



Addis Ababa University
Addis Ababa Institute of Technology

Onboard Energy Storage System in Addis Ababa Light Railway Transit for Energy Efficiency Improvement

A Thesis Submitted to
The school of Electrical and Computer Engineering

By Girmay Abadi

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This is to certify that the thesis prepared by Girmay Abadi, entitled: onboard energy storage system for Addis Ababa Light Railway Transit in Energy Efficiency Improvement, submitted in partial fulfillment of the requirements for the degree of Master of sciences in Railway Electrical Engineering complies with the regulations of the university and meets the accepted standards in respect to originality and quality.

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Declaration

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Abstract

Using onboard Energy storage system for Addis Ababa Light Rail Transit is the main objective of the thesis. In this thesis for analysis of the efficiency of using onboard energy storage system in AALRT, North to South line is used for modeling and simulation. Mathematical modeling of the traction force, Power, and energy consumption has been developed and energy consumption and regenerative energy have calculated for the lines from station to stations in the line. For round trip of Menelik II square station to Kality station the generated brake regenerative energy is 30.01 kWh. This energy is 12.4% of the total energy consumption of the traction for the round trip of Menelik II square to Kality stations.

Hybrid energy storage system is selected for onboard energy storage system. The HESS design has been formulated, with energy capacity of 79.78 kWh and mass 2460Kg. HESS/Hybrid Energy Storage System is used for improving efficiency of energy and power. Super-capacitor is used for power efficiency and efficient brake regenerative recapturing, and Li-ion battery for energy saving efficiency.

From the simulation of onboard energy storage system, the hybrid of Super-capacitor and Li-ion battery with capacity of 79.78kWh is used as per the design. To supply traction energy of 11.28kWh the state of charge of the battery is discharged up to 99.9%, whereas the SoC of the SC is discharged to 94% and recharged to 99% by the brake regenerative energy. In the simulation the ESS supply power during acceleration up to 640kW.

Based on the research result, it is concluded onboard energy storage system is an effective solution for recapturing the brake regenerated energy. The regenerated energy is 12.4% of the traction consumption energy which is used to increase the energy efficiency. By using the regenerated energy saved in ESS to supply energy for traction during power shortage and also for accelerating and up gradient traction. The ESS supply energy for the traction during grid electric energy supply outage and to minimize energy consumption of the traction.

Key Words: onboard Energy Storage system, Regenerative energy, Hybrid Energy Storage, Energy Consumption, Super-capacitor, Li-ion battery

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Abbreviations

a	acceleration
AALRT	Addis Ababa Light Rail Transit
AC	Alternative Current
C	capacitance
C_{eq}	Equivalent Capacitance
DC	Direct Current
E	Energy
EDLC	Electronic Double Layer Capacitor
E_{max}	maximum energy
ERC	Ethiopian Railway Corporation
ESS	Energy Storage system
F_b	Force of braking
F_t	Force of traction
HESS	Hybrid Energy Storage System
LRT	Light Rail Transit
P	power
R	Resistance
R_{eq}	Equivalent Resistance
SC	Super Capacitor
V	Voltage
v	speed
β	deceleration
η	efficiency

Chapter One

1. Introduction

1.1 Background and Motivation

Electrified railway system (ERS) is used widely around the world as a significant means of freight and public transportation. It is expanding at great speed throughout the world. Like many other countries, Ethiopia also has started to use Light Railway transit /LRT for passenger transportation in Addis Ababa city transportation system. The transportation line is an intercity covering two lines from South to North from Kality to Menelik II and East to West from Ayat to Torhayloch with total of 34.2km length coverage and cross-over of 2.6 km.

Addis Ababa Light Railway Transit/AALRT is working with overhead contact power supply system of DC 750V with 17 power substations on both lines North-South and East-West.

The first application for onboard energy storage batteries came with the commercialization of series hybrid drive systems that reduced the fuel consumption of diesel trains on non-electrified railway lines. While collecting field data, Hitachi has also developed an efficient regeneration system to improve energy efficiency on trains, and has verified its effectiveness through operational trials [1].

Modern railway vehicles operating at DC voltage supply are principally able to regenerate the braking energy into the network [1]. The kinetic energy of the braking vehicle is transformed by the traction motors into electrical energy and transferred via the traction inverter to the DC link of the converter [1]. The energy returns to the transmission network and can be used by other vehicles in the network, as far as they are nearby the braking vehicle and has demand of energy.

One of the ways for absorbing regenerative energy is to use optimal timetable scheduling of train movement, as one breaks the next train be on place that can absorb the generated energy and be on acceleration. Since this scheduling is inefficient for urban city passenger railway, Using Energy Storage System is an efficient means of absorbing brake regenerative energy for passenger rail. Regenerative energy is stored in the energy storage and reused later as needed. Therefore, energy storage system is a promising tool to prevent regenerative energy failure for rolling stock [2].

AALRT vehicles have the feature of brake regeneration system which is designed to be preferably absorbed by adjacent vehicle along the line. When energy absorption by adjacent vehicle along the line is not possible, such energy will be absorbed by brake resistor, mounted at the top roof of the vehicle/train [3].

Kibrom Tadelles [4], in his thesis for Analysis of Regenerative Braking System in the Reduction of Energy Consumption in AALRT has obtained that, the brake regenerative energy generated in a single trip traveling from Ayat to Torhayloch is about 48306.54KJ energy which is 3.7% of the consumed energy of the traction. Most of the time this energy is absorbed by the brake resistor.

If brake regenerative energy is not managed properly, does not only incur energy wastage but also likely to cause unexpected shift from electrical regenerative braking to mechanical braking [5]. This sudden change of electrical braking to mechanical braking may further cause for passenger ride discomfort and degradation of the brake shoe with abrasion. Therefore, the brake regenerative energy should be absorbed and stored in the energy storage during braking and reused in the next acceleration or in demand of energy [6, 7].

Energy storage technologies have made significant strides in helping to alleviate the major issue of energy in the railway domain. It helps to stabilize and balance overall peak power demand of the railway system, supplying the rail to make effective operation [8]. During grid energy supply failure, the storage system is used to supply energy to the vehicle, which helps from stopping at middle of the track and improves passenger inconvenience.

Energy storage devices used to achieve the following three goals during regenerative braking:

- Manage over-voltage at the traction motor without significant increase in pantograph voltage;
- Reduce over-current for the pantograph to the feeding system;
- Improve the usage rate of regenerative power.

This thesis aims to study the usage of onboard energy storage systems in the Addis Ababa Light Railway Transit. Using appropriate energy storage system would help to utilize the regenerative energy for improving energy and power efficiency of electric traction. The stored energy is used for: Reduction of energy consumption by reducing the peak power taken from the line, stabilizing of the line voltage, autonomous operation (i.e. operation in catenary free sections) during power

interruption and improves the safety of the systems operation. The study is going to focus on modeling and simulation of onboard energy storage system for the improvement of the energy/power efficiency of AALRT.

1.2 Statement of the problem

The electric power supply system of AALRT is DC 750V through overhead contact line catenary to the train pantograph. Modern railway vehicles operating at DC voltage supply are principally able to regenerate the braking energy into the network. If this energy is not managed with effective train timetable or storage system, it leads to overheating.

In the case of AALRT the vehicles have the feature of brake regenerative system, designed the brake regenerative system to be utilized with effective timetable scheduling else to be absorbed by absorbing resistor found at top floor of the vehicle. From Kibrom's [4] analysis of the regenerative energy of AALRT, 3.7% of the consumed energy is regenerated back to grid. But timetable scheduling is not practiced effectively. So due to this ineffective system it leads to overheating and abrasion which decrease the life of the locomotive equipment.

There is also effective power supply system problem, the power supply system has brake out every time as it can be said daily.

Energy storage system is the essential device for effective utilization of regenerative energy. Energy Storage System collects the regenerate energy during the braking time and reuses the energy for acceleration and for autonomous running of train during the power supply outage. Especially for running of train during power outage without overhead contact line supply is possible using onboard ESS. Thus, this research is going to recommend using onboard energy storage system, which is important for the efficient utilization of the regenerated energy to be utilized when needed for accelerating as well as during supply energy gap at least to reach the next station.

1.3 Objectives

1.3.1 General Objective

The main objective of this thesis is to study the use of onboard energy storage system in Addis Ababa LRT traction system.

1.3.2 Specific Objective

The specific objective of this thesis includes:

- To analyze the system and power efficiency problems of the existing system
- To identify appropriate type of energy storage system
- To model energy storage system
- To simulate the model with MATLAB/SIMULINK and discuss results of simulation
- To identify benefits of using ESS
- Draw Conclusion and recommendation which can be used for implementing the system in AALRT.

1.4 Methodology

The overall procedure of the research work includes.

- Data collection of existing AALRT power supply system: Collecting existing system locomotive and power supply system specifications and related data from ERC office.
- Reviewing literatures: Literature review from the existing data of AALRT and information obtained from internet and different research reviews worked on energy storage system, and selecting the appropriate type of energy storage system for the onboard.
- Model the on-board Energy Storage System.
- Simulate the system using MATLAB/SIMULINK software

1.5 Scope

The thesis covers only the railway line of Addis Ababa LRT project. The thesis focuses on modeling and simulation of onboard Energy Storage system using MAT LAB software for the line of Menelik II to Kality traction line.

1.6 Outline of the Thesis

The thesis is organized into five chapters the contents are briefly described as follows:

The first chapter presents the Introduction and motivation of the research project. This chapter gives introduction of the thesis with motivation, statement of the problem, methodology used in this thesis; the objectives and scope of the thesis work are elaborated.

Chapter two presents theoretical background and Literature review of brake regenerative, Energy storage technology are discussed and review. Energy storage technology types and application have been reviewed and AALRT system specification has been discussed. Literatures related to onboard energy storage system and brake regenerative energy system has been reviewed.

Chapter three describes the modeling part of AALRT track lines traction energy with energy storage technologies.

Chapter Four is presenting the model simulation and result obtained from the simulation.

Chapter Five presents on the conclusion and recommendation of the research work and indicates the future work.

Chapter 2

2. Theoretical Background and Literature Review

Van Mierlo J, Maggetto G, et al., on the study of environmental impact rating of vehicles, stated to reduce emissions of environmental pollution electric powered vehicles are in use in many cities. Although these mass transit vehicles enable large reductions in terms of emissions, their energy efficiency could be significantly improved. This improvement can be reached by the hybridization of their power system, with the inclusion of an energy storage system (ESS) for energy recovery purposes [9], [10].

Today's electric rail transit systems have a peculiar characteristic that the railway vehicles need huge electric power on acceleration and this can be possibly supplied from regenerative power on braking. The regenerative braking systems are becoming the norm in modern trains. The power generated from braking vehicles is fed back into the power supply and distribution network for use by other vehicles drawing power at the same time. If other vehicles are not available to use this regenerated power, the voltage on the distribution network rises to the point where the braking vehicles must terminate regeneration to the network. In these cases, the braking train will dissipate the kinetic energy as heat either through on-board brake resistors or through wayside resistors. In either case, the energy is lost [11].

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. In fact, nowadays, ESS able to guarantee higher values of specific energy, higher values of specific power, longer life cycles, reduced environmental impact and costs, and better dynamic performances. For effective recovering electrical energy during trains' braking, electrical storage devices should be placed onboard of trains, because energy travels along the shortest path from the traction drive to the storage devices, improving the recovery efficiency. It is easy to show that in such a case, the energy capacity of the storage device is much bigger than that necessary for supporting line voltage [12].

For the better energy efficiency of railway vehicles, there is also the possibility to equip the vehicles with an energy storage system, such as rechargeable batteries, electric double layer

capacitors (EDLC), fuel cells or flywheels. Onboard energy storage system can provide up to 30% energy saving effects by restoring regenerative energy during braking and preventing regeneration cancellation problem of conventional railway vehicles. In addition, rapid development of the onboard energy storage system enables catenary-free operation of emerging railway vehicles. Therefore, many railway industries have recently developed energy efficient LRVs with onboard energy storage system [13].

As mentioned before, since the energy storage systems are good for improving energy efficiency in the electric railway systems due to frequent repetition of acceleration and braking of vehicles, there are a number of researches about ESSs' application [14]. Especially, most of research suggests the on-board type storage which installs ESSs in each railway vehicle [15]. In the aspect of loss, it can be expected that the on-board type storage has best performance since this type can eliminate the thermal loss generated when the regenerative current flows between vehicle and substation [16, 17]. However, when considering the cost of storage and energy conversion system and the maintenance cost of a number of ESSs, substation-installed ESSs are more economic [16,17].

The first application for onboard storage batteries came with the commercialization of series hybrid drive systems that reduced the fuel consumption of diesel trains on non-electrified railway lines. While collecting field data, Hitachi has also developed an efficient regeneration system to improve energy efficiency on trains, and has verified its effectiveness through operational trials [18].

Furthermore, the nature of city driving, where low speeds, frequent acceleration and sudden braking occur, implies that the public transportation sector is an ideal candidate to benefit from regenerative energy saving which needs an enhanced ESS. Super-capacitors ESS form an ideal option for this purpose. They can accept high power peaks from regenerative braking, have a long lifetime, need no maintenance and work at a wide temperature range without suffering from a major negative effect on their lifetime [19].

In case to recover the braking energy, an onboard energy storage unit allows absorption of this energy for re-use. Therefore, the energy consumption and the emission of “Greenhouse gases”, e.g. CO₂, can be reduced significantly. Also for without contact line operation mode is possible and realized by an onboard energy storage unit. The hybrid concept of energy storage units the

combination of EDLC energy storage unit for high power and the traction battery to ensure the high energy content allows to expand the distances for the operation without OCL than it would be possible only with EDLC energy storage units. Consequently, increasingly arising requirement of customers due to aesthetical, environmental or operational reasons can be satisfied by the technology of onboard energy storage units [20].

The traction system with energy storage system leads to an energy saving of up to 30% compared to a modern regenerative light rail vehicle [21]. In addition, the vehicles peak power demand from the line is drastically reduced, up to 50% reduction potential [21]. This results in a reduced line voltage drop as well, which can be used for additional benefits on the infrastructure. A further benefit could be the autonomous operation. Also without power supply or even without catenary a certain distance operation can be maintained, which leads to further system advantages. The consideration of all features of the new vehicle with on-board energy storage should lead to an out most attractive system which is also promising concerning economics.

2.1 Energy Storage Technology

Energy Storage Systems (ESS) are tools of great interest, as they can play a vital role in improving the flexibility and efficiency of energy systems and the reliability of energy sources. Energy can neither be created nor destroyed but can be saved. Energy can be transformed from one form to another. Energy storage is a device/system technology that saves the energy and make ready to be used when it is needed. Electrical energy in a power system cannot be stored electrically, rather it can be stored by converting itself as primary source and then storing it electromagnetically, electrochemically, kinetically, or as potential energy and when required to use change again to electric energy [22]. There are several technologies employed in the energy storage system industry; However, the thesis focuses only to the systems that are suitable for the railway system: Chemical Battery, Super Capacitors, Superconducting Magnetic Energy Storage (SMES), and Flywheel. Each will be introduced and explained in this chapter. Energy storages technologies have distinctive characteristics of storage such as: specific energy, specific power densities, useful cycle life, storage capacity, and efficiency are some of these.

2.1.1 Characteristics of Storage Technologies

There are several parameters used to define and describe the characteristics of energy storages. The most relevant parameters that define storage devices are: storage capacity, discharging time, efficiency, durability /Life Cycle, State of charge.

- **Storage capacity:** the amount of energy stored for unit of mass (unit of volume). Defined as the amount of energy available in the storage device after completing the charging cycle. The unit of the storage capacity is the same as for energy kWh. The storage capacity is defined based on the total energy stored, which is higher than the useful energy at a point of operation [22].
- **Energy density/Specific Energy** is the amount of energy stored in a given system per unit volume or mass. This can be measured in watt-hours per kilogram (Wh.kg^{-1}) or kilowatt hours per cubic meter (kWh.m^{-3}). Energy density is a measure of how much energy the technology can store [22, 23].
- **Power density/Specific Power:** is the amount of power (time rate of energy transfer) per unit of mass [23], (unit of volume) [24]. Power density can be measured in watts per kilogram (W.kg^{-1}) or kilowatts per cubic meter (kW.m^{-3}) [22 - 24]. The power density is then a measure of the peak power a technology can deliver.
- **Efficiency (η)** is the ratio between the energy supplied by the storage and the energy required to return the storage to the state of charge [22]. In storage applications refers to the ratio of energy required to store the energy (input) to the use of the energy (output). When this ratio is imbalance or skewed, it results in energy being wasted; hence, the process has low energy efficiency.
- **Operating temperature:** refers to the temperature range a storage technology needs to be kept within for safe or reliable operation, and is particularly relevant for certain storage technologies. The operation of storage technologies outside its preferred temperature range can significantly affect performance and lifetime, and increase the risk of explosion [24].
- **Response time:** is the time taken for the technology to reach its maximum power output over a given time; i.e. the time to go from dormant status to peak operating mode. The response time can range from milliseconds (ms) to minutes (min) to hours (h) [24].

- **Discharge time:** is the time for discharging of the total energy stored as per the maximum power required by the load [22].
- **Cycle life:** is given by the number of times /the number of cycles/ of charging and discharging of the storage device [22, 24]. The lifetime of a battery is often denoted by the total number of cycles that a storage device can deliver [24].
- **Deep-charge cycle:** the process of fully charging and discharging storage. The term is typically used to specify the expected life of storage; that the number of completed deep-charge/discharge cycles the storage can support before its capacity falls below 80% of its original capacity [24].
- **Depth of Discharge (DOD)** is the amount of discharged energy compared to the total storage capacity [22, 23]. A Storage that is 100% charged has a DoD of 0%. If storage is delivered 30% of its available energy, and hence has 70% of its energy reserved, then its DoD is 30%. When a storage is empty, its DoD is 100% [22 - 24].
- **State of Charge (SOC)** is the amount of energy remaining in the system as a percentage of usable storage capacity. The maximum SOC is 100 % corresponding to a fully charged system [22-23].

In addition to the functional requirements, safety and cost also play a key role in the choice of the most suitable storage system for a given application [22, 23].

2.1.2 Types of Energy Storage

Energy storage systems can be categorized according to the characteristic of storing the energy as mechanical, chemical, electrochemical, electrical, electromagnetic.... In this section the common and popular types of energy storage systems and applicable for railway system, with their characteristics and technical details are explained as follows.

2.1.3.1 Flywheel

In flywheel energy storage rotational energy is stored in an accelerated rotor, from a massive rotating cylinder. The main components of a flywheel are the rotating body/cylinder (comprised of a rim attached to a shaft) in a compartment, the bearings and the transmission device (motor/

generator mounted onto the stator) as seen in figure 2.3 [23]. The energy is maintained in the flywheel by keeping the rotating body at a constant speed. An increase in the speed results in a higher amount of energy storage [22]. To accelerate the flywheel, electricity is supplied by a transmission device. If the flywheel's rotational speed is reduced, electricity may be extracted from the system by the same transmission device [22, 23].

During the charging process a motor is used to accelerate a big rotating mass (flywheel). The energy is stored as the rotational kinetic energy of the flywheel [22]. The disc has to remain spinning until energy is requested. By using vacuum and magnetic bearings the rotation resistance is kept as small as possible. During discharging the kinetic energy is extracted by a generator driven by the inertia of the flywheel resulting in a deceleration of the rotating mass.

Flywheels store electric power as kinetic energy, according to expression [22]:

$$E = \frac{1}{2}I \omega^2 \quad (2.1)$$

Where:

E: Energy

I: Momentum of Inertia for the flywheel

ω : Angular speed

The maximum stored energy is limited by the tensile strength of the flywheel material.

Besides, based on the material of the rotor, there are two types of flywheels [23]:

- 1) With advanced composite rotor, such as graphite or carbon-fiber. These materials provide high specific energy.
- 2) With steel rotor. This type of flywheel allows traditional designs (with large diameters, low speed and low power and energy densities) and new high-performance flywheels.

Flywheels have very high cycle life and power density, however only an average energy density and a very high self-discharge rate. Therefore, flywheels perform well for applications, which demand very high power for only a short time with a high number of charging-discharging cycles and only short storing periods (neither charging nor discharging) [22, 24]. They are used, for example, for grid stabilization purposes for trams and underground trains. They absorb energy

during the regenerative braking phases and feed power back during acceleration phases. They can also be used for stabilization purposes in weak grids. Due to their high self-discharge rate they are not able to supply applications with longer storage times [24].

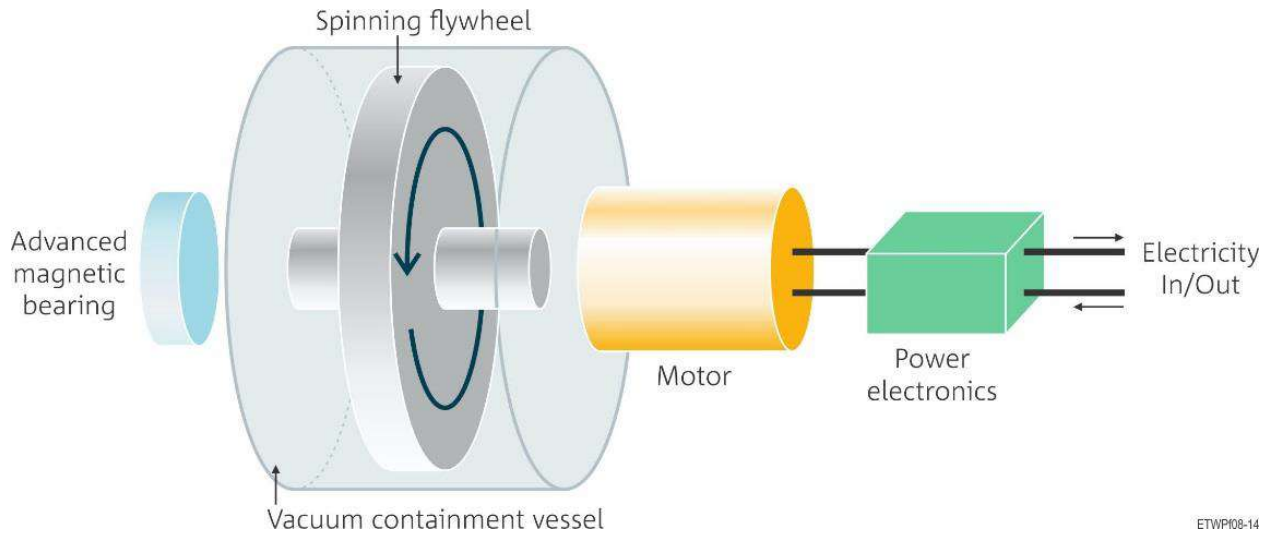


Figure 2-1 Schematic diagram of flywheel energy storage system [23]

2.1.3.2 Superconducting Magnetic Energy Storage (SMES)

Superconducting magnetic energy storage (SMES) systems work according to an electro-dynamic principle. The energy is stored in the magnetic field created by the flow of direct current in a superconducting coil, which is kept below its superconducting critical temperature. 100 years ago at the discovery of superconductivity a temperature of about 4 °K was needed [24]. Much research and some luck have now produced superconducting materials with higher critical temperatures. Today materials are available which can function at around 100 °K [23, 24].

The main component of this storage system is a coil made of superconducting material. Additional components include power conditioning equipment and a cryogenically cooled refrigeration system. The main advantage of SMES is the very quick response time [23]: the requested power is available almost instantaneously. Moreover, the system is characterized by its high overall round-trip efficiency (85 % - 90 %) and the very high-power output which can be provided for a short period of time [21, 22]. There are no moving parts in the main portion of SMES, but the overall reliability depends crucially on the refrigeration system. In principle the energy can be stored

indefinitely as long as the cooling system is operational, but longer storage times are limited by the energy demand of the refrigeration system [23, 24].

During the charging process the superconducting coil is fed with direct current from the inverter. The electric current induces a constant magnetic field in which the energy is stored [22].

$$E = \frac{1}{2} LI^2 \quad (2.2)$$

Where:

L: Inductance

I: Current

To be able to use the superconducting properties without losses of the coil inductance, it must be placed in liquid helium to guarantee temperatures below $-260^\circ\text{C}/130\text{K}$ [24]. The discharging process begins with connecting the coil to an external load by the switching system. The energy is then supplied by the magnetic field which drives a current. The magnetic energy and the current are decreased during discharging.

SMES systems are short-term storage systems for very short periods (power storage). They are only used in some demonstration and niche applications [22]. They have very high standby losses due to the cooling demand. Currently, SMES systems with high-temperature superconductors are under research with the aim of reducing the cooling demand. Due to the limited application areas SMES systems will hardly become competitive with other technologies [22, 24].

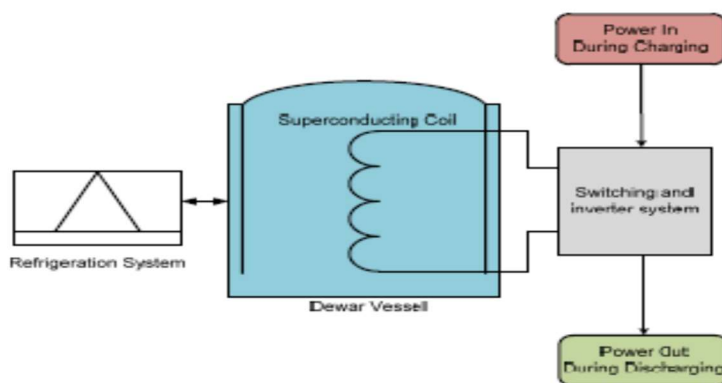


Figure 2-2 Schematic diagram of SMES storage system [25]

2.1.3.3 Battery/Chemical storage

Batteries are energy storage devices that convert stored chemical energy into electrical energy. The basic element of any battery is called a “cell”, and is typically constituted by two electrodes and the electrolyte; the chemical reaction between the electrodes and the electrolyte is responsible for the generation of electricity. Batteries use chemical compounds that can either liberate or accept electrons or ions within an electrochemical cell during a reaction. Depending on the type of battery, the electrolyte can consist of a liquid, gel or solid material. Batteries also contain insulating separators to prevent the electrodes from physical contact and potential short-circuiting. Depending on the chemistry of the battery, additional safety features, such as pressure relief valves may also be incorporated; the type of feature is specific to the device [23]. The choice of chemical compounds determines the nature of the battery device, the reaction, cell voltages and energy storage and power capability [21, 23]. The different types of battery technologies based on the differing chemistries are discussed below.

Lead-Acid Batteries: The best known and most widely used battery for traction systems is the lead acid battery. Although those batteries have a long history and their technology is quite mature, achievable performance does not quite match the requirements of an electric vehicle [22]. Specific energy is typically limited to about 30 Wh/kg, making it virtually impossible to achieve a driving range of few hundred kilometers for an EV that would use such a battery as main energy storage. Moreover, the cycle life of lead acid batteries is relatively poor, if deep discharge is required. On the other hand, cost is quite low, and no safety issues exist related to the use of those batteries for high power, traction applications [23]. As a matter of fact, virtually all modern designs tend to discard the use of lead acid.

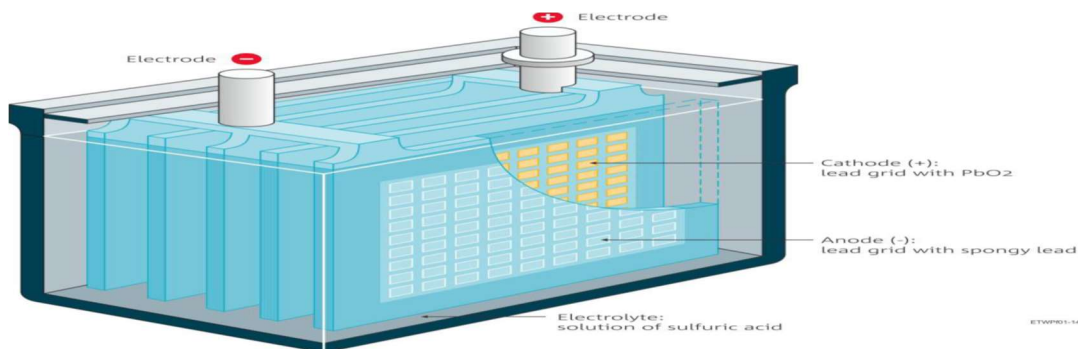


Figure 2-3 Schematic diagram of Lead Acid Battery [26]

Lithium-Ion Batteries: A lithium-ion cell contains a lithium-manganese-oxide alloy, as the cathode and the anode are carbon, typically bound within the host lattice to form the lithium-ion cell. The cell voltage is as high as 4.1V when open circuit (3.68V/cell -30% to +17.6% under load). The specific energy is around 125 Wh/kg and the energy density is more than 300 Wh/L. Life Cycle at 100% DOD is more than 1,000 and operating temperature range is -20 Co to +45 Co. The usable SOC of a lithium-ion battery is nearly four times that of lead-acid batteries [22, 25]. The lithium-ion battery can easily operate from 100% to 10% SOC before recharge. This makes it very suitable for hybrid vehicle applications. However, lithium-ion batteries, like NiMH, require an accurate charge/discharge management system, which can generally be achieved using microprocessor controllers. Also, lithium-ion batteries are larger than NiMH batteries; the lithium-ion battery is sensitive to over-charging or over-discharging with the potential of fire, for which only CO₂ extinguishers can be used [23, 25].

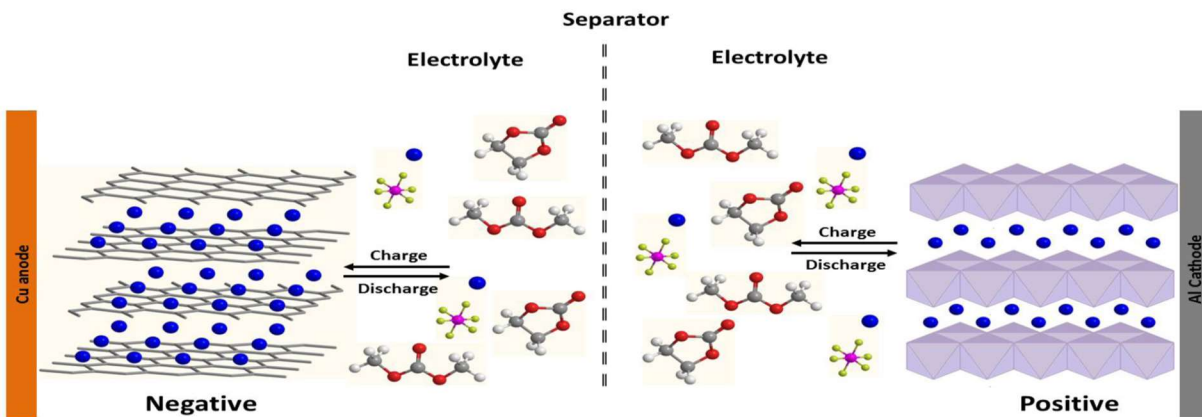


Figure 2-4 Li-ion Battery Schematic structure [26]

Other Types of Batteries: Extensive research and development is being carried out to develop new types of batteries, including research to improve the commercially available batteries such as lithium-ion. There are many new battery types under development, among these batteries are Sodium Sulphate (NaS) and zinc bromide (ZnBr₂) batteries which are being used in America as grid supply storage devices. These batteries have lower specific energy parameter than lithium-ion batteries but are much larger weight and size and are relatively cheap to manufacture. For railway

applications these batteries are not suitable for onboard storage, but could be used on the trackside as energy storage devices, in particular for smoothing out peak load demands [23, 25].

2.1.3.4 Super-Capacitors

Super-capacitors (SC) are also known in the literature as Ultra-capacitors or, more scientifically, Electrical Double Layer Capacitors (EDLC). As the latter name suggests, charge storage in these devices is based on the double layer effect, first described in by Helmholtz in 1861 [21]. Although the effect has been known for many years, and several refined models have been developed since then, its application to the development of devices with extremely high capacitance is relatively new [23].

Super capacitors (SC) are interesting to the automotive industry as energy storage device, since they have the basic characteristics: very high specific power (typically 10-100 times higher than traction batteries); perfectly reversible operation; their efficiency during charging is same as the efficiency during discharge, long lifetime and good cycling capabilities, meaning that they can be fully charged and discharged an extremely high number of times without significant degradation of their electrical characteristics [24].

Super-capacitors are uniquely able to combine the energy storage properties of batteries with the power discharge characteristics of capacitors. They can hold a very high charge which can be released in a controlled manner. By taking advantage of state-of-the-art technologies, the energy transfer becomes more reliable and efficient [25, 26].

The electrical energy in a super-capacitor is stored in the static electric field between the electrodes and the ions in the electrolyte. During charging and discharging the ions move from one electrode to the other. With respect to power density Super-Capacitors can be found between classical capacitors and batteries [24]. Super capacitors have very fast pulse response times, because only stored charge is removed or restored at the interface, rather than reactions occurring in the bulk electrode material [26]. This also results in super capacitors having a life cycle greater than that of electro-chemical cells, by orders of magnitude. Super capacitors are being designed and used to encounter millions of charging and discharging cycles throughout their useful life. The specific power of super capacitors is larger than 1,500 W/kg and the specific energy is approaching 6 Wh/kg. Both figures are continuously improving as the technology develops [23, 24].

Super-capacitors are used for voltage drop compensation in weak networks, allowing a very intense peak power [21].

Advantages are durability, high reliability, no maintenance, long lifetime and operation over a wide temperature range and in diverse environments (hot, cold and moist) [24]. The lifetime reaches one million cycles (or ten years of operation) without any degradation, except for the solvent used in the capacitors whose disadvantage is that it deteriorates in 5 or 6 years irrespective of the number of cycles [25]. The efficiency is typically more than 95% and charge/discharge times are in the range of seconds to hours [26]. Because of their properties, Super-capacitors are suited especially to applications with a large number of short charge/discharge cycles, where their high-performance characteristics can be used. Super-Capacitors are not suitable for the storage of energy over longer periods of time, because of their high self-discharge rate, their low energy density and high investment costs. SC is also ideally suited as a UPS to bridge short voltage failures [21, 22, 24].

The principal super-capacitor characteristic that makes it suitable for using in ESS, is the possibility of fast charge and discharge without loss of efficiency, for thousands of cycles [26]. This is because they store electrical energy directly. Super-capacitors can recharge in a very short time having a great facility to supply high and frequent power demand peaks [23].

2.1.3 ESS Implementation Methods for Brake Regenerative Energy Utilization

For utilizing the regenerative energy there are different methods of implementing energy storage systems. The main types are stationary or track side ESS and Mobile or onboard ESS.

2.1.3.1 Stationary /Track-side Energy Storage Systems

Track-side Energy Storage Systems are a popular for industrial transmissions and distribution power networks in most countries, chiefly in the United States of America [8]. Stationary storage (or track side application) is consisting of one or several ESS placed at the feeding substation or along the tracks. These devices recover the excess energy when no other vehicle is receptive. The principle is shown in Figure 2.5. Stationary energy storage is available for all vehicles running on the same line, and it reduces the peak power demand from main supply by balancing power to the loads over a period [27]. On the other hand, track side application has some assignable disadvantages as well which are solved with usage of onboard energy storage; Its capability

depends on the distance from the train, it cannot account for the losses due to transmission from the location of the storage to the train, it cannot recover all the braking energy some energy could still be lost in the braking resistors [8], it is impossible to have catenary-free run.

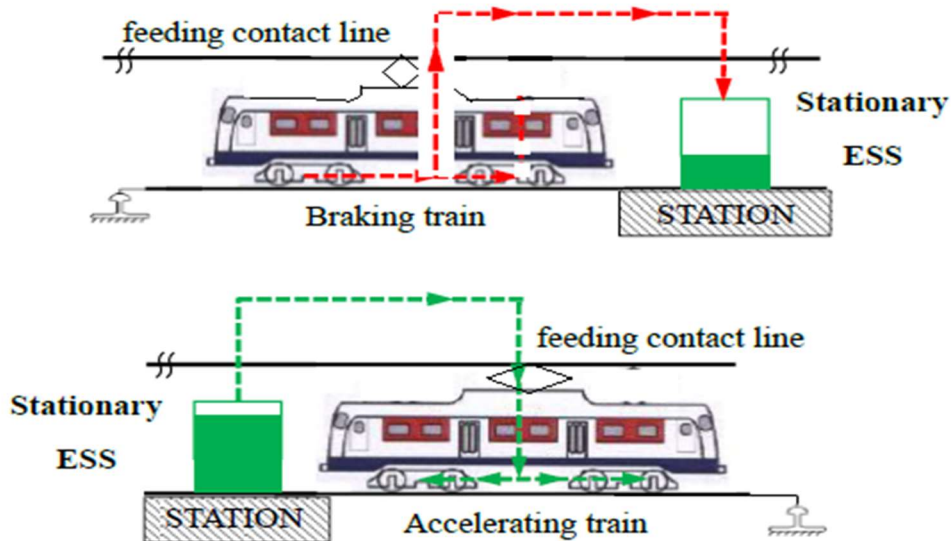


Figure 2-5 Schematic operation of Stationary Energy Storage System for LRT [25]

2.1.3.2 Onboard or Mobile Energy Storage System

The storage device is placed on the roof of the vehicle. The braking energy recovered absorbed directly to the storage energy system without loss in transmission. The energy is available anytime anywhere when the train requires; as the train requires power supply for accelerating, for complex situations such as there is a break in the supply or the train faces power imbalance [27]. On-board energy storage system is a promising tool to prevent regenerative energy failure for rolling stock. In addition to minimizing transmission line voltage drop wastage and protecting resistor heating and energy failure; on board energy storage system is the only option that could be considered for conductor rail gaps solution which is catenary free operation [28].

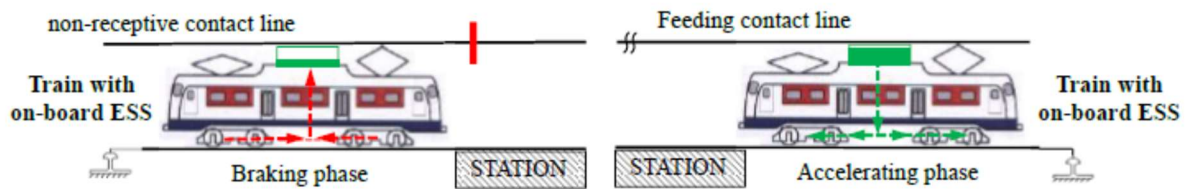


Figure 2-6 Schematic operation of onboard energy storage system [25]

Regenerative energy is stored during braking and reused in the next acceleration. This permits also the limitation of contact line voltage drop during accelerations, since the peak power is supplied by the storage device. With respect to the solution with wayside storage devices, the onboard storage simplifies significantly the energy management, because the control is independent of traffic conditions [29].

An autonomous or catenary free operation gets possible with placing the energy storage on board of the vehicle. The charged energy storage enables the vehicle to operate even during power failures of the infrastructure, at least for short time, can be bridged by the energy storage in case of a failed power supply or in catenary free areas [29].

At the present state of the art, the implementations of ESS in the public transportation sector coming from the rolling stocks suppliers and the operators, and the interest of researchers, is highlighted by the many papers in the relevant literature on stationary and on-board applications to urban railway networks. These mainly discuss their intrinsic capability to save regenerative energy with a consequent increase in the energy saving of the systems. Neither the power supply nor the rolling stock requires substantial modifications in the first solution, but the energy management must be extended at the network level, and lower efficiencies should be expected due to the energy travelling along the contact line. The on-board solution overcomes these inconveniences but requires a redesign of the carriages to accommodate the storage device.

2.2 Brake Regenerative System

Brake Regenerative system technology was first discovered by Toyota motors in 2004 [4]. When an electric train accelerates it takes power from the traction power supply system, this is controlled by the traction converter which applies a positive torque to the traction motor which accelerates the train. In electric brake the opposite occurs where the traction motor provides a negative torque to brake the train and the traction converter then exports the power resulting from the braking event. The use of an electric (dynamic) brake on a vehicle results in reduced usage of the friction brake which beneficially increases brake pad and disc life [26].

Electric braking, also commonly known as dynamic braking, is a braking technology makes it possible to limit the use of friction braking systems during normal operation, which, by their nature, involve considerable costs for maintenance and the replacement of parts subject to wear.

The use of an electric (dynamic) brake on a vehicle results in reduced usage of the friction brake which beneficially increases brake pad and disc life. On electric vehicles the exported energy can be either dissipated as heat or in some cases returned to the traction power supply and used beneficially elsewhere [4, 26]. The AC and DC electrified rail systems differ fundamentally with respect to their ability to accept the power produced from electric braking. On the AC power supply system, the exported power from a regenerating train can also be fed back to the National Grid at feeder stations for use by other loads and consumers. On DC regenerative braking the train can only export power a limited distance as it requires a voltage gradient between the regenerating train and other trains which act as a load [26].

The effective ability of a railway system to produce regenerative energy is mainly characterized with the relevant parameters. The amount of recovered energy depends on the service, electric network configuration, rolling stock type, line voltage, track profile, length of feed sections, and train auxiliary power consumption. The potential energy recovery strongly depends on the track profile (track gradients in particular) and frequency of stops [26].

The use of energy storage devices can become very useful in all means of transport, because they can be made capable either of improving efficiency by recovering braking energy and contributing to starting engines or of boosting contact lines voltages. The use has been in the past limited by the

weight of electrochemical batteries, by their unsuitable overloading capacities, and by their short lives [30].

A proper design of storage system allows one to use electrical storage systems for different practical applications. Researchers are now paying increased attention to different utilizations of these systems in urban and suburban railway traction systems [6, 7]. The uses of energy storage systems (ESS) have been conceived as the main tool to improve energy efficiency in railway systems. The installation of energy storage devices both on-board the vehicle and at the traction substation or along the track, makes the supply network system perform better by combining the requirements of energy saving and comfort. Storage technologies and control schemes for ESS are constantly being improved under the influence of hybrid and pure electrical vehicles, which is leading to new possibilities for the railway sector. 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. In fact, nowadays, ESS can guarantee higher values of specific energy, higher values of specific power, longer life cycles, reduced environmental impact and costs, and better dynamic performances.

The benefits, whatever the technological solutions adopted, are not only reductions in the total energy consumption, power peak, and demand, but voltage regulation, energy and power compensation, and the possibility for light railway vehicles to be independent of an external power supply. Some locations on the rail path cannot be electrified for aesthetic reasons, such as a city center, square, or tracks passing historical buildings, or where it is difficult to install overhead wires, such as on bridges, underground sections, and in tunnels, or in places where there is power reliability is somehow a problem and to safe infrastructures and passengers [25].

2.3 Over view of Addis Ababa Light Railway Transit

Addis Ababa light railway is one of the newly constructed railway transport sector. It has two routes, which are the East-West and North-South. This covers about 34.2km length for both lines with 2.662km in common/cross-over/ of both lines. The train used for Addis Ababa light railway transit (LRT) for both lines are 70% low floor light tramcar. It allows bidirectional drive and it has the capacity of 286 passengers with 64 seats and 6 passengers per m² standing and maximum capacity with 64 seats and 8 persons/m² standing which make a total of 317 passengers. The total weight of the tram car with load and car weight is (44t car and 19.02t passenger) 63.02 tones with full load and length of 29.7 meter and width of 2.65 meter. The Maximum operation speed of the tramcar is 70 km/hr [3]. The rated electric power supply at the pantograph is DC 750V and rated working current of 1050A with voltage range of DC 500V – 900V. Average startup acceleration under rated load capacity and rated supply voltage on straight and dry track is [3, 31]:

Greater or equals to 1m/s² for accelerating 0 - 40km/h and

Greater or equals to 0.5 m/s² for accelerating 0 - 70 km/h.

Average deceleration under rated load on straight and dry track from maximum vehicle operation speed of 70 km/h until stop is:

- Average service brake deceleration: $\geq 1.1 \text{ m/s}^2$
- Emergency brake deceleration: $\geq 2.0 \text{ m/s}^2$
- Longitudinal vehicle jerk rate: $\leq 1.0 \text{ m/s}^3$

A Train has two inverters equipped with two motor bogies, each traction inverter shall be able to power the two traction motors on one bogie. In one train car there are 4 motors used for bidirectional operation. Traction motors are self-ventilated 3-phase asynchronous traction motors with rating of 130 kW and three phase AC 500V with frequency of 71Hz [32]. Traction inverter mainly consists of line contactor, IGBT inverter and chopper power unit, logic control unit and filter capacitor. The role of the inverter is to convert DC voltage into 3-phase AC voltage with variable voltage and variable frequency, which will drive the traction motor to put vehicles into operation (motoring), and also convert the 3-phase AC voltage of traction Asynchronous motors brake regenerated energy into DC voltage for brake regenerative [3, 32].

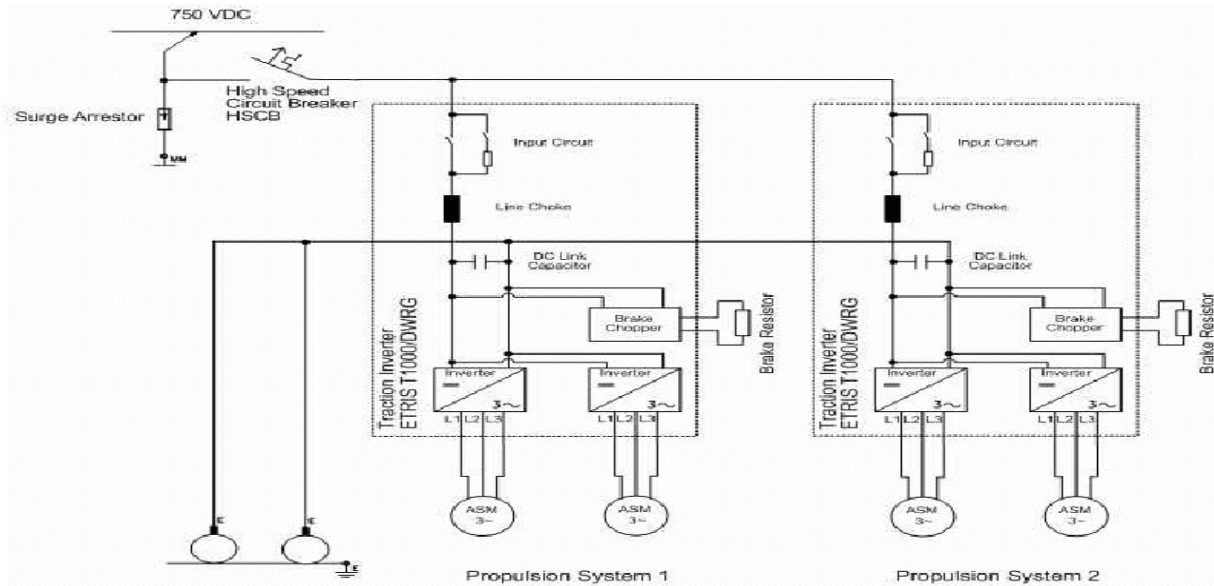


Figure 2-7 Main circuit diagram of the traction system [3]

Vehicles are provided with micro-computer based analog electro-hydraulic brake system to offer service brake (including function for electro-hydraulic blended brake), emergency brake, safety brake and parking brake which will be executed through electrical brake, hydraulic disc brake and magnet track brake.

Electrical brake includes regenerative brake and brake resistor. Brake resistor will be used to convert electrical energy into heat when regenerative brake is inoperative. It is mounted on the roof and cooled by natural ventilation.

Auxiliary power supply system includes auxiliary inverter control unit for output of logic control signal of auxiliary power supply system, to control the operations of auxiliary inverters and charger, to respond to all operation commands and to execute controlled operations of auxiliary power supply system based on special characteristics. Auxiliary inverter mainly consists of line contactor group, IGBT inverter power unit, 3-phase isolation transformer, logic control unit and filter capacitor. It functions to convert 750 VDC into 3-phase 380VAC (with N line for supplying 220 VAC) which will be supplied for auxiliary equipment of vehicles. Similarly, it will also convert 750 VDC into 24 VDC to be supplied as control power supply for vehicle control systems and all equipment [3, 32].

The train is equipped with battery (Ni-Cd battery) sized maximum output power of 8 kW with DC 24V and 330A to retain door control, emergency lighting, external lighting, train horn safety devices, auxiliary parts and communications in operation for duration of not less than 30 minutes in case of vehicle power supply failure.

2.4 Selection of Storage Technology for Onboard of LRT

The selection of the energy storage will be defined by requirements of onboard storage for light rail vehicle and in order to fully utilize the braking regenerative energy. The braking energy, power and braking time, corresponds directly to the requested energy capacity, power density and charging time of the ESS. Consequently, the power capability of the energy storage system, including the related power electronic converter, has to be increased, depending on the required charging/discharge power range.

The choice of the best ESS device for rail application heavily depends on the individual vehicle and service type. The following Table 2.1 shows the main characteristics to be looked in an individual rail application context and the corresponding ESS parameters.

Characteristics of rail application context	Corresponding parameter of energy storage device
Braking time	Charging time / power density
Braking energy	Energy density
Drive cycles in lifetime	Product life / reliability

Table 2-1 some relevant characteristics for matching railways and ESS requirements [25]

In order to compare and assess the suitability of the above discussed technologies for ESS in urban rail applications, one of the first criteria to be considered is energy and power performance. Energy and power density are definitely crucial parameters to be taken into account in the choice of storage technologies for railway applications, especially as far as the on-board ESS is concerned. The most important criteria are power rating, efficiency, respond time, power density, energy density and cycling capability. The technical parameters comparison of the storage technologies with the main parameters is summarized in the Table 2-2.

ESS technology	Energy and Power density			Typical Efficiency (%)	Respond time (s)	Self-discharge (daily % of rated capacity)	Life time (number of cycles)
	(Wh/kg)	(kW/kg)	(kWh/m ³)				
Lead-acid Batteries	20 - 50	0.025 - 0.3	50 - 80	70 - 90	1 - 3600	0.05 - 0.3	200 - 2000
NiCd Batteries	30 - 75	0.05 - 0.3	60 - 150	60 - 80	1 - 3600	0.2 - 0.6	1500 - 3000
NiMH Batteries	60 - 80	0.2 - 0.25	100 - 150	65 - 70	1 - 3600	1 - 2	1500 - 3000
Li-ion Batteries	75 - 200	0.1 - 0.35	150 - 500	90 - 95	1 - 3600	0.1 - 0.3	10 ³ - 10 ⁵
Li-poly Batteries	100 - 200	0.15 - 0.35	150 - 200	90 - 95	1 - 3600	0.15	600 - 1500
NaS Batteries	120 - 240	0.12 - 0.23	110 - 250	70 - 90	1 - 3600	20	2000 - 3000
ZEBRA Batteries	100 - 200	0.15 - 0.2	120 - 180	85 - 90	1 - 3600	15	>2500
Flywheel	5 - 100	1 - 5	20 - 80	90 - 95	0.1 - 60	100	<10 ⁷
EDLC	1 - 6	0.5 - 5	1 - 14	90 - 95	0.1 - 60	20 - 40	<10 ⁶
SMES	0.5 - 5	0.5 - 2	0.2 - 2.5	95 - 98	0.1 - 1	10 - 15	>10 ⁵

Table 2-2 Technical parameters of storage technologies

Superconducting magnetic energy storage (SMES) systems work according to an electro-dynamic principle. They are only used in some demonstration and niche applications. They have very high standby losses due to the cooling demand. Currently, SMES systems with high-temperature superconductors are under research with the aim of reducing the cooling demand. Due to the limited application areas SMES systems will hardly become competitive with other technologies. SMES systems are not applicable energy storage system for railway systems, and it is still under research to use.

The biggest disadvantage of a battery is given by the very limited number of load cycles. Typical lifetimes of lead acid batteries are below a few thousand full load cycles. Batteries typically Lithium ion work only about 10⁵ cycles. In addition the power density is lower than super capacitor, but higher energy density than super capacitor. Batteries have low respond time, this is difficult to work effectively for recovering regenerative energy and to use as onboard energy storage, since it needs fast respond power stabilizing and peak power adjustment, and the charging should be made as the brake is applied. From the paper [36], has done practical experiments to absorb the regenerated energy with Li-ion battery and super-capacitor ESS, it is obtained 97% of regenerated energy can be absorbed with Super-capacitors, whereas with battery only 57% of the regenerative energy can be absorbed. But Li-ion has more energy storage capacity than Super-capacitor with specific volume and weight.

Available flywheels fitting to the required energy content have unfavorable dimensions. The maximum installment height of a low floor tram will be exceeded. In addition there would be at least severe discussions regarding safety of flywheel energy storage on board of a moving vehicle, where the flywheel is installed very close to passengers. The flexibility of a flywheel system is also seen as quite limited, e.g. the motor, typically a permanent magnet motor, is not flexible regarding voltage and power adaptations. In addition, the low leakage inductance of the typically high speed permanent magnet motors results in higher demands on the feeding converter. The flywheel was rejected mainly due to the limitation in dimensions and safety aspects on board of a moving vehicle.

The Super-capacitor (SC) was specially developed for a very high power density compared to other capacitors. The technical progress is enormous. The electrical behavior is between a battery and a dc-link capacitor. Energy and performance density are suited for the application “brake energy storage”. The SC is very flexible regarding dimensions of the energy storage and permits a simple adaptation to different voltages, power ranges and installed energy content, just by adapting the number of SC connected in series and in parallel. The storage principle is on a pure electrical basis and achieves quite high load cycling capability leading to low maintenance costs. But has low energy density which occupies more space and have high mass for onboard energy storage.

Now a day’s most of the energy storage manufacturers are producing a super-capacitor type of technology for storage of regenerative energy especially for Electric Vehicles. When we see the energy storage system produced by Bombardier (for onboard and stationary ESS), Hitachi (onboard ESS), MITRAC ESS and Toshiba (onboard ESS) producing for use in Electric railway system are using a super-capacitor technology due to its nature for efficient absorption of brake regenerative energy and this is due to fast respond charging and discharging technology, long cycle life and low maintenance.

On these aspects for the implementation of onboard energy storage system, working in utilizing braking energy, and to supply efficient power Super-capacitor is better than others but to store enough energy with limited area and mass to supply appropriate energy to traction battery is selected, from chemical batteries Li-ion is more reliable and feasible as to its energy density and responding and life cycle duration.

2.5 Power Converters

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

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

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

In order of use energy storage for railways, Bidirectional DC/DC converters are essential. Bidirectional DC/DC converters have both features of converting step-down and step-up. Railway voltage supply demands that a large number of storage cells are connected in series.

This leads to the possibility of unbalancing of the cells' voltages over time. Such unbalancing occurs when a number of cells are connected in series. Each individual cell in a battery has fairly different capacity and may be at different State of Charge, therefore causing the entire storage to have an unbalanced voltage [27].

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

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 [27].

The DC-DC converter is used in order to manage the energy flow between SC and the supply line; in particular it works as a buck converter when it charges SC and as a boost converter when discharges SC. In the latter case, the efficiency of the converter is acceptable if the maximum amplification voltage ratio is less than or equal to three [25]. For a line voltage of 750 V, the voltage of SC should be greater than 250 V (to be triple of the voltage).

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 gradable.

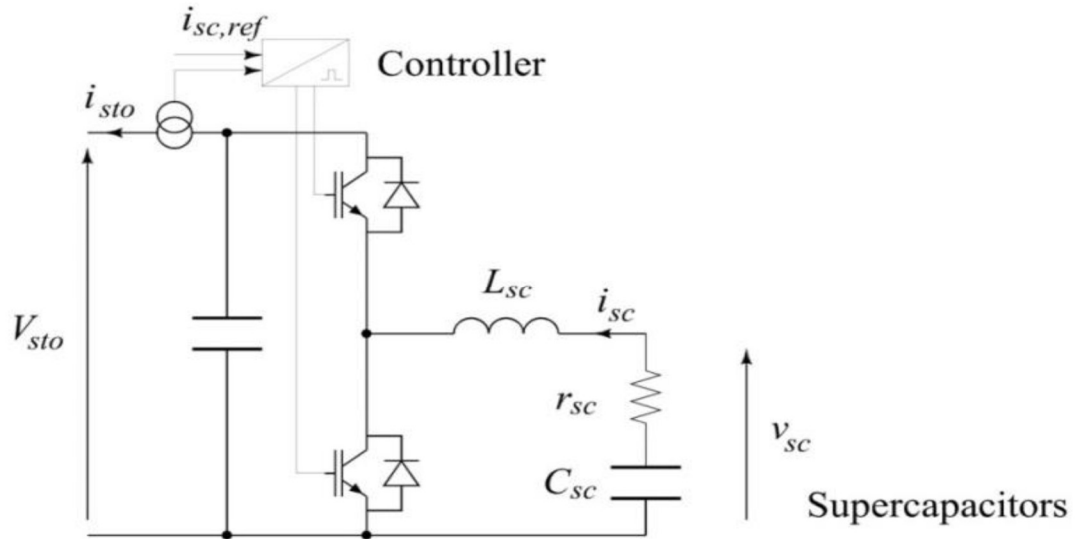


Figure 2-8 Bidirectional DC-DC converter interfaced with the SC module [25]

In this case, by neglecting the switching phenomena on the inductor L_{sc} , the storage current i_{sto} (can be supplied to the high voltage side) SC current i_{sc} related by the following expression [27]:

$$i_{sto} = (i_{sc} \times V_{sc}) \times \eta_{dcdc} / V_{sto} \quad (2.1)$$

In which V_{sto} is the voltage on the high-voltage side of the DC-DC converter and, $\eta_{dcdc} = 0.98$ is the rated efficiency of the DC-DC converter. The Bi-directional DC-DC converter can work in buck mode to control the recharge current of the energy storage system. During the discharging phase the Bi-directional DC-DC converter can work in boost mode in order to regulate the voltage at the supply link. The DC-DC is working for regulating the charging and discharging rate of the storage as well as switching power is done from control signal to it.

2.6 Literature Review

There are many researches done on energy storage system. As the main focus of this thesis is onboard energy storage system technology and regenerative energy literatures are reviewed.

For effective recovering electrical energy during trains' braking, electrical storage devices should be placed onboard of trains, because energy travels along the shortest path from the traction drive to the storage devices, improving the recovery efficiency [12]. Many railway industries have recently developed energy efficient LRVs with onboard energy storage system [13].

The energy storage systems are good for improving energy efficiency in the electric railway systems due to frequent repetition of acceleration and braking of vehicles, there are a number of researches about ESSs' application [14]. Especially, most of research suggests the on-board type storage which installs ESSs in each railway vehicle [15]. In the aspect of loss, it can be expected that the on-board type storage has best performance since this type can eliminate the thermal loss generated when the regenerative current flows between vehicle and substation [16, 17]. However, when considering the cost of storage and energy conversion system and the maintenance cost of a number of ESSs, substation-installed ESSs are more economic [17].

Flavio Ciccarelli on his PhD thesis on energy management and control [25] verified that Lithium ion super Capacitor (LiC) is able to reach an overall energy saving efficiency up to 16.5 % using onboard ESS, and 12 % using trackside ESS. The charging energy is from the regenerated energy and also during stopping at stations and reuse (discharging) for acceleration and up gradient. He has stated it may vary according to the mechanism of control system of the energy management.

Siavash Hajiabady [27] in the research of using energy storage system for London underground when trains are passing the conductor rail gaps; evaluated onboard energy storage system. Consequently, in order to keep the train performance the same during the gaps, batteries and super capacitor has been tested for power up the train through the gaps. Because of high current need to be discharged in short period of time, super-capacitors have been better compared with batteries for discharging the high current. In regard to the life cycle super-capacitors have been evaluated and found 10 times longer than that of batteries. But the charging is from the grid during stopping at stations. In the recommendation it was stated that the use of hybrid Super-capacitor/battery ESS

is more efficient. And also, Dr. Michael Meinert [36], who has done practical experiments to absorb the regenerated energy with Li-ion battery and super-capacitor ESS, verified 97% efficiency with Super-capacitors, whereas only 57% efficiency with battery for absorbing the regenerative energy.

The hybrid energy storage units, (the combination of Super-capacitor and Chemical Batteries energy storage unit) can ensure for high power demand and the high energy content. Using combined feature helps to expand the distances for the operation without OCL. Consequently, increasingly arising requirement of onboard energy storage units due to aesthetical, environmental or reliable operational reasons can be satisfied [20].

Chapter 3

3. Modeling

Modeling is the representation of a system. For this mathematical modeling followed by Simulink block modeling is going to be used. The modeling is done for traction energy consumption, regenerative energy, energy storage system with DC/DC converter.

3.1 Modeling the Traction Energy Consumption

Traction energy is an energy necessary for the operation of the train(motoring). Estimating the train energy consumption requires detailed train running states outputted from train performance simulator (TPS) or speed profile generator, including train velocity, running time, corresponding tractive effort and braking force. The model employs numerical integration method to estimate the overall energy consumption of a single train operation. Majumdar proposes four main stages of train movement including acceleration, balancing, coasting, and deceleration [4]. Equation (3.1) is the summary of his ideas for calculating energy consumption. It shows that the total energy consumed in train operations is the product of force and displacement. Coefficients in the equation are energy efficiency and factors for converting the work done in ton-km into electric power units.

$$W_T = \left[\frac{2.725}{0.814} \left(\sum_A^D F \times d \right) \right] + \left[\frac{P_a}{0.964} \left(\sum_A^D \left(\frac{d}{v} \right) \right) \right] \quad (3.1)$$

Where

W_T = total power energy consumption (kWh)

F = force in tones due to traction effort (ton)

d = distance traveled in km at that speed range (km)

v = traction speed (km/hr)

P_a = power consumption by all auxiliaries (kWh)

A,B,C,D= Acceleration, Balancing, Coasting and Deceleration stages respectively,

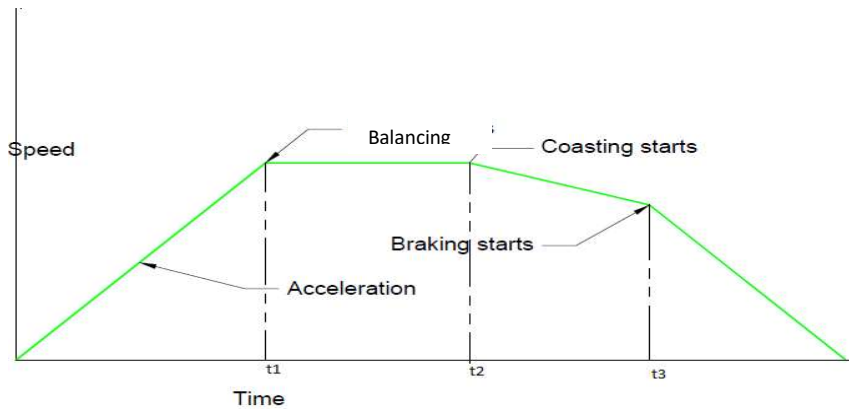


Figure 3-1 Speed time profile of train [4]

Estimation of energy consumption can be categorized mainly into electric-power approach and kinematics approach. Generally, the electric-power method calculates electric energy that is directly imported into the train. The kinematics method estimate energy consumption via kinetic energy and efficiency factor. The two models are explained more in detail in the following subsections.

Electric-Power Based Model

Wardrop (1989) proposes an electric-power based model to estimate energy consumption. The basic calculation, as shown in equation (4.2), requires line voltage, current and motor combination code, etc. The k value is the number of parallel motor circuits. According to equation (3.2), this method contains an assumption that energy consumption has a linear relationship with the proportion between actual traction and maximum traction [4, 25].

$$E = \frac{1}{3.6 \times 10^6} \times k \times V \int (I_m \times \gamma) dt \quad (3.2)$$

Where

E = main power energy consumption (kWh)

V = voltage (V)

I_m = motor current (A)

K = motor combination code, $k \geq 1$

$\gamma = \frac{T_{\text{actual}}}{T_{\text{max}}}$, the proportion between T_{actual} actual traction and T_{max} maximum traction,

$0 < \gamma \leq 1$ (Since actual traction can't be greater than the maximum)

t = operation time (s)

Kinematics Based Model

As electric power inputs to rolling stocks, it will go through converter, motor, and mechanic devices to output traction power for train movements. The entire procedure involves more or less energy loss. The motor efficiency is defined as the division of Output power over Input power. In equation (3.3), motor efficiency, train traction, and speed are inputs for estimating input power. Energy consumption is estimated via equation (3.4) [4].

$$\eta = \frac{P_{out}}{P_{in}} = \frac{0.28 \times F \times v}{P_{in}} \quad (3.3)$$

From this model it is possible to derive the total power supplied for traction [4].

$$\left. \begin{aligned} P_{in} &= \frac{0.28 \times F \times v}{\eta} \\ E_{in} &= \int P_{in} dt \end{aligned} \right\} \quad (3.4)$$

Where

η = motor efficiency, $0 < \eta \leq 1$

P_{out} = output power (kW)

P_{in} = Input power (kW)

F = tractive effort (kN)

v = train velocity (km/h)

E = Energy consumption (KJ)

3.1.1 Traction Force Modeling

Traction force is the force required to overcome the resistance forces and makes to run, which is formulated for acceleration, balancing and coasting and for deceleration forces.

Traction force is given as [4, 8, 25]:

$$F_t = M_{tot} a + (F_{rol} + F_{grad} + F_{aer}) \quad (3.5)$$

Where:

M_{tot} = total mass of the traction

a = acceleration

F_t = traction force

F_{rol} = rolling resistance force

F_{grad} = gradient force

F_{aer} = aerodynamic force

$$D = s_1 + s_2 + s_3$$

$$t_1 = v_m / a;$$

$$t_3 = -v_m / \beta;$$

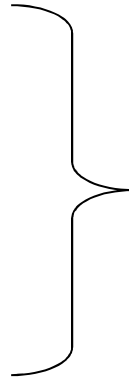
$$s_1 = 0.5(v_m)^2 / a;$$

$$s_3 = -0.5(v_m)^2 / \beta;$$

$$s_2 = D - (s_1 + s_3)$$

$$t_2 = \frac{s_2}{v_m}$$

$$T = t_1 + t_2 + t_3$$



(3.6)

Where

t_1 = Accelerating time

t_2 = Time taking for running at constant speed

t_3 = decelerating time

s_1 = distance covered during acceleration

s_2 = distance covered with constant speed

s_3 = distance covered during deceleration

D = total distance from station to station

T = total time taking to run from station to station

β = deceleration

v_m = maximum /constant running/ speed

2.1.3.3 Resistance Forces

Resistance forces are forces which opposes the forward motion of a body. It is composed by the sum of the different forces that act against its movement. These forces are [4]:

- The rolling resistance;
- The aerodynamic drag;
- The gradient /slope resistance;
- Accelerating and decelerating force

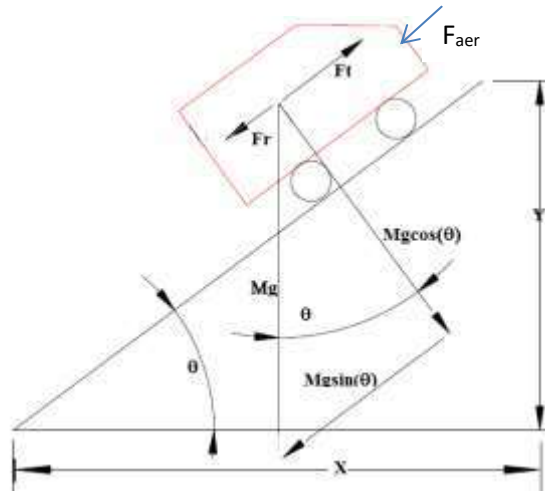


Figure 3-2 Motion of vehicle and forces exist [4]

The mathematical equations that define all those forces are listed below.

Aerodynamic resistance

The aerodynamic force F_{aer} is consequence of the friction of the vehicle body moving through the air. The aerodynamic resistance is dependent on the frontal area of the train, its shape and its speed.

The mathematical equations that define the aerodynamic resistance can be calculated as: [4]

$$F_{aer} = 0.5 \times \rho \times C_d \times A_{fr} \times (v + v_{wind})^2 \quad (3.7)$$

Where

F_{aer} = total aerodynamic resistance in (N)

ρ = the air density in (kg/m^3)

C_d = aerodynamic resistance drag coefficient (0.4)

V_{wind} = is the wind speed in m/s

A_{fr} = frontal area in m^2

V = is the train's speed in m/s

The drag coefficient is a geometrical property of the vehicle body design and it varies in a range of 0.3 to 0.52 for passenger cars and 0.5 to 1 for heavy duty vehicles such as container carriers and trucks [33]. And now it is taken 0.4 as an average for AALRT [4].

Rolling Resistance

The rolling resistance force, F_{ro} , is due primarily to the friction of the vehicle wheel on the rail, but friction in bearings and on the gearing system must also be considered [4, 33].

The rolling resistance is a function of the total mass of the train and the rolling resistance coefficient and given by: [25, 33]

$$F_{Rol} = C_{Rol} \times M_{tot} \times g \quad (3.8)$$

Where

F_{Rol} is the total rolling resistance in (N)

C_{Rol} is the rolling resistance coefficient (0.0071)

M_{tot} is the train mass in kg

g is the acceleration of gravity (9.81 m/s²)

Gradient Resistance

The hill climbing force F_{gr} (gradient force) is the force needed to drive the vehicle up a slope. It may have a negative impact on the movement of the vehicle as moving uphill, acting indeed as a resistance force but also a positive impact, if the vehicle is going down a hill. The sign of the gradient angle is directly proportional to its force effect.

The gradient resistance is dependent on the weight of the train and the size of the gradient to which the train is exposed. Expressed as: [4, 25, 33]

$$F_{gr} = M_{tot} \times g \times \sin \alpha \quad (3.9)$$

$$F_{gr} = M_{tot} \times g \times \left(\frac{\Delta h}{x}\right) \quad (3.10)$$

Where:

F_{gr} is the total gradient resistance in N

M_{tot} is the train's mass in kg

g is the acceleration of gravity (9.81m/s²)

α is the angle of the gradient

Δh is the height difference [m] over the traveling distance x [m]

Acceleration Force

The accelerating force is the force for decelerating of mass: [4, 33]

$$F_{acc} = M_{tot} \times a \quad (3.11)$$

Where

F_{acc} is the acceleration resistance in N

M_{tot} is the mass of the train or vehicle with load in kg

a is the deceleration in m/s^2 (for braking force it is deceleration)

Traction Torque

The torque of the load or traction force is proportional to the distance traveled. So it is given by [34]:

$$\tau = F_t \times R \quad (3.12)$$

where:

τ = Torque of traction

F_t = Traction force

R = Relative wheel radius

Motor current varies in relation to the amount of load torque applied. When a motor is decelerating, the motor torque is less than the load torque. Conversely, when a motor is accelerating the motor torque is higher than the load torque.

3.2 Modeling of the brake regenerative energy

Modern electric trains are usually equipped with regenerative braking. During braking period, electric power is generated from kinetic energy of the train. Note that the braking force of the train is composed of friction braking force and motor braking force. Only the latter can be used to produce electricity. Thus, the product of the motor braking force, velocity and regenerative efficiency yields the electric power produced by the regenerative braking, as expressed in equation below [4].

$$P_{reg} = F_b \times v \times \eta_{reg} \quad (3.13)$$

Where

P_{reg} = electric power of regenerative braking (kW)

F_b = regenerative braking force (kN)

v = Velocity of the train

η_{reg} = regenerative system efficiency

The power consumption for braking and regenerated power of a train can be calculated based on the traction braking force. Braking force is a force applied in addition to resistance forces to overcome the motion of the vehicle. This force act to decelerate and to stop the moving body. A force has to be applied in addition to the forces already mentioned as resistance forces, to overcome its inertia [25].

As Newton's 2nd law the travel in opposite direction, the relation between the driving resistance and motion of vehicle. From the formula of traction force in equation (3.5) it is given as: [4, 25]

$$M_{tot}\beta = -(F_B + F_{aer} + F_{gr} + F_{Rol}) \quad (3.14)$$

$$-F_B = M_{tot}\beta + F_{aer} + F_{gr} + F_{Rol} \quad (3.15)$$

Where

F_B = is the braking force in N.

F_{gr} = is the total gradient resistance in N

F_{aer} = total aerodynamic resistance in N

F_{Rol} = is the total rolling resistance in N

F_{acc} = is the accelerating force in N

β = deceleration (m/s^2) it is negative

Braking consumed power and regenerated power

The consumed power to break the motion is the brake force F_B , times the change in velocity gives the power to be provided for braking: [4, 29]

$$P_{consumed} = F_B \times \Delta V \quad (3.16)$$

Where:

$P_{consumed}$ = Power consumed to break

ΔV = change of Speed when braking to stop

It is possible to calculate the regenerated power for break at stations: [25, 29]

$$P_{reg} = P_{consumed} \times \eta_{reg} \quad (3.17)$$

Where:

P_{reg} = regenerated power

η_{reg} = brake regeneration efficiency

$$\eta_{reg} = \frac{1}{e^{\alpha|a|}} \quad (3.18) [29]$$

Where

α = Optimum model parameter (commonly used 0.65 for Asynchronous motor driven machines)[29]

a = maximum deceleration of the vehicle

Energy regenerated can found with integration of the power with the braking time [4, 25, 29]

$$E_{reg} = \int P_{reg} dt \quad (3.19)$$

After you have defined the mathematical equations that describe each Subsystem, you can begin building a block diagram of your model in Simulink. Build the block diagram for each of your subcomponents separately. After you have modeled each subcomponent, you can then integrate them into a complete model of the system.

3.3 Brake regenerative in AALRT

Addis Ababa Light rail transit system stations are more of a plane landmark. Also, there are track lines inclined slope and curved lines [31]. In this section regenerated energy when a train is break to stop at stations is calculated and discussed based on the specification of the vehicle.

Specifications of the AALRT train [3, 31, 32]

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

Table 3-1 Technical specification of AALRT train [3, 31, 32]

Let calculate the braking force for station. It is chosen two specific areas Menelik II square to Atikilt Tera which has more downhill area, Lancha – Nefas Silk II is chosen for it is the longest line and its track topography which has uphill and downhill in one line, here I calculate for forward and return (i.e. Lancha – Nefas Silk II and Nefas Silk II - Lancha)

First consider a train moves from Menelik II square and stop at Atikilt Tera

values obtained from the specification of the train and track topography taken for the calculation are:

Maximum speed = 40km/hr,

Acceleration = 0.9m/s^2 ,

Deceleration = 1m/s^2

Efficiency of motor $\eta = 89\%$

Efficiency of brake regeneration $\eta_{\text{reg}} = \frac{1}{e^{\frac{0.65}{1.1}}} = \frac{1}{1.8} = 0.56$

Total distance of Menelik II square station to Atiklit Tera station = 740m

Elevation of 80m distance to the destination station (α) = -0.3796°

Let calculate the braking force of the train using equation 3.9 – 3.15.

Aerodynamic resistance

$$F_{\text{aer}} = 0.5 \times \rho \times C_d \times A_{\text{fr}} \times (v + v_{\text{wind}})^2$$

$$V_{\text{wind}} = 15\text{m/s}$$

$$\rho = 1.2\text{kg/m}^3$$

$$A_{\text{fr}} = 10\text{m}^2$$

$$\begin{aligned} F_{\text{aer}} &= 0.5 \times 1.2\text{kg/m}^3 \times 0.4 \times 10\text{m}^2 \times (40\text{km/hr} + 15\text{m/s})^2 \\ &= 2.4\text{kg/m} \times (26.1\text{m/s})^2 \\ &= 1634.90\text{N} \text{ (for one brake from 40km/hr to stop)} \end{aligned}$$

Rolling Resistance for the last distance during brake with its gradient

$$\begin{aligned} F_{\text{Rol}} &= C_{\text{Rol}} \times M_{\text{tot}} \times g \times \cos(\alpha) \\ &= 0.0071 \times 63020\text{kg} \times 9.81\text{m/s}^2 \times \cos(-0.3796) \\ &= 4389.31\text{N} \end{aligned}$$

Decelerating force

$$\begin{aligned} F_{\text{decc}} &= M_{\text{tot}} \times a \\ &= 63020\text{kg} \times -1\text{m/s}^2 \\ &= -63020\text{N} \text{ (since it is decelerating)} \end{aligned}$$

Gradient force

$$\begin{aligned} F_{\text{gr}} &= M_{\text{tot}} \times g \times \sin \alpha \\ F_{\text{gr}} &= 63020\text{kg} \times 9.81\text{m/s}^2 \times \sin(-0.3796) \\ &= -4095.56\text{N} \end{aligned}$$

As degree of inclination is negative the impact is accelerating the mass

not resisting (decelerating) which is increasing the required braking force.

To stop at station N26 Atikilt Tera traveling from Menelik II square the braking force becomes:

$$\begin{aligned} \text{Braking Force (F}_B) &= F_{acc} + F_{Rol} + F_{aer} + F_{gr} \\ &= -63020\text{N} + 4389.31\text{N} + 1634.90\text{N} + (-4095.56\text{N}) \\ &= -61091.35\text{N} = -61.09\text{KN} \end{aligned}$$

The power consumed for braking is ($P_{consumed}$) using equation 3.16

$$\begin{aligned} P_{consumed} &= F_B \times \Delta V \\ &= -61.09 \text{ KN} \times -40 \text{ Km/hr} \\ &= -61.09 \text{ KN} \times -11.11 \text{ m/s} \\ &= 678.72 \text{ kW} \end{aligned}$$

Regenerated power is (P_{reg}) = $P_{consumed} \times \eta_{reg}$ using equations 3.17 and 3.18

$$\begin{aligned} &= 678.72 \text{ kW} \times 0.56 \quad (\eta_{reg} \text{ determined in equation 3.18} = 0.56) \\ &= 380.09 \text{ kW} \quad (\text{maximum brake regenerated power}) \end{aligned}$$

To get regenerative energy using equation 3.19 and 3.6

$$\begin{aligned} E_{reg} &= \int P_{reg} dt \\ t_3 &= \frac{V}{a} = \frac{40 \text{ Km/hr}}{1 \text{ m/s}^2} = 0.28 \times 40/1 = 11.2 \text{ sec} \\ E_{reg} &= t_3 \times P_{reg} = 11.2 \text{ sec} \times 380.09 \text{ kW} = 1.18 \text{ kWh} \end{aligned}$$

Let calculate the energy consumption of the train to move from station to station. First let find the traction force using Equation 3.5,

$$\begin{aligned} \text{For accelerating } F_t &= 50840.76 \text{ N} \\ \text{For constant speed/balancing/ } F_t &= 23324.03 \text{ N} \\ \text{For braking } F_b &= 61091.35 \text{ KN} \end{aligned}$$

Calculating total energy required can be done using Majumdar equation (3.1)

$$\begin{aligned} E_t &= E_{acc} + E_{bala} + E_B + E_{aux} \\ &= 1.94 \text{ kWh} + 3.95 \text{ kWh} + 2.11 \text{ kWh} + E_{aux} \\ &= \underline{8 \text{ kWh}} + E_{aux} \end{aligned}$$

To find the total energy let find the energy consumed by the auxiliary parts which is 41 kW power; total time is calculated using equation 3.6

$$E_{aux} = P_{aux} \times T = 41 \text{ kW} \times 78.33 \text{ sec} = 0.89 \text{ kWh}$$

So the total energy consumption is: $E_{total} = 8 \text{ kWh} + 0.89 \text{ kWh} = \underline{8.89 \text{ kWh}}$

In addition let's take the energy consumption of the longest track line and with up gradient and down gradient at single line from Lancha to Nefas-Silk II stations. It is covering 1940m length of track line.

Accelerating energy = 2.02 kWh

For constant /balanced/ speed running with ups and downs = 4.2 kWh

For braking or decelerating to stop = 1.78 kWh

Auxiliary parts energy consumption = 2.11 kWh

Total energy consumption $E_t = E_{acc} + E_{bala} + E_B + E_{aux} = \underline{10.11 \text{ kWh}}$

The brake regenerated energy = 0.998 kWh

If we calculate the energy for traveling from Nefas Silk II to Lancha station, it is obtained as:

Accelerating energy = 2.2 kWh

For constant /balanced/ speed running with ups and downs = 6.07 kWh

For braking or decelerating to stop = 1.62 kWh

Total energy consumption $E_t = E_{acc} + E_{bala} + E_B + E_{aux} = \underline{12 \text{ kWh}}$

The brake regenerated energy = 0.91 kWh

From this result we have seen that, the energy consumption is varying with gradient direction and distance. For the same line in the two directions give different energy consumption. During uphill movement for braking it needs less energy but high energy to accelerate, whereas for downhill movement for braking needs more braking energy but less energy for accelerating. The regenerated energy is also varying. The brake regenerated energy is from 0.9 kWh to 1.2 kWh for a station. Currently in the existing system, this energy is lost as heat at the break resistor and dissipates as heat. This may cause for the damage of the train equipment and leads to decreasing the age of the train and also causes emission of CO₂ to the environment. Instead this energy can be saved in storage system and can be utilized. The stored energy can be used for stabilizing of power with the catenary feed. As well as used to supply power for uphill gradient movement of train and for catenary free movement of the train during power outage. So for such solutions and to utilize the regenerated energy effectively without wastage and to get necessary energy for travel of the train to nearest station instead of stopping at middle of the track onboard energy storage system is proposed.

3.4 Modeling and Designing of Energy Storage System

Before modeling and designing energy storage system it is better to decide on the amount of energy to be store in the energy storage system (i.e. the capacity of energy storage). It is required to have a capacity of supplying power/energy for the required target (at least to move for one station to next station). So that for this paper the targets of onboard energy storage system is to supply power for the traction when excess power is required in addition to the grid, efficiently capture the regenerated energy and to supply power for the traction when there is grid supply is outage. From these the basic target to decide the capacity of the storage is the capacity to supply for traction at least to the nearest station.

Thus, the largest traction track line requiring more energy in AALRT project is lancha to Nefas-Silk II stations track for this it needs energy of 12 kWh to move from Nefas-Silk II to Lancha. If the storage can supply this it is possible also to supply other stations traction.

As per the standard of American association of energy, it should be considered that from the total energy capacity of the ESS the usable energy is only 75% (i.e. the usable energy should be less than or equal to 75% of the maximum storage capacity of the ESS). And also, the ratio of the minimum discharging voltage to the maximum charging voltage of super-capacitor is 0.5 [25].

The SC storage system is the set consisting of a stack of individual SC modules appropriately connected in series and parallel and by a static bidirectional DC/DC converter. The series connection and parallel connection is required in order to obtain the desired values of voltage and current [25]. The SC mathematical model is hence given by eq. (3.20) assuming that it is pre-charged to its maximum allowable voltage $V_{sc,max}$:

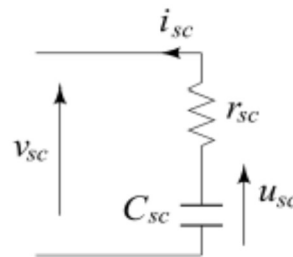


Figure 3-3RC model of the Super-capacitor ESS [25]

The energy stored in a super-capacitor, as in a conventional capacitor, is [25]

$$\left. \begin{aligned} E &= \frac{1}{2} C_{sc} V_{sc}^2 \\ i_{sc} &= \frac{d(C_{sc} U_{sc})}{d(t)} \\ V_{sc} &= U_{sc} - r_{sc} i_{sc} \\ U_{sc}(0) &= V_{sc,max} \end{aligned} \right\} \quad (3.20)$$

The maximum energy stored in the super-capacitor storage depends on its equivalent capacitance C_{eq} . The expression for maximum energy storage can be represented as following [25]:

$$E_{max} = \frac{1}{2} (C_{eq} \times (V_{sc,max})^2) \quad (3.21)$$

In practice it is not feasible to discharge all the energy stored, therefore minimum allowable voltage limit is fixed that limits available energy. In super-capacitors as per the standard the minimum limit of voltage to discharge is half of the maximum voltage limit of the cell/module.

Since the voltage constraint is determined to be $V_{min} < V < V_{max}$ the useful energy to be used for supply by the super-capacitor can be expressed as:

$$E_{ua} = \frac{1}{2} \times C_{eq} (V_{max}^2 - V_{min}^2) \quad (3.22)$$

Then, using equation 3.21 and equation 3.22

$$\frac{E_{ua}}{E_{ma}} = 1 - \left(\frac{V_{min}}{V_{max}} \right)^2$$

Where

- E_{ua} = useable energy of the super-capacitor
- C_{eq} = Equivalent capacitance
- V_{max} = maximum voltage of the super-capacitor
- V_{min} = minimum voltage of the super-capacitor
- E_{max} = maximum energy in the super-capacitor

Usable Energy stored in the super-capacitor in terms of discharge rate

$$E_{ua} = E_{max} [1 - (d)^2] \quad (3.23)$$

$$d = \frac{V_{min}}{V_{max}} \quad (3.24)$$

Based on equation 3.23 and 3.24 and from the characteristic of the super-capacitor $d=0.5$. In the literature, variously sized on-board ESSs for different type electric vehicles are described. Most of them are sized for $d = 0.5$, which is recommended by SC manufacturers and gives the maximum available useful energy (75% of the energy stored in an SC) [35, 36]. The maximum energy capacity of the supercapacitor to have 12 kWh usable energy to cover Lancha to Nefas Silk II is:

$$E_{\max} = \frac{E_{ua}}{1 - d^2} = 12\text{kWh}/0.75 = \underline{16\text{kWh}}$$

The maximum energy storage capacity of the storage should be $\geq \underline{16\text{kWh}}$

Using equation 3.21 let's determine the equivalent capacitance of needed for the maximum energy with output voltage 750V for the catenary.

$$E_{\max} = \frac{1}{2} (C_{eq} \times (V_{sc,max})^2)$$

$$16\text{kWh} = 0.5(C_{eq} \times 750\text{v}^2)$$

$$C_{eq} = \frac{2 \times 16\text{Kwh}}{750\text{v}^2} = 204.8\text{F}$$

The determination of the storage entity allows defining the dimensions and weights of the storage device. Moreover, the sizing consists also in the choice of the size of the DC-DC interfacing converter, determination of the maximum and minimum input and output voltage levels and the maximum allowable current. For these it is better to search market available scientific ESS for determining the size and weight of the storage.

From different types of ESS devices available in the market BMOD0063P125 SC module chosen, it is applicable for this project considering its specific power to weight and found as module and easy for implementation of onboard storage system.

Parameters	Value
Rated Capacitance	63 F
Maximum Capacitance, initial	76 F
Maximum ESR DC, initial	18 mΩ
Rated Voltage	125 V
Absolute Maximum Voltage ¹⁵	136 V
Maximum Continuous Current (ΔT = 40 °C)	240 A
Maximum Peak Current, 1 second (non-repetitive)	1800 A
Leakage Current at 25 °C, maximum	10 mA
Maximum Series Voltage	1500 V
Capacitance of individual cells	3000 F
Number of cells	48
Minimum Operating Temperature (Ambient)	-40 °C
Maximum Operating Temperature (Ambient)	65 °C
Specific Power	1.7 W/kg
Specific Energy	2.3 Wh/kg
Storable Energy	140 Wh
Projected DC Life at 25 °C	10 years
Projected Cycle Life at 25 °C	10 ⁶ cycles
Mass, typical	58 kg

Table 3-2 Main characteristics of BMOD0063P125 SC module [25, 35]

Based on the characteristics of the module to store 16kWh energy and with required maximum voltage (750V) let calculate the number of modules.

$$C_{eq} = C_{cell} \times \frac{M}{N} \quad (3.25) [25]$$

Where :

N number of cells/modules/ in series

M number of parallel branches

C_{cell} capacitance of cell /module/ in Farad

First let determine number of cells in series based on the required voltage, so $750v \div 125v = 6$ is number of series connected modules to get the demined voltage. Then the number of parallel connected series is determined from equivalent capacitance using equation 3.25.

$$204.8F = 63F \times \frac{M}{6} \quad \text{From the table 3.2 it is given C of module is 63F}$$

$M = 19.5$ which is approximated and round to 20 since it is number of modules. So the total number of modules used becomes $M \times N = 20 \times 6 = 120$ modules for storing ≥ 16 kWh energy.

This result is obtained to supply directly 750v from supercapacitor ESS to with out boosting and charging with 750v without using buck converter.

Let see the result using DC-DC converter, with boosting of 2 and buck with 0.5 duty ratio. So, the voltage output from SC storage would be $750V/2 = 375V$ to be boost by the converter.

$$E = \frac{1}{2} (C_{eq} \times V_{max}^2) \dots\dots\dots \text{(from equation 3.21)}$$

So, based on the maximum allowable energy capacity of the storage let's calculate the equivalent Capacitance of the storage

$$C_{eq} = \frac{2xE}{V_{sc,max}^2} = \frac{2 \times 16Kwh}{375V^2} = 819.2F$$

The number of series connected modules would be $375v \div 125v = 3$ modules in series from table 3.2 a module has 125V maximum voltage

$C_{eq,SC} = 63 \times \frac{M}{3}$ (From the table 3.2 it is given C of module is 63F which is taken as C_{cell} and number of modules in series is 3 determined from the determination of maximum voltage of ESS)

$$M = C_{eq,SC} \times \frac{3}{63} = 819.2F \times \frac{3}{63} = 39.05 \text{ number of parallel branch}$$

This number should be approximated to the nearest large whole number to get better storage capacity, so which is 40 parallel branches. Then, equivalent capacitance with 40 parallel branches and 3 series modules is

Thus, the total number of modules required for ESS is $40 \times 3 = 120$ modules (40 branches with 3 modules in series) are used. So, in 120 modules it can store:

$$C_{eq,SC} = 63 \times \frac{40}{3} = 840F \text{ (as the value for number of parallel modules is rounded)}$$

$E_{\max} = 0.5 \times 840 \times (375)^2 = 16.4\text{kWh}$ (the maximum storage capacity of SC storage system from the arrangement of modules is fulfilling the maximum energy requirement of the storage which is greater than 16kWh).

For 120 modules the ESS would add a mass of $58\text{kg} \times 120 = 6960\text{kg}$ (i.e. 6.96tone) load to the vehicle. Then now the total mass of the train with full load becomes 69980kg (i.e. 69.98tone \cong 70tone).

The size is becoming a crucial problem to be used as onboard energy storage the mass becomes 11.04% of the gross weight of the vehicle is added and also the volume space (0.57m*0.58m per module) would become difficult to put on the train. So it is difficult to use this ESS onboard of AALRT due to its weight and volume. For improving the size of the ESS the better mechanism is using hybrid storage technologies.

The Hybrid technology of Li-ion battery and the super-capacitor is the best, with its life cycle, Energy density, recapturing ability. The super-capacitor is high power efficient and fast responder. For an effective to recapturing the regenerative energy and for immediate respond of powering the traction on acceleration Super-capacitor is used. As well as to supply energy for long distance and energy efficiency the Li-ion battery is designed.

Super-capacitor for hybrid: As it is determined early to have an output voltage of supercapacitor be 375V which would be boost by DC-DC to 750V the number of series modules of SC is 3. For the number of branches, it should have the capability to recapture regenerated power so, the power is the determinant. Then to have enough power capability to recapture the braking power and supply in the gradient. The current should be greater than or equal to 1800A (i.e $1800\text{A} \times 375\text{v} = 675\text{kW}$)

To have this current capability the number of connections in parallel branch are determinant.

$$1800\text{A} \div 240\text{A} = 7.5 \approx 8 \text{ number of parallel branch connections.}$$

Now let determine the equivalent capacitance of the ESS of the supercapacitor.

$$C_{\text{eq}} = 63 \times \frac{8}{3} = 168\text{F}$$

Then the maximum Energy to be saved in SC ESS is

$$E_{\max} = 0.5 \times C_{\text{eq}} \times V^2 = 0.5 \times 168\text{F} \times 375\text{V}^2 = 3.28\text{kWh}$$

From this the usable energy is determined using equation 3.23

$$E_{\text{ua}} = E_{\max} [1 - (d)^2] = 3.28\text{kWh} \times (1 - 0.25) = 3.28\text{kWh} \times 0.75 = 2.46\text{kWh energy}$$

2.46kWh energy capacity is used for fast respond to capture and supply regenerated power in supplement to the hybrid battery. For energy efficiency purpose battery is used as supplementary supply and storage. Here the supercapacitor modules used for the hybrid are $3 \times 8 = 24$ modules, the mass is $58\text{kg} \times 24 = 1392\text{kg}$.

Design of the Li-ion Battery

The capacity of a battery represents the amount of the electrical charge available and it is often described in Ampere-hours (Ah). The capacity of a battery depends on the construction factors of the cells that include the materials contained in the electrodes and the acid solution. Besides the capacity of a battery is not a fixed quantity but depends on to the discharge rate. According to the Peukert's law (27)

$$C_p = I^k t \tag{3.27}$$

Where:

- C_p is the capacity at one-ampere discharge rate,
- I is the discharge current (A)
- K is Peukert constant (ranging 1.1 – 1.3)
- t is time of discharge (hr)

The energy of the battery is calculated using [27]

$$E = CV \tag{3.28}$$

where

C is capacity in Ah

V is voltage

Battery characteristics	Lithium ion (model ms9535)	Lithium ion (model 9522)
Rated max. output Voltage (V)	75 (20 cells in series with 3.7v)	28.5
Max. Discharge current (A)	250	125
Weight of battery(kg)	21.73	11.34
Capacity (Ah)	34	25

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

As it demonstrated in the table above Lithium ion (model 9535) with output voltage of 75V and max discharge current of 250A which is a suitable battery for onboard design since it has better power density than 9522. Therefore, to get the voltage required, 5 of these batteries need to be connected in series to be regulated and boost with the DC/DC converter the duty ratio of boosting 2. Furthermore, to get appropriate discharging current, 7 set parallel branches of these batteries need to be connected. The Lithium ion batteries has a total capacity of 238Ah, 88 kWh and total weight of 760.5kg, this capacity is more than demanded, but to have the required power capacity it is accepted.

The hybrid ESS designed would have $1392\text{kg} + 760.5\text{kg} = 2152.5\text{kg}$ total mass to be added to the vehicle mass. The gross mass of train with full load becomes 654500kg is equal to 65.5tone.

The total Energy Capacity of the ESS becomes 90.46kWh, this energy capacity more than the initial capacity required, but to have the capability to capture and supply the system demanding power these energy storages are required for the design.

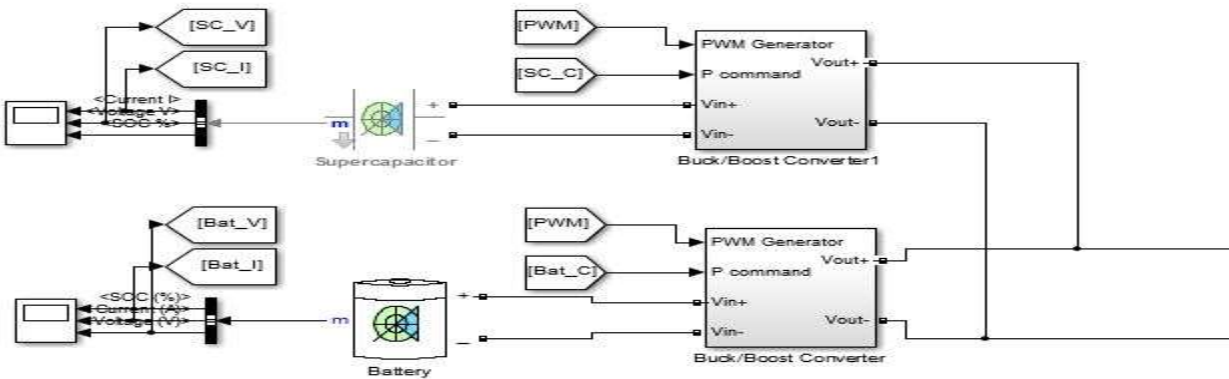


Figure 3-4 Parallel connection of Super-capacitor and Li-ion Battery with Converter

3.5 DC/DC converter

The DC/DC converter is used for this system is bidirectional buck/boost converter of voltage for the battery and SC and controls the switching of charging and discharging. The converter is used as switch for the supply of power from the storage /this is the main advantage of it using the command from the power control. The other usage is to boost the voltage from the storages and buck when charging the storage and regulates the output voltage from both sides (Battery and SC) be 750V since in parallel for the occurrence of imbalance.

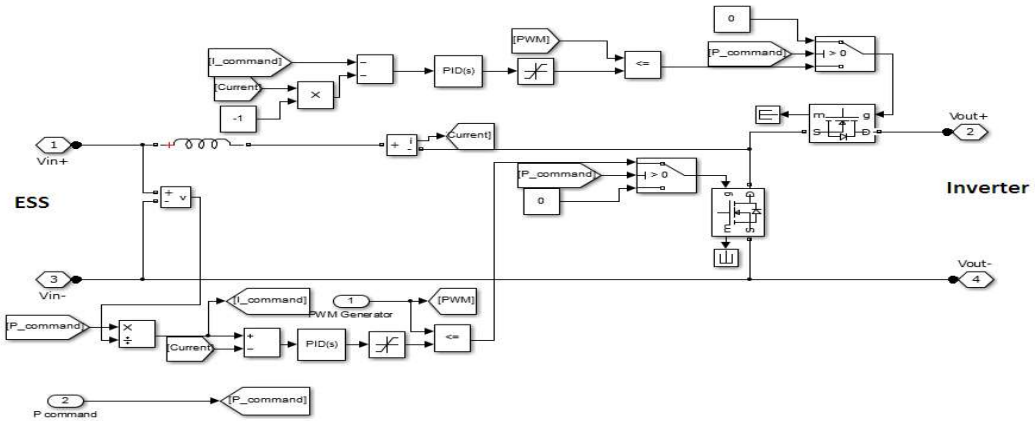


Figure 3-5 DC/DC converter with control signals

The converter is proposed to work as buck and boost the inductor and capacitor components of the converter need to be determined.

Let D is duty ratio of buck converter and D_h be duty ratio of boosting.

$$D_h = \frac{1}{D} \quad \text{switching period} = T = t_{on} + t_{off}$$

$$D = \frac{t_{on}}{t_{on} + t_{off}} \quad \text{or} \quad D = \frac{V_H - V_L}{V_H} \quad V_H \text{ high voltage side and } V_L \text{ Low voltage side}$$

$$D = \frac{750 - 375}{750} = 0.5 \quad \text{so, } D_h = 2$$

$$\text{Inductance of the inductor (L)} = \frac{(1-D)V_L^2}{2Pf} \quad 3.29 [38]$$

$$\text{DC link Capacitor capacitance (C)} = \frac{DP}{V_H f \Delta V_H} \quad 3.30 [38]$$

Where D is duty ratio, ΔV_H High voltage side ripple, P is power, and f is frequency = $\frac{1}{T} = 1\text{KHz}$

For the simulation based on the equation 3.29 and 3.30 $L=5.2\text{mH}$ and $C = 150\mu\text{F}$

Chapter 4

4. Simulation results and discussion

Simulation is defined as the construction of a mathematical model to reproduce the characteristics of a phenomenon, system, or process, often using a computer, in order to infer / gain information or solve problems. Based on the mathematical modeling of the components of the system, now the simulation of each model will be performed and discussed. Also, at last the simulation of the ESS SoC/state of charge/ and energy level from brake regenerative will be discussed.

First of all the models are built with Simulink block diagram. After building the Simulink block diagram, it is possible to simulate the model and analyze the results. Simulink allows interactively defining system inputs, simulating the model, and observing changes in behavior. This allows to quickly evaluating models.

This section shows all the results of the programs which are properly fed to the MATLAB Simulink software. The mathematical models of the system which are provided in the above chapters are properly modeled to the Simulink MATLAB program.

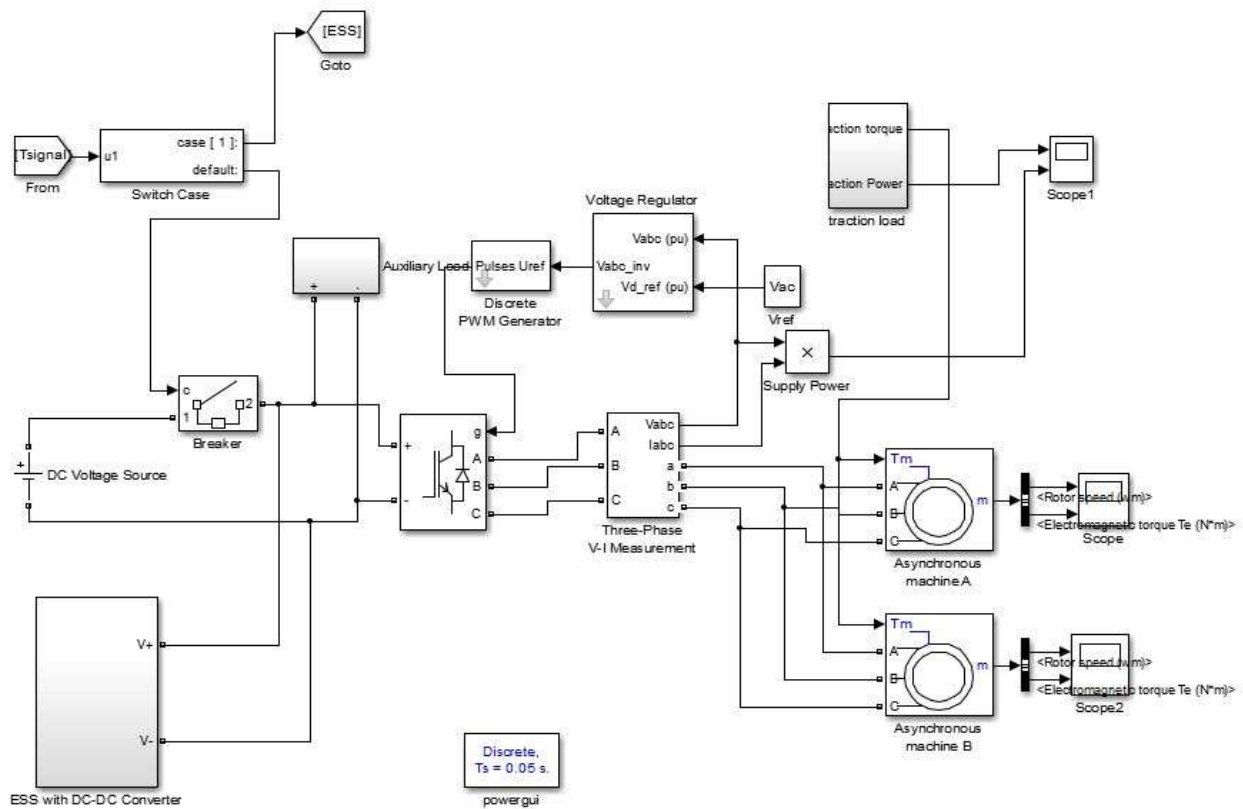


Figure 4-1 Matlab SIMULINK model of Onboard Energy Storage System

The Matlab/Simulink block diagram represents the onboard Hybrid energy storage system. The main elements of the block diagram are listed below.

DC power supply 750V DC

Hybrid Energy storage system with DC/DC converter (Figure 3-4 and Figure 3-5)

Inverter (Universal converter IGBT with diode for bidirectional inverting 750v DC to 500v AC with 71Hz and back rectifier brake regenerated AC to DC to supply for the ESS)

Inverter gate signal (voltage regulator based PWM switching the IGBT and diode based on the traction power and to produce the required frequency of the voltage)

Asynchronous Motor with traction load torque for the running of AC motor

4.1 Train movement and Traction force

When the train is moving from one station to next station it does have acceleration, constant speed and deceleration states. On these three states of traction the force, power and energy applied is different. These are the main constraints which can be seen in the traction profile simulation. For simulation the following Simulink block diagram is used.

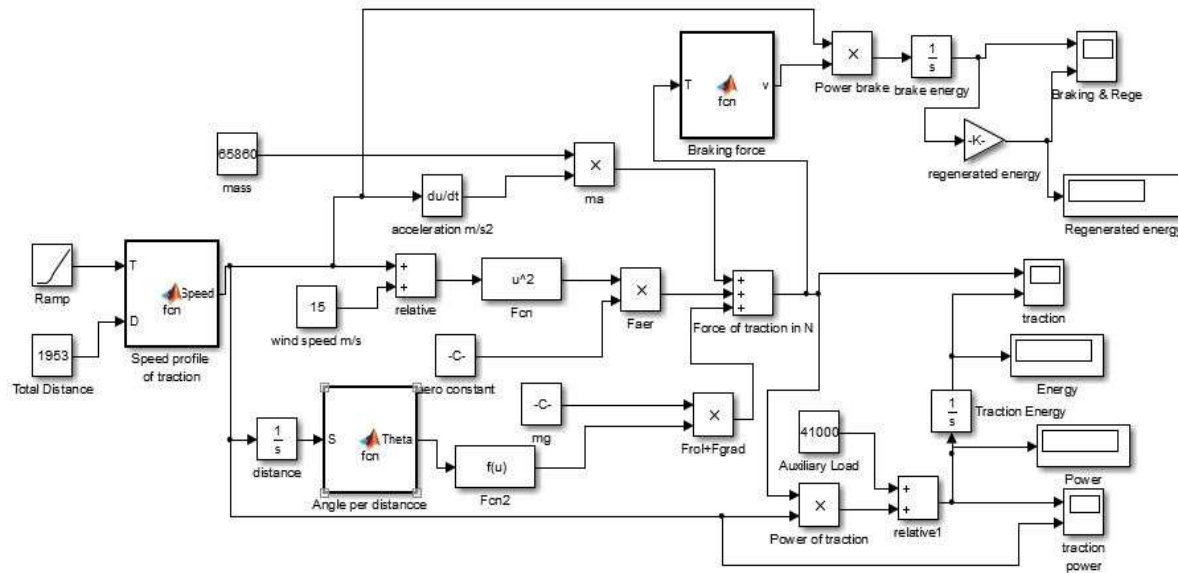


Figure 4-2: Traction force, power and energy with regenerative energy simulation model

The Traction simulation block diagram represents the mathematical model discussed. The main elements of the block diagram used as input and output components are listed below.

Station to station Distance (m)	Traction force
Total mass of the vehicle (kg)	Traction power
Air dragging coefficient	Traction energy consumption
Gravitational constant	Braking power
Wind speed	Braking energy
Air density	Brake Regenerated energy
Angle of inclination/gradient/	Resistance forces

The speed profile of the train vehicle is calculated with in the distance from station to station, using the general specification of AALRT, acceleration 0.9m/s^2 , accelerating speed $0\text{-}40\text{km/hr}$, deceleration $(40\text{-}0\text{ km/hr}) -1\text{m/s}^2$ [3].

Rolling resistance and gradient resistance are calculating using the gradient slope angle with in distance and total mass of the vehicle. And the aerodynamic resistance force is determined from air constants/i.e. wind speed 15m/s , air density 1.2kg/m^3 , dragging constant 0.4 and frontal area of the vehicle 10m^2 [4]

Traction force has been determined by adding the accelerating force, rolling resistance force, aerodynamic resistance force and gradient resistance force. From traction force traction power and braking power is determined. With integration of the power traction energy consumption and regenerative energy are determined.

The result of the running of the Matlab SIMULINK is discussed below.

4.1.1 Traction force and speed profile

In the figure 4-3 below the relation of the speed and traction force from the simulation of train movement on leveled /no gradient track is shown.

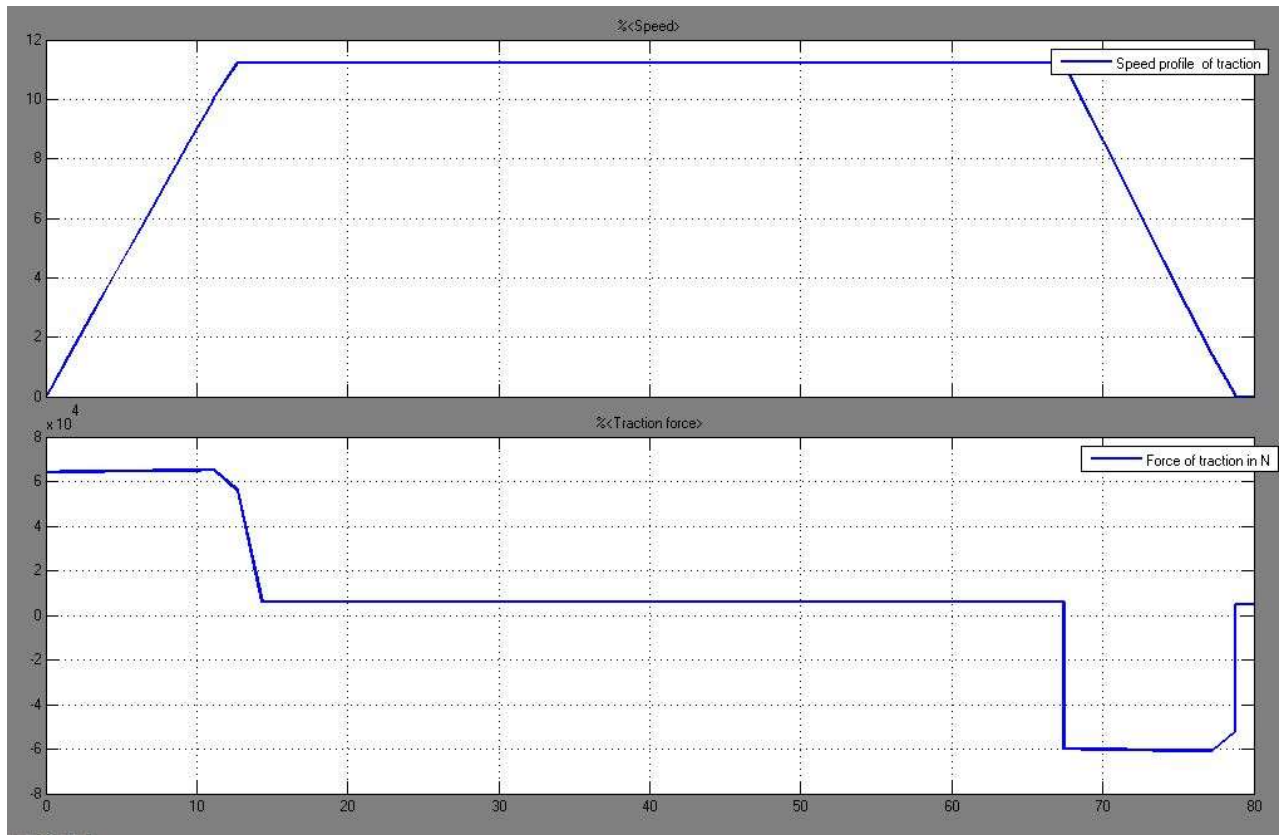


Figure 4-3 Speed profile (m/s) and traction force (N) on time (sec) domain graph for leveled track

Figure 4-3 shows the speed time curve and the tractive force of the train which is required to overcome resistance force and make the train to move at the required speed. The traction force is maximum during the acceleration period. The force in this period is the summation of the rolling resistance force, aerodynamic resistance force, gradient resistance force (it is zero at leveled track) and accelerating force. During constant speed period the force is less because the accelerating force is zero. At the decelerating period the force is at its maximum negative value, it is the breaking force.

4.1.2 Traction energy and power

The traction power and Energy graph in time domain change in accordance to traction force at states of accelerating, constant speed and decelerating /braking.

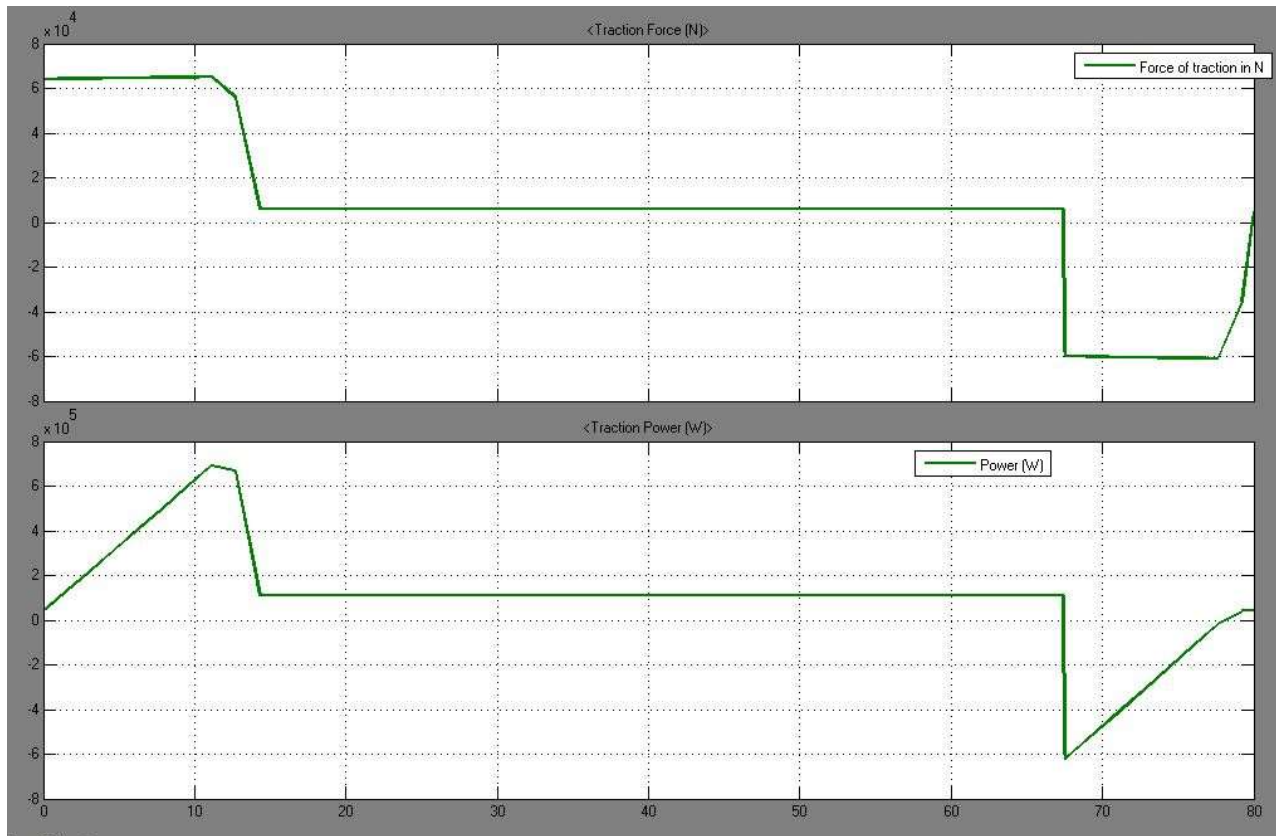


Figure 4-4: Traction force (N) and Traction Power (W) graph in time domain or leveled track

Here as it is seen in figure 4-4 the power graph changes with the change of force on time domain at zero gradients. In the three states acceleration, constant speed and braking periods, the power graph increases for the acceleration period from zero to its maximum point with in the period of acceleration, as the force is smooth at its maximum. At constant speed stage it decline to lower positive value of constant speed power value, as the power is related to force, at this state there is no acceleration force means also required power is less. For decelerating state /the traction force is at its negative maximum value, also the power graph is changes to negative maximum peak power and return with decelerating rate of slope to stopping.

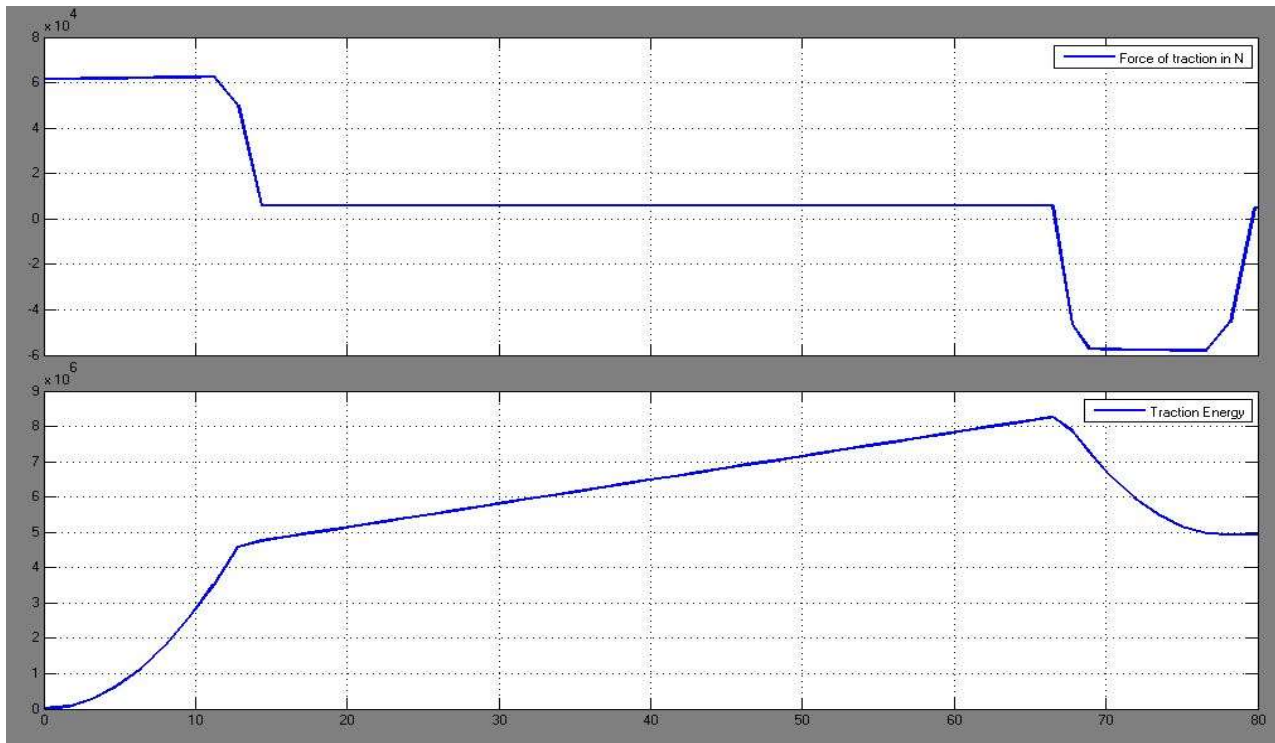


Figure 4-5 Traction force and traction energy graph for leveled track on time domain

Figure 4-5 shows the simulation result of the traction energy curve in comparison to the traction force for leveled track on time domain. For the acceleration period the traction energy is forming positive parabolic curve as traction force is constant positive maximum value. At constant speed phase /zero acceleration state Energy is increasing at constant smooth increasing rate. During braking period, the force of traction is at the negative maximum value whereas, the energy curve forms negative parabolic /i.e. braking energy. This shows how the braking energy is resembling to negative value.

4.1.3 Gradient effect of Traction

To see the effect of gradient change on the traction force, energy and power, we will see the simulation result for the track line of Lancha to Nefasilk II and for reverse direction.

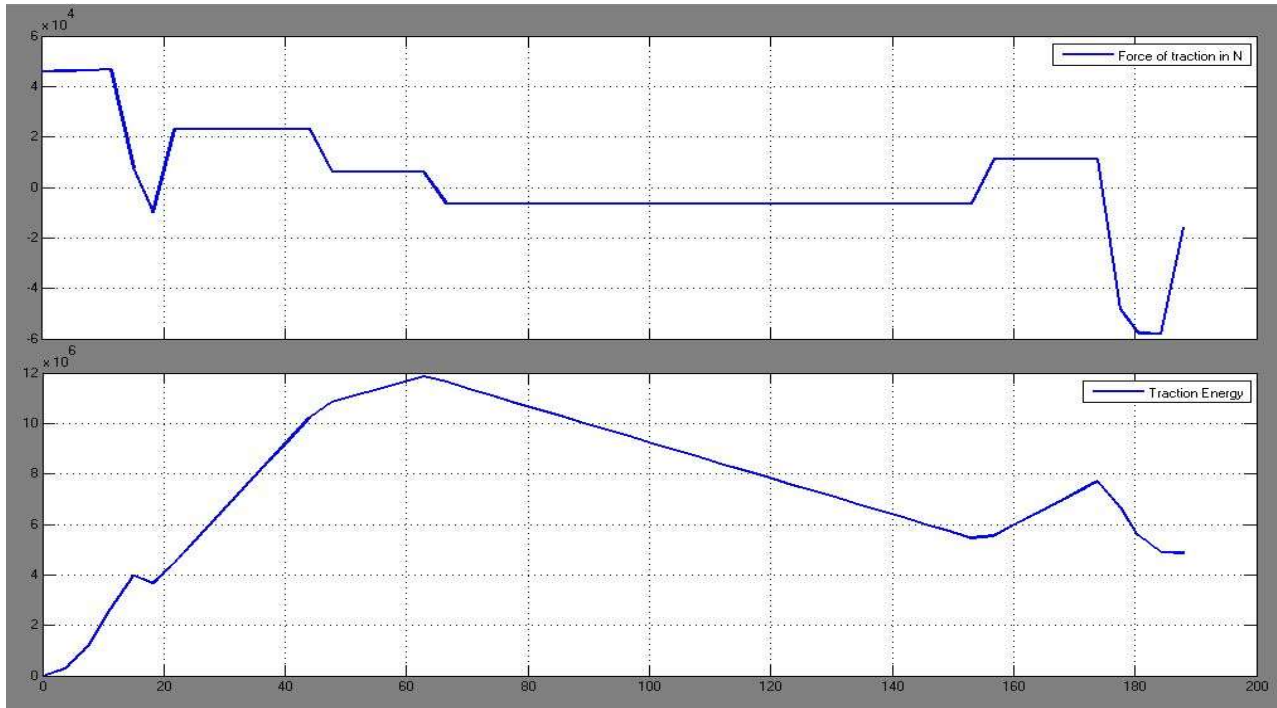


Figure 4-6: Force of traction(N) and Traction Energy(J) in time(sec) domain for the track line Lancha - Nefas Silk II

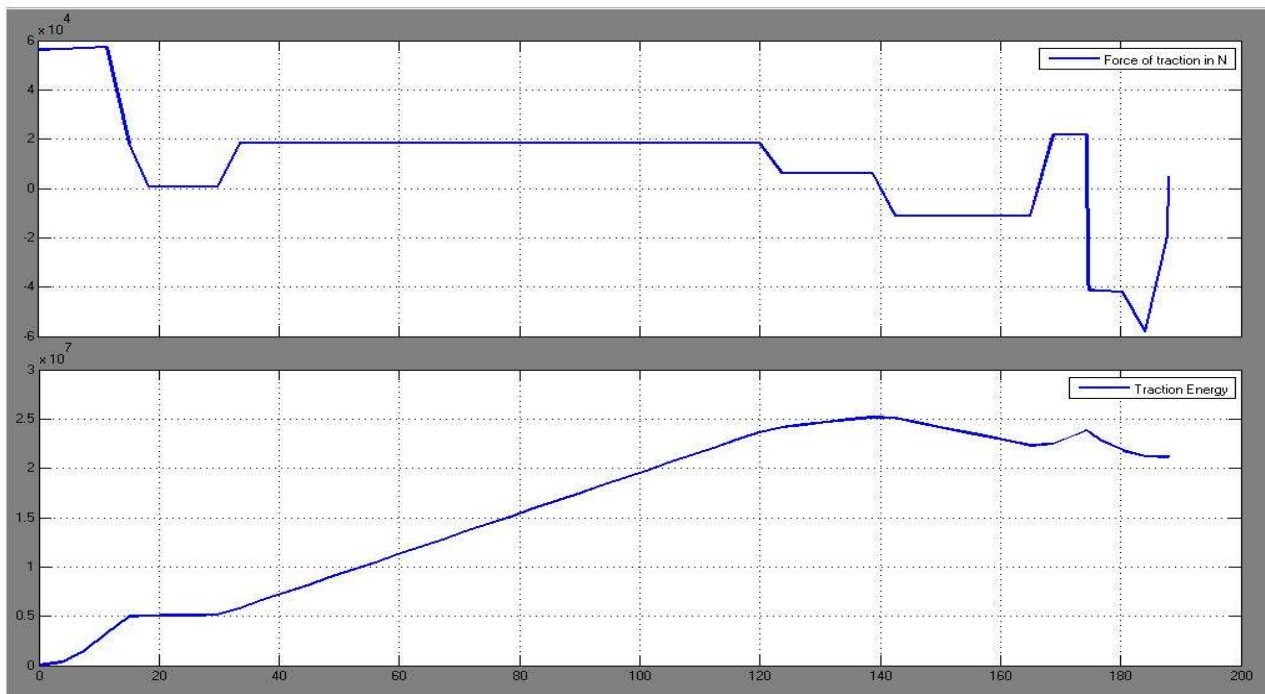


Figure 4-7 Force of traction and Traction Energy simulation curve of NefasSilk II - Lancha

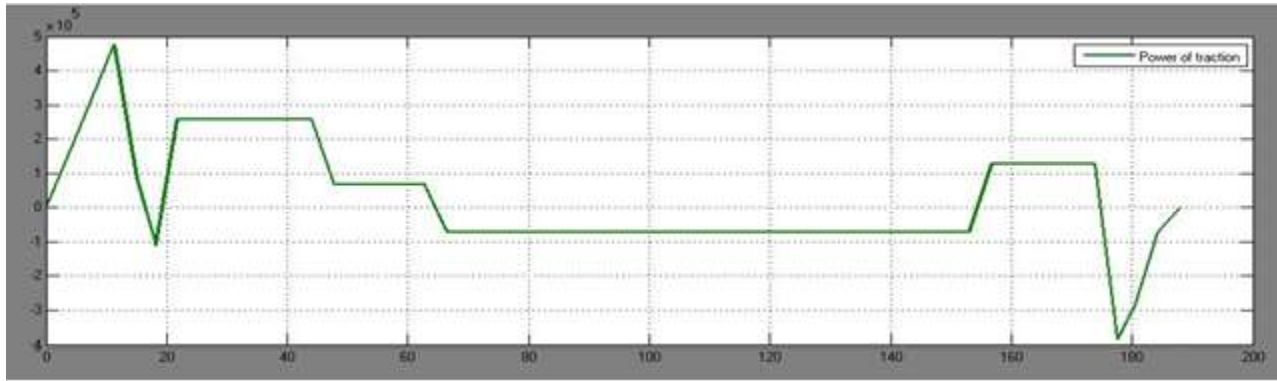


Figure 4-8 The simulation curve of traction Power (W) on time domain for Lancha-NefasSilk II

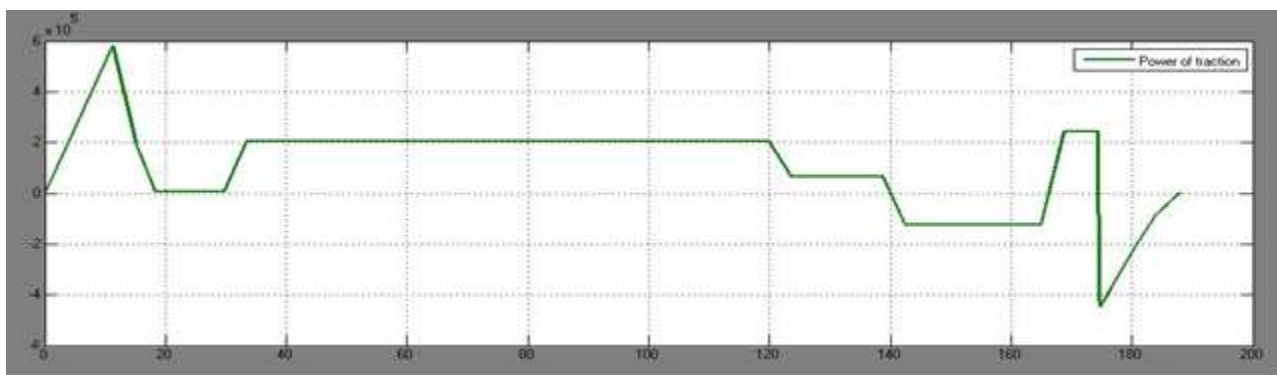


Figure 4-9 The simulation curve of traction Power (W) on time domain for NefasSilk II - Lancha

As shown in figure 4-6 and figure 4-7 the curves of traction force and traction energy on time domain with presence of gradient change for the lines Lancha-NefasSilk II and NefasSilk II – Lancha. Figure 4-8 and figure 4-9 shows the curves of traction power in presence of gradient change for the lines Lancha-NefasSilk II and NefasSilk II – Lancha. As the gradient is more negative gradient the vehicle is forced to accelerating downhill to control it and made to run at the required speed braking force is needed; which means the force, energy and power features resemble to braking. For uphill gradient or positive gradient it needs more positive force to overtake the gradient; which means the force, energy and power are positive increasing. In the uphill tracks large energy is needed to overcome resistance forces applied on the train movement.

4.1.4 Simulating Brake Regenerative Energy

The brake regenerative energy is an energy regenerated back by the traction motor during braking. It is more or less expected during the decelerating time of the vehicle from its maximum speed to stop. As shown in the figure 4-10 the braking energy and regenerative energy are obtained during the braking time to stop for leveled track line.

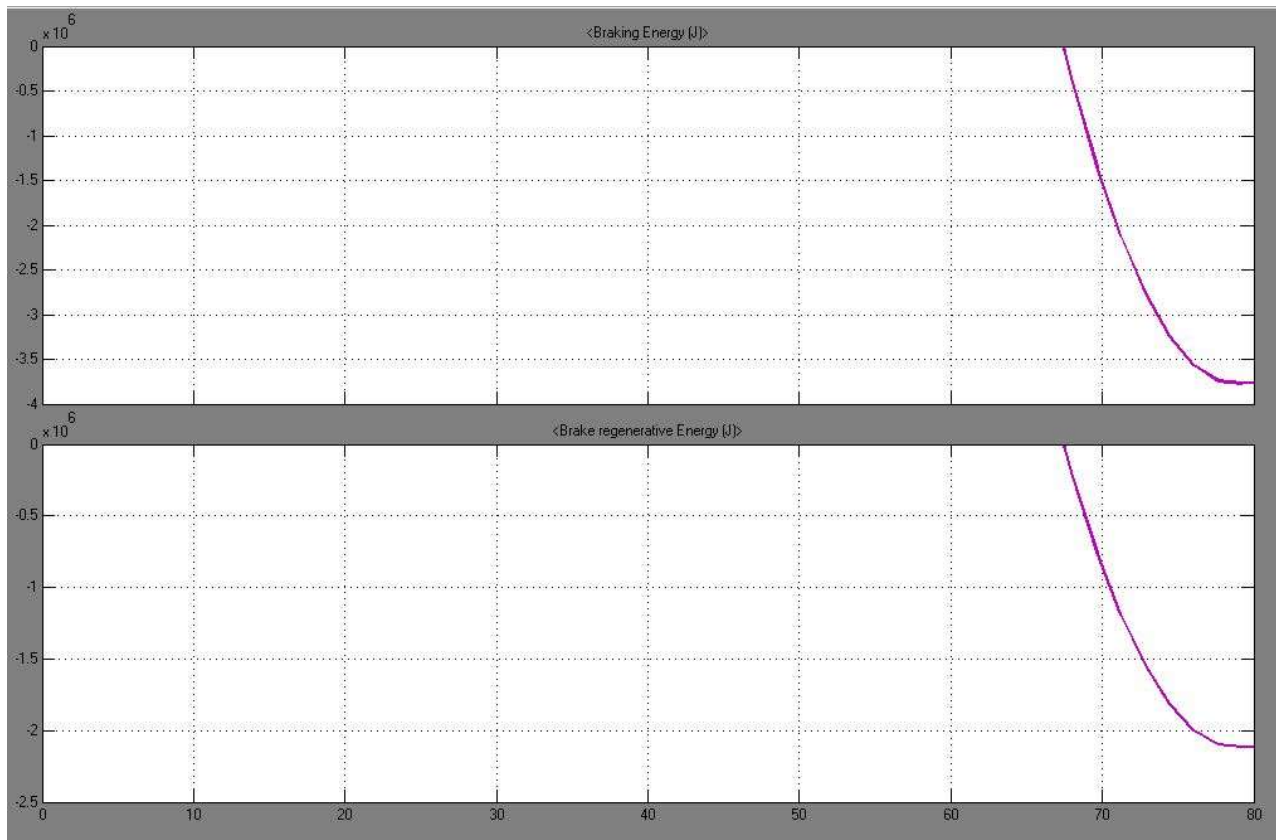


Figure 4-10 The Braking energy and regenerated energy on time domain for leveled track

During simulation for unlevelled track lines braking energy is available out of the braking period to stop. It is obtained by the gradient effect in the downhill movement.

At the downhill tracks more energy is generated due to the down gradient needs braking/dragging force to balance to the required speed movement. During this period of braking the downhill gradient effect leads to generate regenerative energy. As the track is more downhill the braking energy is produced even out of the decelerating period to stop as shown in figures 4-11 and 4-12.

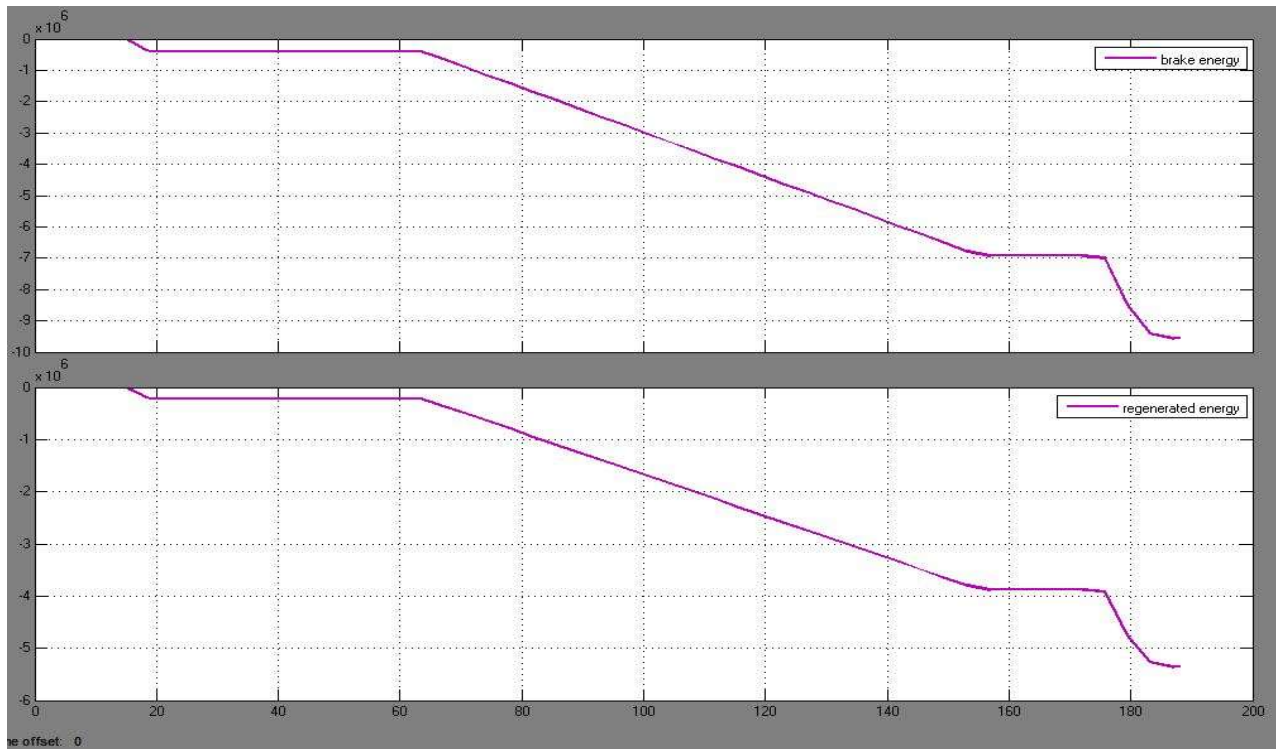


Figure 4-11: The Braking energy and regenerated energy on time domain for Lancha– NefasSilk II station.

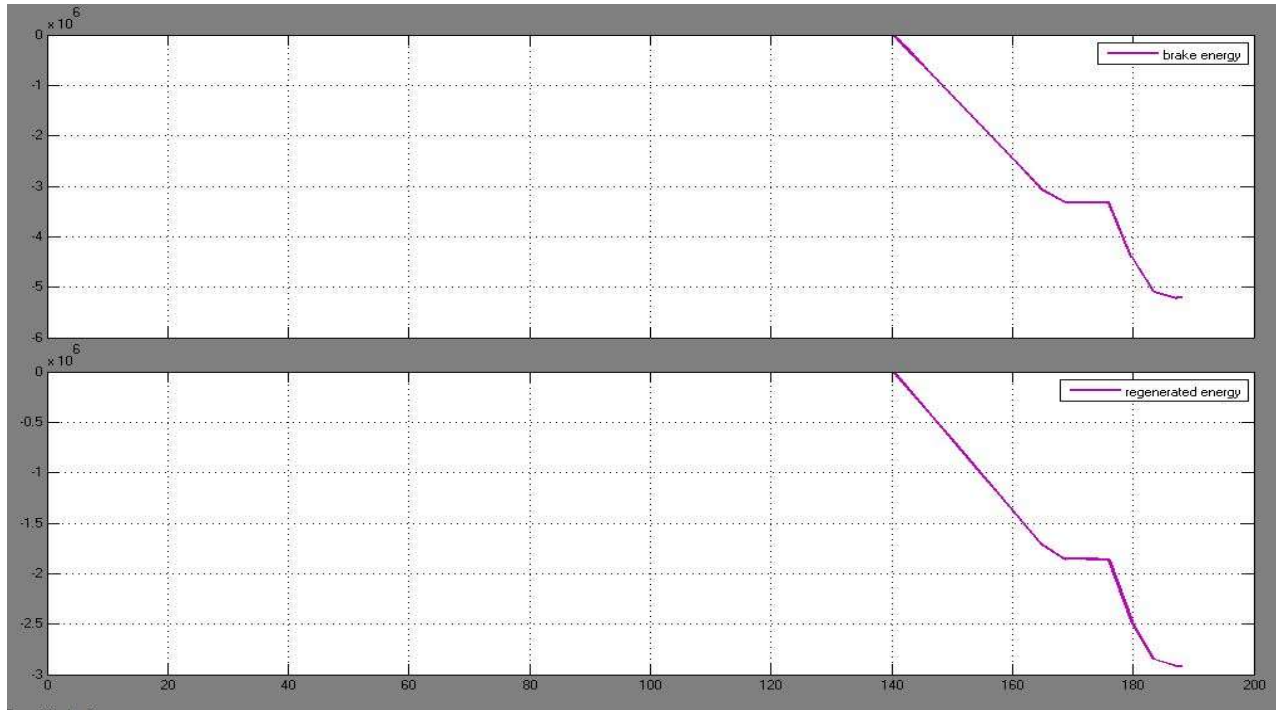


Figure 4-12 The Braking energy and regenerated energy on time domain for NefasSilk II – Lancha station

As it can be seen from figure 4-11 and figure 4-12 in more downhill gradient tracks there is breaking energy outside of the braking time to stop at station. Due to this the regenerated energy is also larger than the regenerated energy produced at the braking to stop. On the track line between NefasSilk II and Lancha; Lancha to NefasSilk II the track line is more downhill than NefasSilk II to Lancha. Due to its downhill gradient feature on the driving of Lancha to NefasSilk II has generates more brake regenerative energy than driving NefasSilk II to Lancha.

The generated and consumed energy is presented in table 4-1 below to allow for a comparison between the different cases in this study from Menelik II to Kality the whole track and should be relative.

	Stations		Forward		Return	
	Depart Station	Destination Station	Consumed energy (kWh)	Regenerative energy(kWh)	Consumed energy (kWh)	Regenerative energy(kWh)
1	Menelik II square	Atiklittera	6.32	1.25	8.76	0.42
2	AtiklitTera	Gojamberenda	7.92	0.95	7.44	2.03
3	Gojam berenda	Autobus Tera	4.97	0.76	3.97	0.91
4	Autobus Tera	Sebategna	4.69	0.70	6.39	0.58
5	Sebategna	Abinet	7.61	1.83	11.47	0.43
6	Abinet	Darmar	5.00	1.18	8.33	0.43
7	Darmar	Lideta	3.94	0.61	6.58	0.58
8	Lideta	Tegibareid	5.23	0.48	5.75	0.78
9	Tegibareid	Mexico	4.97	0.60	4.08	0.96
10	Mexico	Leghar	2.83	0.38	4.94	0.30
11	Leghar	Stadium	3.01	0.52	5.17	0.56
12	Stadium	Meshalokiya	6.44	0.98	7.2	0.58
12	Meshalokiya	Riche	3.19	0.60	5.19	0.55
13	Riche	Temenjayazhi	3.50	0.73	6.31	0.37
14	Temenjayazhi	Lancha	2.75	0.48	5.00	0.42
15	Lancha	Nefas Silk II	8.89	1.44	11.28	1.01
16	Nefas Silk II	Nefas Silk I	3.91	0.55	6.31	0.61
17	Nefas Silk I	Adeyababa	5.25	1.19	9.78	0.46
18	Adeyababa	Saris	2.43	0.45	4.94	0.39
19	Saris	Abo Mazoriya	3.40	0.71	7.22	0.42
20	Abo Mazoriya	Kaliti	2.39	0.33	6.36	0.50

Table 4-1 Consumed energy and regenerated energy in each station

4.2 Simulation of Onboard Energy Storage System

The simulation is done to validate the capacity of the storage device to provide the required power to the train motor. The simulation used for driving the line NefasSilk II to Lancha to validate the capacity of hybrid ESS supply in the longest, large energy consumption and gradient effect track line.

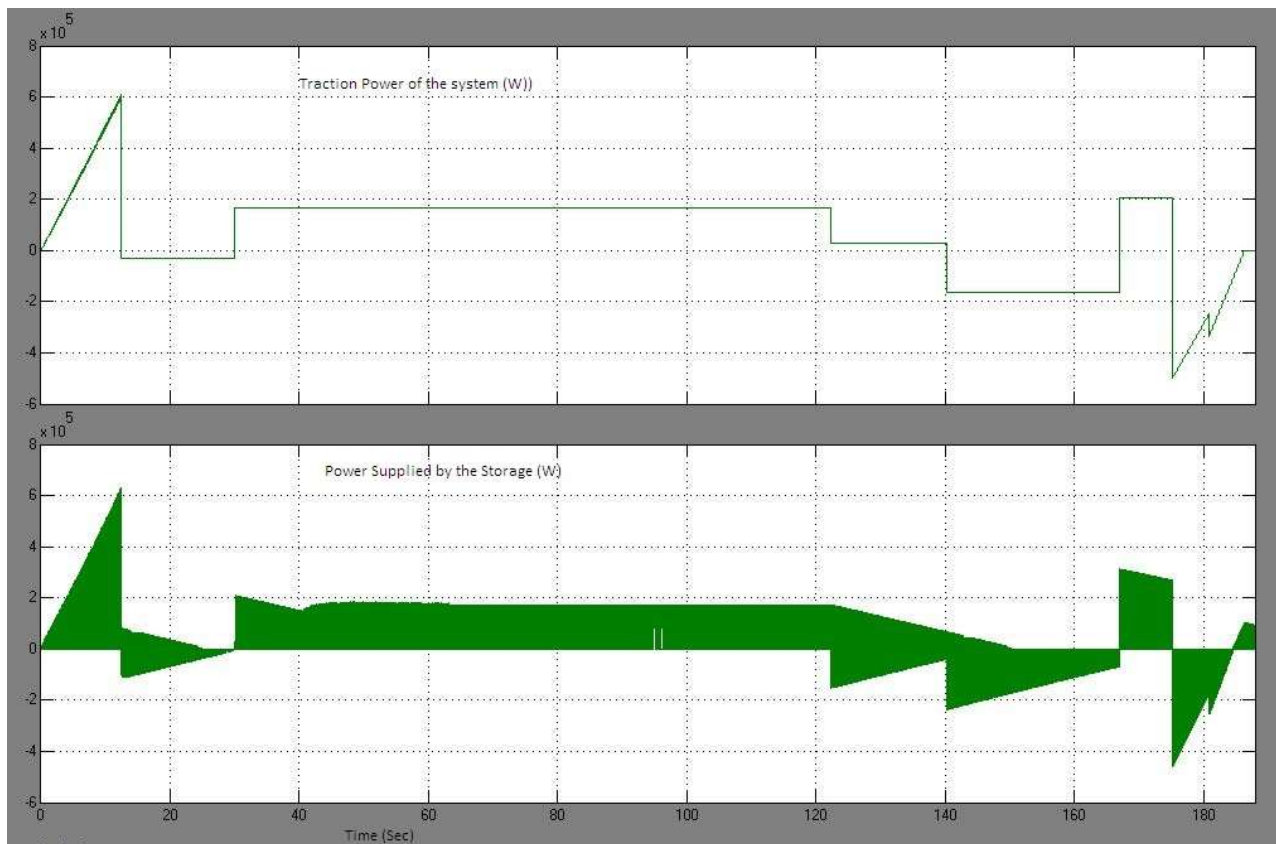


Figure 4-13 Power Supply from ESS for traction of NefasSilk II to Lancha stations

NefasSilk II to Lancha is the longest track covering 1955m. This track line has uphill and downhill gradients. As it is seen from the graph power supply from the ESS is matching with the power required curve of the track line. This shows the ESS has the capability to deliver the required power at required time. For this long track with variable power demand as per the gradient change can be supplied from the ESS.

As it is validated for power capability of the ESS to the traction, let check the states of charge and discharge of the storage in consideration to as the power demand for traction. It is also the validation for recapturing ability of the regenerated power and energy.

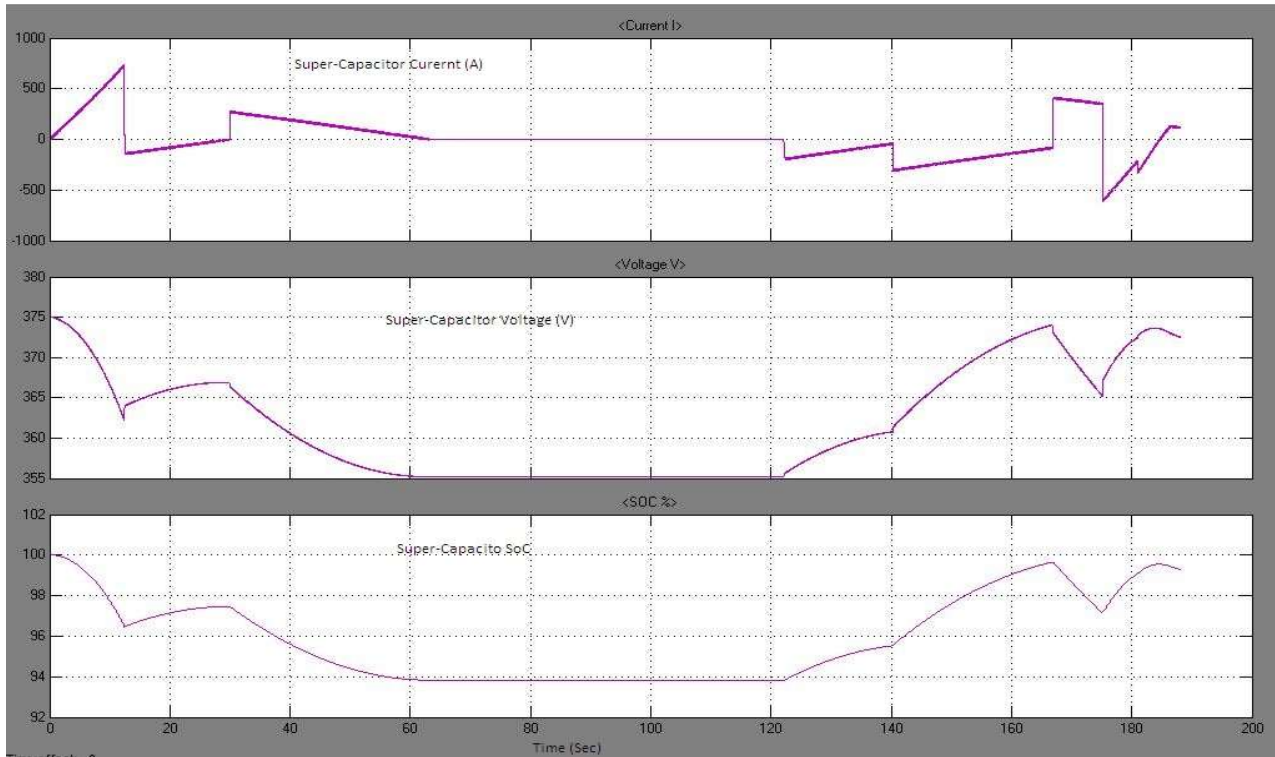


Figure 4-14: Super-Capacitor SoC, current and voltage chart for the traction of NefasSilk II – Lancha

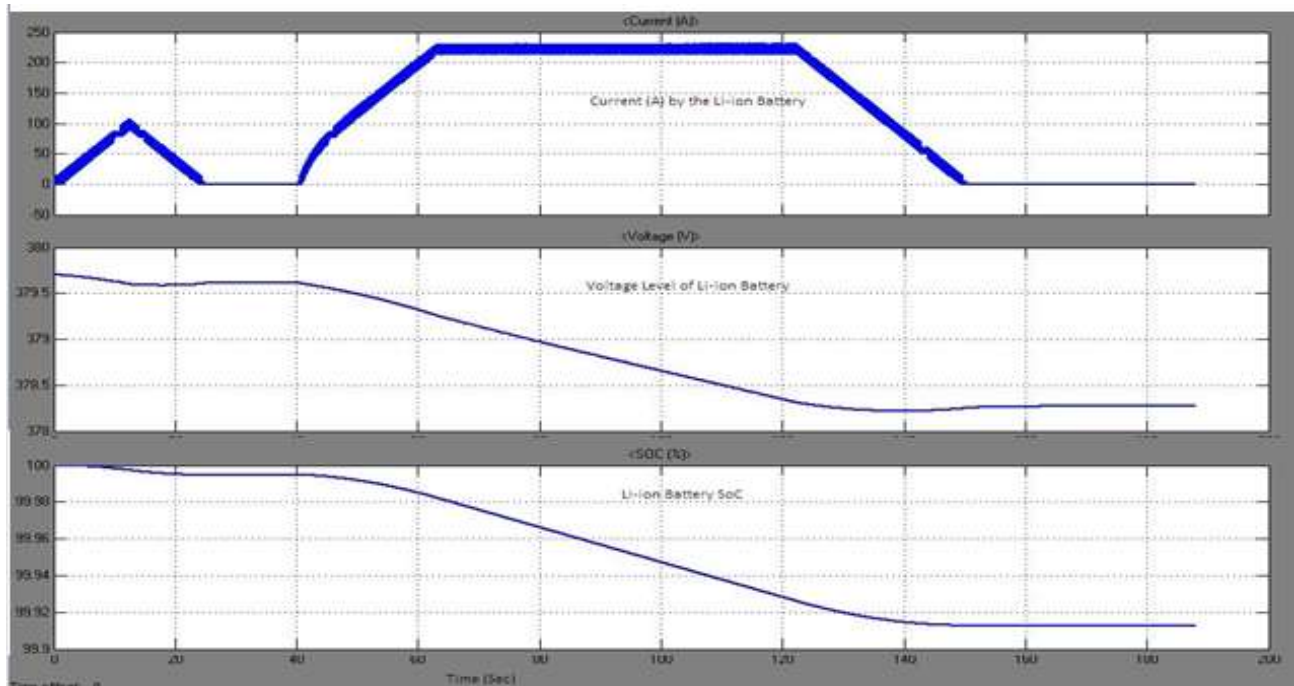


Figure 4-15 Li-ion Battery Level of voltage and charge for the traction of NefassilkII – Lancha

Figure 4-14 shows the current, voltage and SoC% status of the Super-Capacitor ESS in the hybrid. And Figure 4-15 shows the Current, Voltage and SoC% status of the Li-ion Battery ESS in the hybrid system in the traction of NefasSilk II to Lancha track line. As seen in the curves the SoC for SC is not discharged below 94% and for Battery it is not below 99.9%. The voltage and current curves are balanced with the required power to supply. The total Energy delivered for the traction is 11.28kWh and which is 14.14% of the ESS total capacity. To supply this energy the SoC is not discharged more than 5%. This shows the HESS has a good potential to supply the traction required energy.

From the Regenerative energy the Super-Capacitor is recharging during regenerative energy generation. The battery SoC is not charging, b/se the battery is set not to charge when the SoC of the battery is more than 80% for saving the life cycle of the battery. The life cycle of the battery is extending using the super-capacitor long life cycle efficiency.

On the accelerating phase means peak power demand more of the power is delivered from the super-capacitor, on its high-power efficiency of SC. On the constant speed level for long time delivery the power is delivered from the battery. This shows how the hybrid system is essential to satisfy the demand supply of the system, with integration.

On the high-power demand of the storage the Super-capacitor SoC discharges up to 96% and the voltage discharge from 375V to 363V and recharged back to 367V with SoC 97%. Then again discharged to 355V with SoC goes to 94%. During braking time SC charging to 374V with SoC 99%. This is the dynamic nature of the Super-capacitor due to the fast respond to charge and discharge, which makes SC be the appropriate ESS for regenerative energy storage. The state of charge of the battery discharge to 99.9% with voltage level change from 379.6V to 378.3V.

Using the hybrid ESS system it is possible to recapture regenerated energy in full round trip 30.01kWh and with its full capacity charge of 79.78kWh. The HESS can drive the train for 60kWh energy (i.e. 75% of the full capacity).

The HESS is design to have the capacity of 750kW Power. It is expected at maximum power of 750kW for traction accelerating at the gradients. The grid can supply at maximum 637.5kW power. So the ESS can improve the power efficiency of the traction with 15% minimum. And energy

efficiency improved with 12.4% in a day. It is considered without the voltage drop for distance of the train from the substation.

4.3 Cost analysis

Based on the design for the ESS, to have appropriate hybrid energy storage system, it is selected BMOD0063P125 Super-capacitor and Lithium ion MX9535 battery with its appropriate feature for onboard energy storage, and compatibility of its voltage and current value for the design requirement. The purchase of the ESS and its service can be calculated based on the current market price. Current market price of SC ESS of BMOD0063P125 is 500USD per module [36]. For the designed SC we need 24 (3 in series with 8 parallel branches) modules per vehicle (Table 3-2). The calculation is done only for one vehicle, the total initial cost of the SC ESS modules will become: $24 \times 500 \text{USD} = 12,000 \text{USD/vehicle}$

The DC-DC converter with duty ratio of 2 and SC side 375V and Supply side 750V with current rating of up to 2200A costs 278USD and hence the total cost for Super-capacitor costs will become 12,278USD.

And the price of each Lithium ion MX9535 battery (Table 3.3) cost 365.60 USD. Therefore, for this design 36 modules (6 in series with 6 parallel branches) are used and will cost 13161.60USD DC-DC converter for battery side (with duty ratio of 2 and rating battery side 380V and Supply side 750V with current rating of up to 1200A) cost about 278USD therefore the total cost of this energy storage is 13439.60USD.

For a vehicle 65272.10USD is required for installing ESS in a train which is $25715.60 \times 23.35 = 600,459.26 \text{ ETB/Train}$

For securing the market variation $600,459.26 \text{ ETB/Train} + (600,459.26 \text{ ETB/Train} \times 15\%) = 690,528.15 \text{ ETB/Train}$

Return Calculation

In a single round trip from north to south (i.e. Menelik II to Kality) 30.01kWh energy can be regenerated. In a day a train works 8 rounds. The regenerated energy obtained in a day is 240.08kWh.

This energy is utilized by the train at any time required for power consumption stabilization and for catenary free running.

In a month 6722.24 kWh energy can be brake regenerated and utilized with the ESS. According to the current Ethiopian electric energy tariff for industrial 3 phase users $6722.24 \text{ kWh} \times 0.46 \text{ birr} = 3092.23 \text{ Birr}$ and service payment 56 Birr total 3148.23 Birr/month.

In a year $3148.23 \times 12 = 37778.76$

It is impossible to recover the cost of the ESS from the energy cost only. It can recover the cost in more than 10 years and the expected service time of the ESS is 10 years. So let consider the cost from the service.

This energy is used for transporting passengers. The energy consumption for traveling from MenelikII square station to Kality station with round return is 241.11kWh.

Let calculate the energy availability impact on the transportation service availability with passenger's tariff.

On average with 6 persons/m² a train capacity is 254 people. And for one person to travel from Menelik II square to Kality or Kality to Menelik II square pays 6 birr/person.

So, in a day a train can move one single trip Menelik II – Kality with the energy supply of the ESS, then it can get $256 \times 6 = 1536 \text{ Birr}$ can be collected in a day by using the ESS. It can consume 145 kWh Energy for traveling Kality to Menelik II, and this energy is less than the regenerated energy saved by the ESS in a day.

So, in a month 43008 Birr/month can be collected from passengers for transportation service. In a year 516,096 Birr can be collected.

Within three years 1,548,288.00 Birr can be obtained from the transportation service tariff collection. The cost of the ESS can be returned within 3 years' service. In addition to its power availability benefit the ESS onboard availability has high probability of solving in optimizing power demand problem, increases the insurance level /which minimizes insurance risk, increase vehicle and infrastructure durability.

Chapter 5

5. Conclusion and Recommendation

5.1 Conclusion

The objective of this thesis is to study the use of onboard energy storage system for the Addis Ababa Light Railway Transit. Energy storage technologies and application in railway has been reviewed. The regenerative energy technology also reviewed and studied for the AALRT system. Different literatures related to onboard energy storage system and brake regenerative energy have been reviewed.

Super-Capacitor energy storage technology is the fitting technology for recapturing of the brake regenerative energy as it has fast responding and power efficiency features. But SC is not efficient to store more energy with small area and mass. For energy efficiency Li-ion is better storage technology from other chemical batteries on its responding time and life cycle. So to have efficient mechanism of recapturing brake regenerative energy and efficient energy density, hybrid energy storage technology better situated. The design for Hybrid ESS has been made with energy capacity of 79.78kWh, and mass of 2460kg. For the effectiveness of energy and reduction of additional mass to the vehicle HESS/Hybrid Energy Storage System is the accurate choice for the onboard ESS.

Simulations of energy consumption, regenerative energy and ESS have been done using Matlab/SIMULINK software.

As the result of the simulation the energy consumption for the round trip is 241.11kWh. 30.01kWh energy can be generated and saved in the ESS from the brake regenerative energy. So the regenerated energy is 12.4% of the total energy consumption.

And also from the simulation the effect of gradient slope on the uphill and downhill has been observed. The uphill gradient slope demands more positive power, whereas the downhill movement of the traction system dragging force /negative power is more resembled. Due to this

dragging requirement on the downhill traction movement brake regenerative energy can be generated outside of stopping stations. This increases the amount of regenerative energy. From simulation result to travel from menelik II to Kality 16.72kWh energy can be regenerated whereas for Kality – Menelik II 13.29kWh energy can be regenerated. This energy difference for the same line is obtained due to the gradient effect.

Energy storage system validating simulation has been conducted for the traction of NefasSilk II to Lancha station. This track is selected, because it has the feature of uphill - downhill gradient, it is the longest station distance and the largest energy consuming track line.

From the simulation of the track the ESS supplies 11.28kWh energy with maximum power of 640kW. The SoC of SC fails up to 94% SoC of battery moves up to 99.9%. The Super-Capacitor has got charged to 99% SoC from the brake regenerative energy.

The implementation of the ESS costs 1,524,103.54 ETB/Train. This cost can be returned from the storage of the regenerative energy with ESS for increasing the availability and reliability of the operational service. It can be returned within 3 years of service by the cost of the conveying of passengers.

Based on the research result, it can be concluded that onboard energy storage system is an effective solution for recapturing the brake regenerated energy 240.08 kWh in a day. This is 12.4% energy of consumption; it increases the energy efficiency by recapturing and using the regenerated energy. And also improves the power efficiency with 15% for supplying power for accelerating with gradients up to 750 kW. The ESS supply energy for the traction during grid supply outage and to minimize energy consumption of the traction.

5.2 Recommendations

The recommendation of this thesis is to use onboard Hybrid Energy storage system for AALRT. Since it improves the energy availability of the operation system and also improves the reliability of the operation. And improves the energy efficiency by recapturing the energy from loss.

The implementation of onboard Energy storage system for AALRT in addition to improving Power and energy efficiency, it also increases the insurance level /which minimizes insurance risk, improve durability of vehicle parts and infrastructure.

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