 10 hours (that would be signified by a C/10 60 Ah rating).

ii. **Reserve Capacity:** The reserve capacity denotes the length of time, in minutes, that a battery can produce a specified level of discharge. A value of 35 minutes at 25Amps for the reserve capacity for a battery means that the fully charged battery can produce 25Amps for 35 minutes.

iii. **kWh Capacity:** The kWh capacity metric is a measure of the energy (Volt * Amps * Time) required to fully charge a depleted battery. A depleted battery is usually not a fully discharged battery; a 12V car battery is considered depleted when its voltage drops to 10.5V. Similarly, a 6V battery is usually considered depleted when its voltage drops to 5.25V. None of these capacity ratings completely describe the capacity of a battery. Each one is a measure of the capacity under specific conditions. The performance of a battery in an actual application may vary substantially due to different discharge/recharge rates, battery age, cycle history, and/or temperature.

2. VOLTAGE

By definition a battery consists of two or more cells wired together. A lead-acid type cell produces approximately 2.1V. A three cell lead-acid battery thus produces 6.3V (6.3 = 2.1 * 3) and a six cell lead-acid battery produces 12.6V. For a battery with fill caps, the number of cells can be determined by counting the number of fill caps. The voltage rating is that of a fully charged battery; its voltage will decrease as the battery is discharged.

3. CYCLE DEPTH

Fully discharging a battery often destroys the battery or, at a minimum, dramatically shortens its life. Deep-cycle lead-acid batteries can be routinely discharged down to 15-20% of their capacity this represents a depth of discharge (DOD) of 85 to 80%. These deep-cycle batteries are constructed with thick plates for the cathodes and anodes in order to resist warping whereas in conventional lead-acid batteries the plates are paper-thin. Regardless of whether or not the battery is deep-cycle or not, deep discharges shorten the life of a battery. A deep-cycle battery that can last 300 discharge-recharge cycles of 80% DOD (depth of discharge) may last 600 cycles at 50% DOD.

4. WEIGHT/VOLUME

The designer must consider the weight and volume of the battery pack during the vehicle design process. Different battery types will provide the designer with different energy and power capacities per given weight or volume. The key ratings to consider are the Specific Power/Energy and the Power/Energy densities. These ratings reveal how much power or energy the battery will provide per given weight or volume.

5. ENERGY DENSITY/SPECIFIC ENERGY

Energy density is a measure of how much energy can be extracted from a battery per unit of battery weight or volume. By default, deep-cycle batteries provide the potential for higher energy densities than non-deep cycle varieties since more of the energy in the battery can be extracted (e.g. larger acceptable DOD).

6. POWER DENSITY/SPECIFIC POWER

Power density is a measure of how much power can be extracted from a battery per unit of battery weight or volume. Using the analogy of a car's fuel system, the energy density is analogous to the size of the fuel tank and the power density is analogous to the octane of the fuel.

7. OPERATING TEMPERATURE

Batteries work best within a limited temperature range. Most wet-cell lead-acid batteries perform best around 85 to 95F. At temperatures above 125F, lead-acid batteries will be damaged and, consequently, their life shortened. Performance of lead-acid batteries suffers at temperatures below 72F; the colder it is the greater the degradation in performance. As the temperature falls below freezing (32F), lead-acid batteries become sluggish, the battery has not lost its energy; its chemistry restrains it from delivering the energy. Batteries can also freeze. A fully charged lead-acid battery can survive 40 to 50 degrees below freezing, but a battery with a low state of charge (SOC) can freeze at temperatures as high as 30F. When the water in a battery freezes it expands and can cause irreparable damage to the cells.

8. SULPHATION

A low state of charge (SOC) in a lead acid battery can lead to sulphation that can seriously damage the battery. In a low SOC state, lead crystals that are formed during discharge can become so large that they resist being dissolved during the recharge process. This prevents the battery from being recharged. Sulphation can occur when the battery is left at a low SOC for a long period of time.

9. SELF-DISCHARGE

A battery that is left alone will eventually discharge itself. This is particularly true of secondary (rechargeable) batteries as opposed to primary (non-rechargeable) batteries.

APPENDIX C: MATLAB FUNCTION FOR SPEED PROFILE GENERATION

```
function Speed = fcn(T,D)
%#codegen
a= 0.9;% acceleration
b= -1;% deceleration
Vm= 19.4; % maximum speed
Vt= 0; %initial speed
T1= (Vm-0)/a;
T3=(0-Vm)/b;
T2= (D/Vm)-0.5*(T1+T3);
if T<T1
    Vt= a*T;
elseif T<(T1+T2)
    Vt=Vm;
elseif T<(T1+T2+T3)
    Vt= b*T-b*(T1+T2+T3);
end
Speed = Vt;
```