Addis Ababa Univesity

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Electrical Railway Engineering – Graduate Studies

Management of Regenerative Braking Energy for Addis Ababa Light Rail Transit System

By

Mequanint Biazen Ayalew

Addis Ababa, Ethiopia

April 2015

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Management of Regenerative Braking Energy for Addis Ababa Light Rail Transit System

A Thesis Submitted to School of Electrical and Computer Engineering
in Partial Fulfillment of the Requirements for the Degree of Master of
Science in Railway Electrical Engineering

By

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Advisor

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Addis Ababa, Ethiopia

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DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in any other university.

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ABSTRACT

Addis Ababa light railway is one of the newly constructing railway transport system in Ethiopia. Urban rail plays a key role in the sustainable development of metropolitan areas for several reasons such as its high capacity, energy efficiency and lack of local air pollution. Electricity has become the primary source of traction power in modern railways. DC-electrification is often used for urban public transport.

Most electric trains in DC-electrified railways are presently equipped with regenerative braking system. Regenerative braking is a means to save energy and reduce maintenance costs in railway industry. Ultra-capacitor is a major promising alternative of energy storage technologies in the urban rail system. Compared to other storage technology, the ultra-capacitor has the advantages of **rapid charging** and discharging frequencies, a long cycle life and high power density, which highly match the characteristics of urban rail transit such as short running time between stations, frequent accelerating and braking and booming power within a short time.

In this thesis a braking energy recovery system based on super-capacitor is presented for Addis Ababa light rail transit system. Regenerative brake is preferably applied as service brake for AART vehicles. Taking the movement of Addis Ababa light rail transit trains between two stations for design purpose, it is shown that ***34*** percent of consumed energy can be regenerated using regenerative braking system. Regenerated energy is fed back to power other train in the network through brake chopper module or such energy is depleted by brake resistor when there is no train in the network to consume this energy. The thesis assesses **design of onboard super capacitor** based energy storage system for saving energy which is to be depleted by brake resistor. Based on the design $\mathbf{1.645 * 10^3} \boldsymbol{Farad}$ capacitance of super capacitor is required to save regenerated pick energy.

In order to validate the design and do further research, the thesis presents a mathematical model of the whole system. At the end, the simulation is done, the results of simulation has been developed in Matlab programs and Simulink with theoretical analysis.

KEY WORDS: Bidirectional DC–DC converter, Energy Efficiency, Light railway transportation, Rail Vehicles, Regenerative braking, Simulation, Stationary Energy Storage, Super capacitor

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LIST OF ACRONYMS

AALRT	Addis Ababa Light Rail Transit
AC	Alternative current
AT	Autotransformer
ACU	Auxiliary Control Unit
BT	Booster Transformer
CSI	Current Source Inverter
DC	Direct current
EDLC	Electric Double-Layer Capacitors
EMF	Electro Motive Force
ESD	Energy Storage Devices
g	Acceleration due to gravity
GTO	Gate-Turn-Off
HSCB	High Speed Circuit Breaker
IGBT	Insulated Gate Bi-polar Transistor
IM	Induction Motor
MG	Main traction Generators
Ni-H	Lithium-Ion or Nickel-Hydrogen
PWM	Pulse Width Modulation
RPSSs	Railway power supply systems
SC	Super Capacitor
SCU	Switch Control Unit
SRAM	Static Random-Access Memory
TSSs	Traction Substations
VFD	Variable Frequency Drive
VSI	Voltage Source Inverter
VVVF	Variable Voltage Variable Frequency

1. INTRODUCTION

1.1. Background

The railway transportation industry is often regarded as an energy efficient and environmentally friendly mode of transport [2]. Urban rail plays a key role in the sustainable development of metropolitan areas for several reasons such as its high capacity, energy efficiency and lack of local air pollution. Urban rail typically includes tramway, light rail, metro and commuter rail systems. They offer different levels of service. But they are all characterized by being electrically powered and by presenting short distances between stations [2].

1.1.1. History of rail way technology in Ethiopia

Railway transportation system had been used as a major freight and passenger transport in Ethiopia from 1917 to 2010. The system comes to existence during the reign of Emperor Menelik II and covers a total of 781km powered by diesel engine and jointly owned by Ethiopia and Djibouti [1].

Now Addis Ababa light railway is one of the newly constructing railway transport system. East-West and South-North lines are under construction in Addis Ababa (Phase I). Total length of main lines is around 33.6875km, where the East-West main line is around 16.998km long; the South-North main line is around 16.689km long. It has the subgrade section about 10.057km in length, the elevated section about 5.977km in length (including a common rail section 2.662km in length), and the underground section about 0.655km in length [1]. There are 39 LRT stations and five of them are shared with both South-North and East-West corridor. The minimum separation distance between stations is 435 meter; the maximum separation is 1972 meter and the average interval is 775 meter for both South-North and East-West corridor [1].

Addis Ababa light railway vehicles are 70% low floor modern trams with maximum operating speed of 70km/h. The vehicles shall be able to operate under the ground, on the ground or on elevated lines. It is ensured that the vehicles be able to safely operate at lower speeds with grade 8 wind (20.7m/s) when operating on the ground and elevated lines and that the empty vehicles be able to safely park on the lines with grade 9 wind (24.4m/s). The vehicles shall be maintained and checked inside the on-ground depot and parked outside the depot [1].

1.1.2. Railway power supply systems (RPSSs)

Railway power supply systems (RPSSs) differ mainly from public power systems from that the loads are moving [20]**.** These moving loads are motoring trains. Trains can also be regenerating when braking and are then power sources. The evolution in electrical traction systems has produced a variety of electrification systems used to provide energy for rolling stocks either in DC or in AC with different voltage levels [9]. By practical reasons most RPSSs are single-phase AC or DC. Three-phase public grid power is either converted into single-phase for feeding the railway or the RPSS is compartmentalized into separate sections fed individually from alternating phase-pairs of the public grid [15]**.**

DC-electrification is often used for urban public transport. The metro train electrified lines employ the low voltage DC systems, generally supplied at 0.75kV or 1.5kV, which are usually the most economic. In this case the pantograph connects directly the contact line to the power invertors of the train by means of filter capacitors; conversely in case of AC lines the inverter is connected instead in cascade to an AC-DC rectifier [25].

1.1.3. Energy consumption and regenerative braking system of train

Energy used by train operations accounts for around 70% of all energy used by the railway system [4]. It follows that it is not only environmentally beneficial but also economically advantageous to reduce energy consumption. Because of electric traction system of metro frequent start-up, braking process, braking energy is considerable. Statistics show that apart from certain percentage energy (usually 25%~35%) being absorbed by other adjacent train, the rest braking energy is mainly consumed by braking resistance, which leads to both massive energy waste and temperature increment in tunnel and platform [15].

The improvement of traction electrical energy efficiency for urban rail vehicles has been one of the primarily objective in recent years [12]. Regenerative braking has been used to improve energy efficiency for railway system. A **regenerative brake** is an energy recovery mechanism which slows a vehicle or object down by converting its kinetic energy into another form, which can be either used immediately or stored until needed. During braking, the traction motor connections are altered to turn them into electrical generators [5].

Although many trains have power electronic components for regenerative braking as well as powering motors for acceleration recently, it is often difficult to fully use the regenerative electric brake, since the regenerative action requires simultaneous electric loads, which may be mainly other powering trains, in the same electrified line. If there is no considerable electric load in the system, the pantograph voltage immediately increases up to the maximal limitation during its electric braking action, which results in failure of electric motion and supplemental compensation or the braking action by its mechanical braking system [4].

The recovery and reuse of braking energy is one of the most promising measures to reduce urban rail energy consumption, on account of the numerous and frequent stops involved [1]. One approach is to install energy storage devices, such as batteries or super capacitors either track side or on-board trains [2]. This technology could potentially reduce the energy consumption of urban rail between 10% and 45%, depending on the track gradients and the service characteristics [4].

The recovered energy is primarily used to supply the auxiliary functions of the rolling stock itself, whilst the excess energy is returned to the distribution line to power other vehicles within the network. However, as the energy demand of auxiliaries is relatively minor and the simultaneous braking and acceleration of different vehicles in the same electric section is unlikely to occur, a significant amount of the braking energy is dissipated into resistors. Most of urban rail systems are powered by direct current (DC) networks which are less receptive than alternating current (AC) networks, and therefore cannot always absorb the regenerated energy fed back [2].

1.1.4. Energy storage devices

Energy storage technologies are getting more attention to overcome the receptivity issues. On-board and wayside energy storage devices (ESD) combining higher power and energy density with acceptable losses and longer life, such as lithium-ion or nickel-hydrogen (Ni-H) batteries and electric double-layer capacitors (EDLC), promise more efficient train operation. On-board energy storage is an accepted means of conserving energy [4], [9].

1.2. Problem Statement

East-west and South-north line of Addis Ababa light rail transit (AALRT) project have 39 passenger stations with many hill or mountain parts and trains stop frequently within average of 775 meter gap. Regenerative brake is applied preferably as service brake for Addis Ababa light rail transit electric trains. Energy generated by regenerative brake is to be absorbed by adjacent cars along the line. When energy absorption by adjacent cars along the line is not possible, such energy is depleted by brake resistor. Therefore to save this dissipated energy more efficient and reliable power consumption systems should be available for AALRT electric train drive applications. In this thesis management of this dissipated energy using on-board energy storage system (super capacitor) design is studied.

1.3. Objectives of the thesis

1.3.1. General objective

The objective of this thesis is to manage electric power consumption system efficiency of AALRT trains.

1.3.2. Specific objectives

The goal of this study is to introduce and recommend the advantages of implementing onboard energy storage technologies (super-capacitor) to AALRT trains energy regeneration system. Specific objectives of the thesis are listed below.

- Studying and analyzing electric railway traction systems, energy storage device and regenerative braking system used in railway systems of AALRT system
- Mathematical modeling of train movement and power consumption system, Energy model for regenerative braking and Super-capacitor
- Design super-capacitor braking energy recovery system
- Simulate modeled systems using MATLAB Simulink

1.4. Structure of the thesis

The thesis consists of five main parts. The first part is introduction of the thesis.

Part 2 provides a literature survey of history and related works on railway electrification power supply system, Electric drive for railway traction systems, and Power electronics device on railway traction system

Part 3 describes regenerative braking in railway traction system, regenerative braking in dc-electrified railway, efficient use of regenerative electric power, benefits of regenerative braking, and braking systems used in in Ethiopian AALRT systems.

Part 4 describes energy storage devices used in railway systems, stationary and onboard storage devices, and energy storage system based on super capacitor device

Part 5 gives the basic concept, mathematical model derivation, solution method, and analysis of train movement, traction system, regenerative braking energy, energy model for auxiliary equipment, and super capacitor braking energy recovery system.

Finally simulation results of train motion models and energy storage systems are presented.

2. ELECTRIC RAILWAY TRACTION SYSTEMS OVER VIEW

2.1. Power supply for railway traction systems

Electricity has become the primary source of traction power in modern railways. All metro systems are now operated by electricity in one form or another **[40].** DC and AC electric traction systems are commonly deployed in the railway industry. Very different power transmission system requirements exist for each system. Multiple power electronic control stages are commonly used for such traction systems in order to create a smooth power supply from the power network **[18]**. For a DC power supply system, electrical power is usually supplied through a conductor rail which is adjacent to the running rails [24]. The original advantage of a DC power supply system was because it is easy to control the vehicle-mounted traction equipment. With the development of power electronics technology, DC supply is regarded as advantageous due to its compact size and weight of control devices. Typical voltage for a DC power supply system is between 600V and 15kV. This implies higher current going through the supply circuits and higher electrical loss. DC power supply system is mostly applied for urban and regional lines [18].

An AC power supply system is usually using an overhead line consists of a contact line carrying live current and catenaries, which is an insulated suspension system supporting the contact line. An overhead line is located at a certain height above the rails. Power for AC railway traction is obtained from utility supply system, at transmission or sub-transmission voltage level, through traction feeding substations. 25kV traction network at 50 or 60Hz is the most commonly adopted system [19]. Higher voltage level in an AC power supply system reduces the current and electrical loss. Also, fewer substations are required compared with the lower voltage in DC traction networks. A traction power network is employed to supply the electrical power to the entire electrified rail network. Generally, it is economic to use such system for a high speed or heavy-haul railways [13].

2.1.1. Overview of Power supply system used in Ethiopia AALRT

15kV distributed power supply is used as the external power supply for the power supply system of Addis Ababa Light Rail Transit Project. For traction power supply system, DC 750V overhead contact system and current mode of running rail are adopted.

15/0.4kV TN-S system is adopted for power lighting, and the traction substation and step-down substation are integrated into a combined substation. There are 19 combined substations and 1 independent step-down substation set along the whole line.

The boundary point between external power supply and substation is located at the incoming terminal of the 15kV switchgear of the substation. According to the EPC contract, the design and construction of the external power supply and its supporting facilities above the incoming terminal of substation are excluded in the EPC contract of Chinese party. Sketch map for the boundary interface between power supply system and external power source is shown in Figure 2.1.

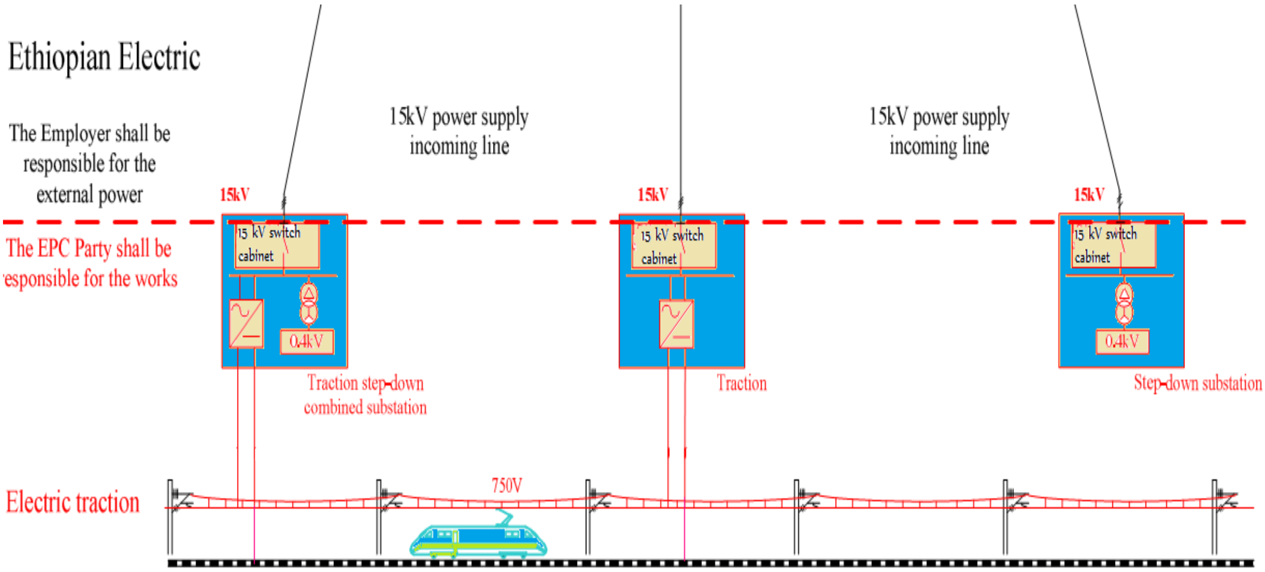

Figure 2-1: Schematic diagram of dividing interface between power supply system and external power supply [1]

The power supply system discipline should set out the requirements for 15kV external power source and determine its capacity. The external power source discipline is responsible for the design of electrical, civil engineering and relevant electromechanical systems introduced by the 15kV external power source of substation.

2.1.2. Auxiliary Power Supply System

Auxiliary power supply system in Ethiopia AALRT includes auxiliary inverter and batteries. Auxiliary inverter supplies AC 380V and DC 24V to vehicles and charges the batteries. When high input voltage of DC 750V is not available (auxiliary inverter not working) for vehicles, it also supplies vehicles with control power and emergency power supply.

1. Auxiliary inverter

Auxiliary inverter mainly consists of line contactor group, IGBT inverter power unit, 3-phase isolation transformer, and logic control unit and filter capacitor. It functions to convert 750V DC into 3-phase 380V AC which will be supplied for auxiliary equipment of vehicles. Similarly, it will also convert 750V DC into 24V DC to be supplied as control power supply for vehicle control systems and all equipment.

There are totally two auxiliary power supply systems throughout the train. Power supplies for auxiliary systems are directly connected in parallel. Each auxiliary power supply system can directly supply power to AC bus on the train and supply auxiliary power of 380V AC throughout the train. In case of failure of one auxiliary inverter during operation, it will automatically disconnect output contactor of auxiliary inverter and isolate AC vehicle bus from such auxiliary inverter. All AC loads on the train will be supplied by remaining auxiliary inverter through AC bus on the train. In such case, failure signal will be provided by faulty auxiliary inverter or auxiliary loads on the train will have degraded operations through TMS.

2. Main loads for auxiliary system

AC loads

- Traction converter fan
- Passenger saloon air conditioning
- Lighting inside the car
- Brake system
- PIS system
- Train borne fare collection equipment
- Cab air supply unit
- DC loads
- External lighting
- Air supply system
- Battery
- Wireless communication equipment

Electrical parameters for auxiliary systems

Table 2-1: Auxiliary AC power supply parameters [1]

Rated capacity:	Input voltage:	Range of voltage:	Output voltage:	Output frequency:
35kVA	DC 750V	DC 500V～900V	3-phase: 380V; single phase: 220V	50Hz±1%

Auxiliary DC power supply

Main electrical parameters for the charger

Output power: 24V/8kW

Accuracy of voltage: 24V±3%

Ripple coefficient: ＜5%

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.

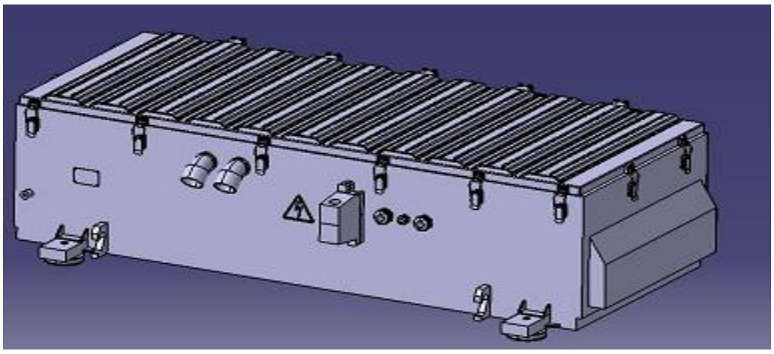

Figure 2-2: Auxiliary inverter [1]

3. Battery

Battery should be sized to retain door control, emergency lighting, external lighting, train borne safety devices and communications in operation for duration of not less than 30 minutes in case of vehicle failure.

Type: Ni-Cd battery

Capacity: 2×60 Ah

Rated voltage: 1.2V/cell

Float charging voltage: 1.45~1.55V/cell

2.2. Electric drive for railway traction systems

The first practical application of electric traction dates back to the second half of the 19th century. At the early stage of development, DC motors, together with low-voltage DC traction lines, were the main traction power supply methods, due to their simple torque control characteristics. Subsequently, low-voltage DC transmission networks and high-voltage, low frequency (16 1/2Hz and 25 Hz) AC transmission networks became the two major electric supply methods for traction power. The reason for the emergence of the AC transmission network was due to the inherent tractive characteristics of induction motors and the difficulties of supplying electrical power from a DC or single phase AC transmission line [12].

The induction motor has long been regarded as a suitable final drive for railway traction systems due to its inherent capability for regeneration and steep speed and torque characteristics. However, the wide spread introduction of induction motors could only be realized after modern power electronics became available [9]. The two reasons for this are as follows:

1. Speed control of the induction motor is achieved by changing the input frequency and voltage of the input power supply;
2. The difficulty of obtaining the proper three-phase supply from a DC or single-phase AC traction line should be solved by power electronics techniques.

2.2.1. Electric traction and Vehicle control system used in Ethiopia AALRT

Traction system used in Ethiopia AALRT includes traction inverter, brake resistor and traction motors as key electrical equipment, as well as high voltage electric equipment such as pantograph, main circuit breaker, and surge arrestor. Pantograph shall collect current from the catenary of DC 750V. It is connected to the traction inverter via high speed circuit breaker (HSCB). The switching on/off of the main circuit of traction system is controlled by HSCB. Each car equipped with a traction inverter for supplying power to the two traction motors on local bogie. Traction motor is subject to axle control. The traction system shall have complete diagnosis functions, and is provided with protective measures against corresponding failures.

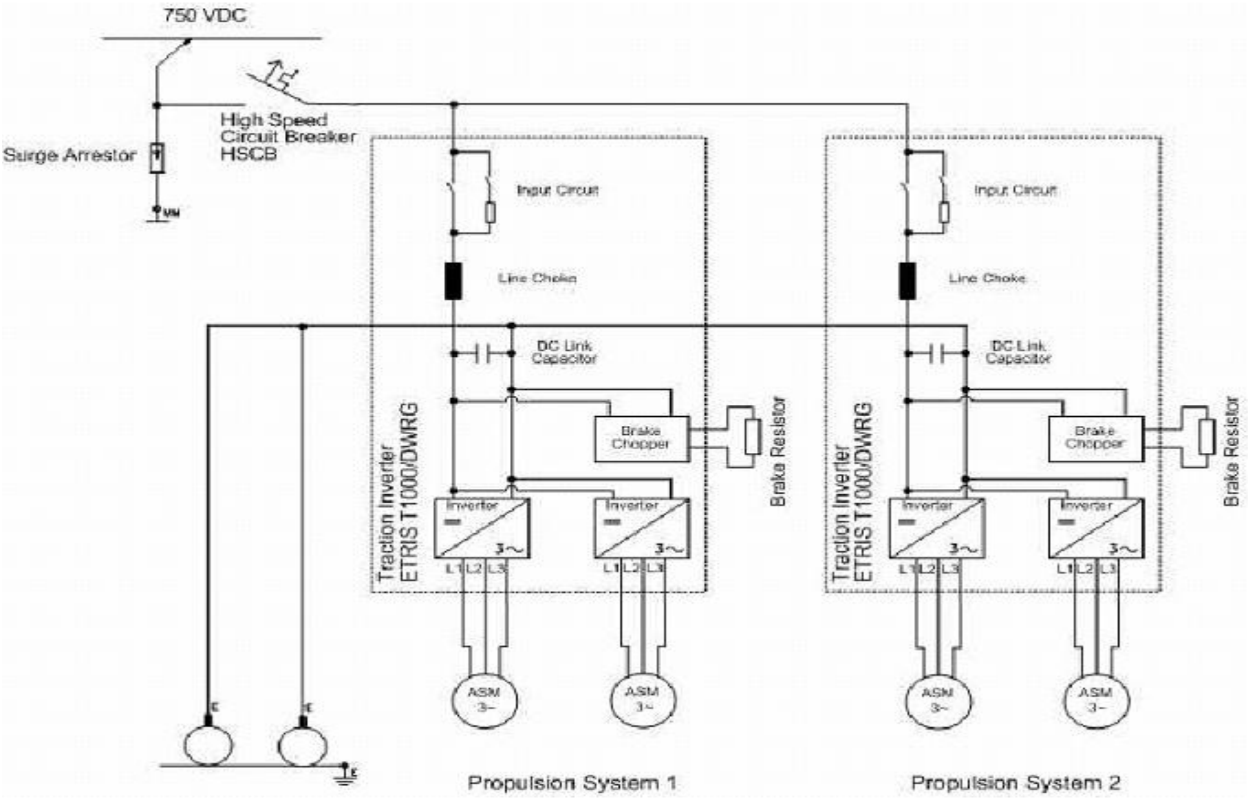

Figure 2-3: Illustration of main circuit of traction system of AALRT [1]

Electric traction system is variable voltage variable frequency (VVVF) controlled AC transmission system. The torque control of traction motor is vector control. The power element of VVVF inverter is IGBT, a heavy duty power electronic element. Electrical brake includes regenerative brake and resistance brake. Electrical brake system has skid/slide protection functions to prevent skid/slide in a quick and effective manner and make utmost of wheel/rail adhesion.

Vehicles are provided with micro-computer based analog electric brake (regenerative 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. The vehicles shall have fail-safe brake system.

Auxiliary power supply of the vehicles consists of static inverter, DC power supply and battery group. Each vehicle shall be equipped with two auxiliary power supplies with sufficient output capacity needed by vehicles under all load conditions. Static inverter shall adopt microcomputer control and self-diagnosis function. Power element to be used is IGBT, a heavy duty power electronic element.

Vehicle is provided mainly with network based control, supported by hardwired control. In addition to vehicle communication network, operation and safety specific control should also be provided with hardwired redundancy. Vehicle control shall meet the requirements of manned driving and double-heading for two vehicles. System is provided with functions for automatic collection, recording and display of information related to vehicle operation and failure. Data can be read and printed by the reader. Data can be retained for at least 30 days after power interruption. System should offer high level of resistance to interference and have high reliability.

Train shall be equipped with two motor bogies and one trailer bogie, each traction inverter shall be able to power the two traction motors on one bogie. Traction motor shall be self-ventilated 3-phase asynchronous traction motor. Resistance brake 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.

2.2.2. Main traction equipment

1. Traction converter box

Traction inverter mainly consists of line contactor, IGBT inverter and chopper power unit, logic control unit and filter capacitor. The role of it 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 will convert the 3-phase AC voltage of traction motors into DC voltage to be fed back to the catenary (regenerative braking).

Provision should be provided that traction converter shall be able to withstand sudden variation to input voltage, and should be protected against input overvoltage, input under voltage, output over voltage, overheat failure, output overload and overcurrent, open phase and short circuit.

Main performance parameters

Rated input voltage of main circuit: DC 750V

Rated input voltage of control circuit: DC 24V

Range of input voltage of control circuit: DC 16.8—30V

Rated traction power: 2×130kW

Cooling: forced air cooling

One traction converter should drive 2 sets of traction motors.

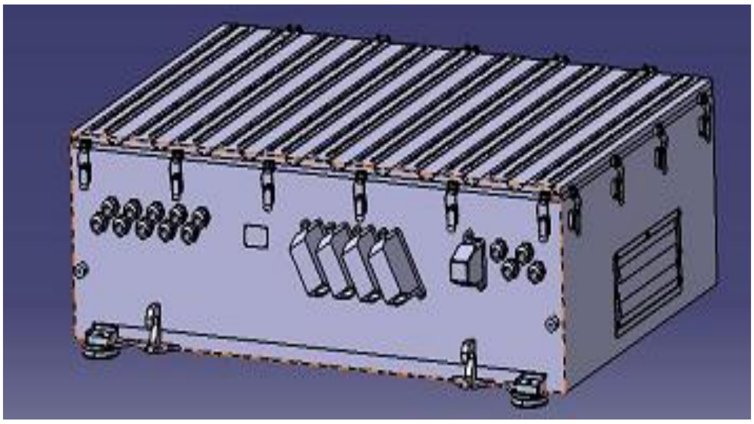

Figure 2-4: Traction converter [1]

2. Brake resistor box

Resistor should be used when traction inverter is under resistance braking to deplete energy generated by traction motor in braking mode.

Main performance parameters

Resistance value:	1.55 ohm (20°C)
Range of variation to resistance value of brake resistor:	7%/-5%
Rated voltage:	DC 750V

One traction inverter is provided with 1 brake resistor cabinet housing 2 groups of brake resistor modules.

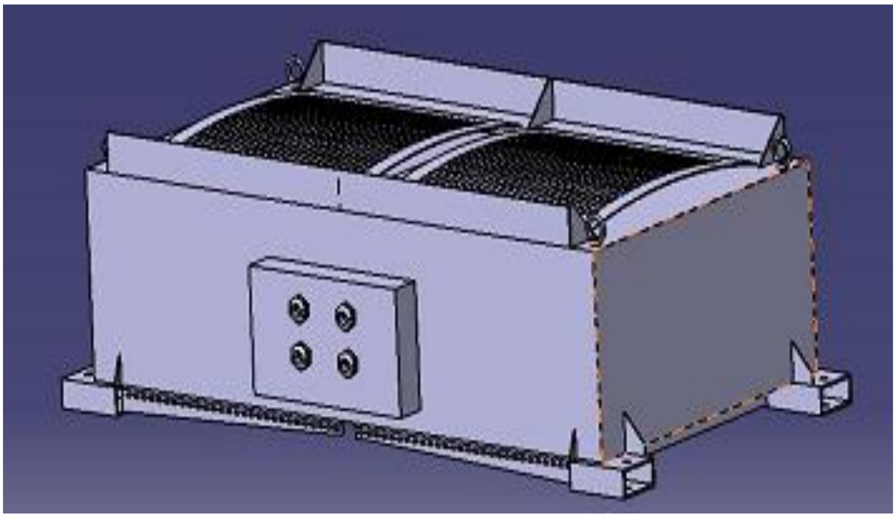

Figure 2-5: Brake resistor [1]

3. Traction motor

Traction motor variable used in AALRT is 3-phase squirrel cage asynchronous traction motor, and cooled by self-ventilation. Traction motor is applied for vehicle traction and braking. Motoring is supplied by traction inverter. Traction motor drives the axles through gear transmission unit. Braking is supplied by traction motor. Energy is fed back to power network through brake chopper module (regenerative braking) or such energy is depleted by brake resistor (resistance braking).

Table 2-2: Main performance parameters of Traction motor [1]

Rated power:	Number of phases:	Number of poles:	Rated voltage AC	Rated current	Rated frequency	Rated rotation speed:	Maximum rotation speed
130 kW	3	6	3X500V	210 A	71 Hz	1800 r/min	4377 r/min

4. High voltage equipment

A. Pantograph

Each car of vehicles should be installed with one pantograph. Under all track conditions, pantograph should have good and stable contact with catenary. All exposed elements which are easy to wear and damage should be easily replaced. For operations on roof, pantograph shall be mechanically locked up. Touch on switches for raising/lowering pantograph or pantograph body shall not cause the pantograph to rise.

Main technical parameters

Nominal voltage:	DC 750V
Rated working current:	1050 A
Operation speed:	70km/h
Lowering height:	310±10mm (including insulator)
Minimum working height:	380±10mm (including insulator)
Maximum working height:	2400 mm (including insulator)

B. High speed circuit breaker

High speed circuit breaker shall be able to provide protection of the traction inverter on motor vehicles, and shall be used for traction loops only. Operation of high speed circuit breaker shall be triggered by the traction inverter or overcurrent trigging devices.

Main technical parameters

Rated voltage: 1000V

Rated current: 1000A

Short circuit current: 30kA

Mechanical response time: 2ms

Type: Single pole DC based electromagnetic control, natural cooling

C. Surge arrestor

Surge arrestor shall be used to prevent damages to the insulation of electric equipment due to external over voltages other than from outside vehicles and over voltage due to operations by mistake.

Main technical parameters

Rated voltage: DC 1000V

Nominal discharge current: 20kA (8/20μs)

Maximum residual voltage: 2100V (1kA), 2400V (10kA), 2640V (20kA)

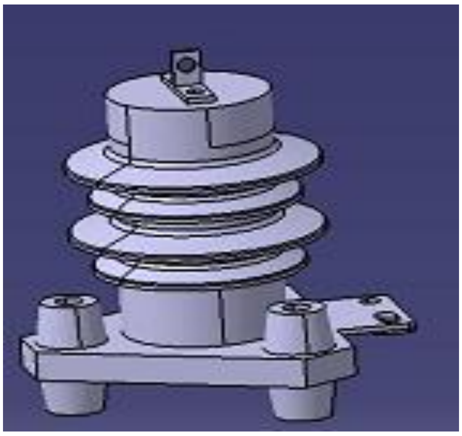

Figure 2-6: Surge arrestor [1]

2.3. Power electronics device on railway traction system

The development of power electronics relies on advancement of semiconductor devices. In the1960s, the development of the power thyristor gave rise to trials of several experimental inverter-fed induction motor locomotive drives [22]. The main drawback of this type of device is the lower current and voltage level which it could with stand which limits its application in high power fields. In the 1970s, the development of a high-power force-commutated thyristor led to the deployment of the Current Source Inverter (CSI) in DC-fed metro traction drives. Later, the large power Gate-Turn-Off (GTO) thyristor realized the Voltage Source Inverter (VSI) in railway applications. Until very recently, the Insulated Gate Bi-polar Transistor (IGBT), which has a lower operation current and higher switching speed has taken the place of the GTO. In the 1980s, the pulse converter was developed, which is a four-quadrant AC-DC line converter that enables three-phase VSI-Induction Motor drives on single-phase AC supplied railways [41].

2.3.1. DC-DC chopper converter traction drive

The DC-DC chopper converter converts fixed DC voltage into various output voltages. Bidirectional operation is possible with a combination of step up and step down converters, which realizes regenerative braking for railway vehicles. This type of converter is referred to as a two quadrant converter for two different characteristics of operation. A DC-DC chopper converter helps to realize a smooth, step-less control and fast response to the target due to the flexibility of output voltage control. Additionally, compared to traditional electromechanical equipment, chopper operation significantly lowers maintenance costs as no mechanical requirement is needed in such a system [15]. The possibility and capability of regeneration of chopper converter traction led to the development of way side storage substations. These are used as an alternative to the conventional way of consuming the energy recovered from nearby trains [8].

It is noted that the chopper operation inherently gives rise to the harmonics content to the output current and voltage. The fundamental element of the harmonics caused by the chopper is the chopping frequency. In addition, the substation rectifier which rectifies AC power supply into the required DC power will usually introduce harmonics. Neither of these harmonics is desirable, due to their interference with the signaling system along the railway line. Consequently, bulky filters are usually employed at the power collection terminal and within the chopper controllers to reduce the harmonics [8].

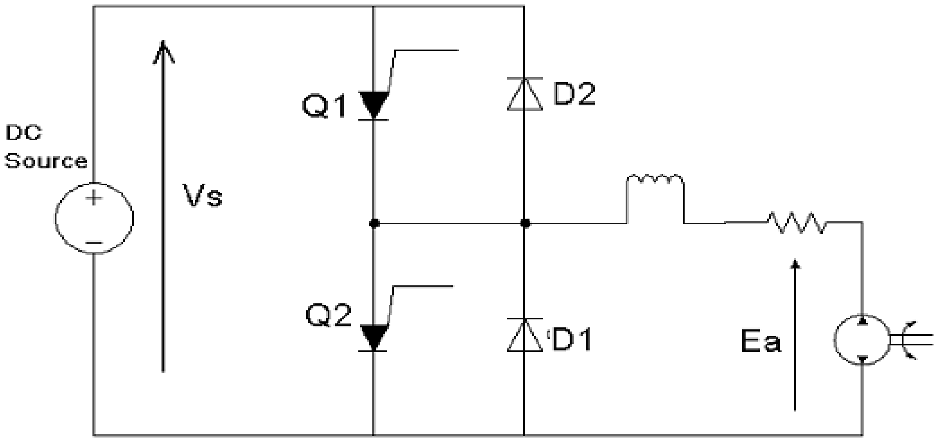

Figure 2-7: Two-quadrant traction chopper power operational circuit diagram [15]

The thyristor Q1 turns on and off with firing angle. The current through the inductor increases during the "on" period as the voltage from the sources is higher than the terminal voltage on the motor and decays due to the back EMF applied [8].Though the current increases and then decays, the power flows from the power supply to the motor. With the current turning from positive to negative, the system changes into regenerative mode where the motor acts as a generator and energy is returned to the supply. At this stage, the operational devices are $Q_2$and D_2. With Q_2 turning on, the current goes through and energy is stored in inductance L; with Q_2 off, the current decays due to the negative voltage difference $V_s - E_a$ applied on it and the power is delivered to the source via the diode D_2. One important feature of this circuit is that the thyristors do not work simultaneously to avoid the short circuit of the power supply. Two groups of devices Q_1, D_1, Q_2, and D_2 work separately to realize the respective working mode. The speed or torque requirement determines the working mode of this chopper [15].

2.3.2. DC-fed Current Source Inverter drive

The current source inverter has the current from a DC source which is effectively constant over a period of a few cycles [17]. In practice, the constant current is realized by a large inductance and the value of the current is adjusted by the duty cycle of the pre-converter before the current source inverter. Figure 2-8 shows the circuit diagram for a 3-phase constant current source inverter. Thyristors are fired in sequence to produce a quasi-square wave load current on each phase of the induction motor. During regeneration, the current direction remains the same while the DC source voltage reverses [19].

Pulse Width Modulation (PWM), which replaces the square wave by a set of discrete pulses in the same duty cycle, could be applied to the output current of the inverter.

The advantage of PWM is to eliminate the low order harmonics and achieve a more stable operation of the motor [24].

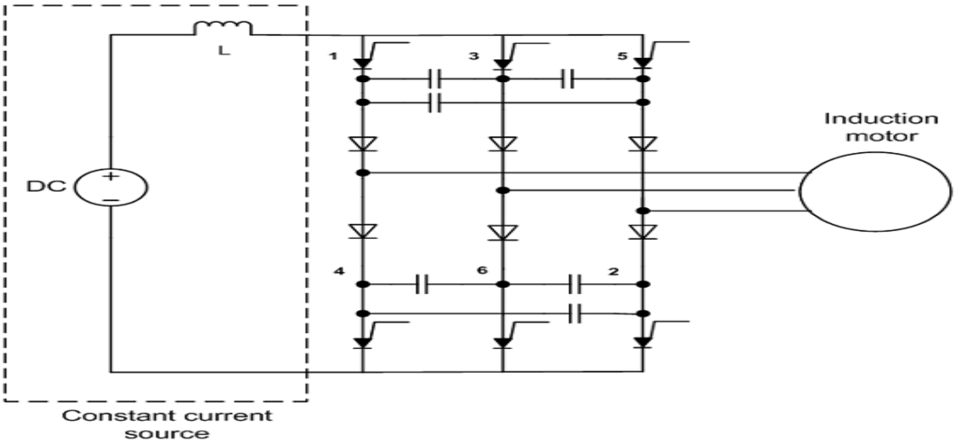

Figure 2-8: Current source inverter circuit diagram [19]

2.3.3. DC-fed Voltage Source Inverter drive

The VSI inverts the constant voltage into various voltage outputs on the load. Constant voltage implies that over the short time of one cycle of the output AC waveform, any change in the DC source voltage is negligible [18]. The reversal of power flow occurs during braking. At this stage, the induction motor works as a generator and the inverter output frequency is lower than the rotor rotational speed. The current direction will reverse while the phase of voltage remains unchanged.

2.3.4. Pulse Width Modulated Variable Frequency Drives

The application of PWM in the DC-AC converter has several advantages [39]. Firstly, it is easy to achieve the unity power factor by PWM. Secondly, it improves the line current wave form by reducing harmonics. Thirdly, both dynamic and regenerative braking operations are feasible. Finally, the DC link voltage is larger than the line peak voltage. When operated from a constant frequency power source (typically 60Hz), AC induction motors are fixed speed devices. A variable frequency drive controls the speed of an AC motor by varying the frequency supplied to the motor [8].

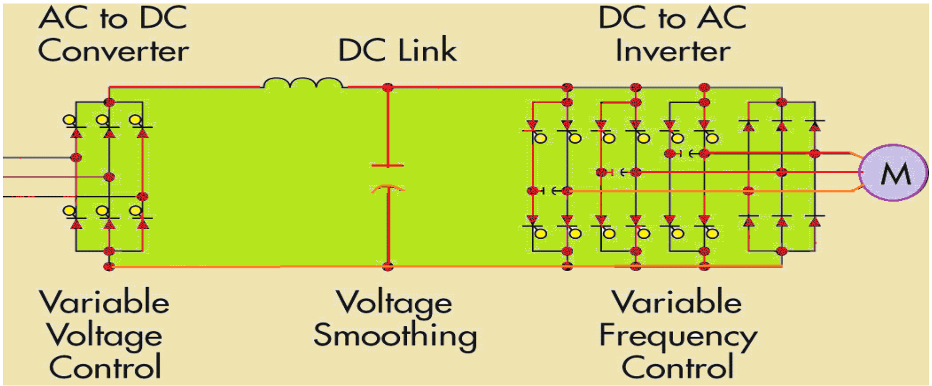

Figure 2-9: Circuit diagram for a Pulse Width Modulated Variable Frequency Drive [17]

The drive also regulates the output voltage in proportion to the output frequency to provide a relatively constant ratio of voltage to frequency (V/Hz), as required by the characteristics of the AC motor to produce adequate torque. The first step in this process is to convert the AC supply voltage into DC by the use of a rectifier. DC power contains voltage ripples which are smoothed using filter capacitors. This section of the VFD is often referred to as the DC link [18].

This DC voltage is then converted back into AC. This conversion is typically achieved through the use of power electronic devices such as IGBT power transistors using a technique called Pulse Width Modulation (PWM). The output voltage is turned on and off at a high frequency, with the duration of on-time, or width of the pulse, controlled to approximate a sinusoidal waveform. The entire process is controlled by a microprocessor which monitors the incoming voltage supply, speed set-point, DC link voltage, output voltage and current to ensure operation of the motor within established parameters [41].

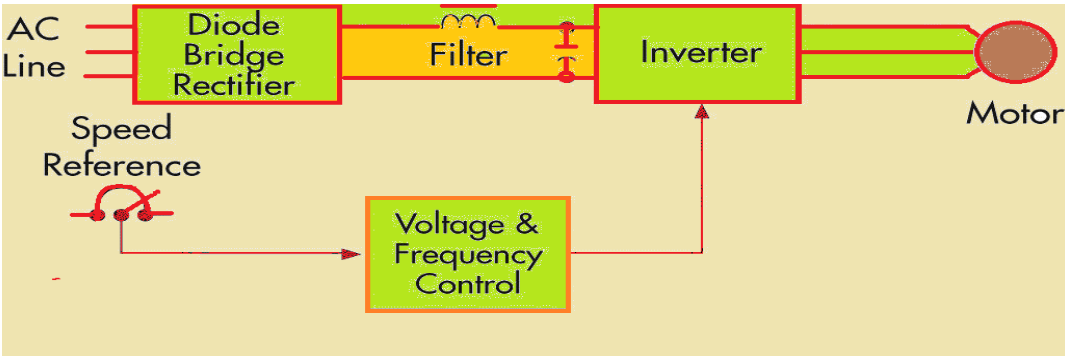

Figure 2-10: Block diagram of a typical PWM VFD [6]

In the simplest drives or applications, the speed reference is simply a set-point; however, in more complex applications, the speed reference comes from a process controller such as a Programmable Logic Controller (PLC) or a tachometer [6].

3. REGENERATIVE BRAKING IN RAILWAY TRACTION SYSTEM

3.1. Introduction

The transportation industry is embracing regenerative braking as a means to save energy and reduce maintenance costs. During regenerative braking vehicles' electric motor is reconnected as a generator and its output is connected to an electrical load, which provides the braking effort. The current thus generated could be employed either for rheostat/dynamic or regenerative braking. In regenerative braking on railways, the regenerated current is either returned to the overhead line/third rail or stored in onboard energy storage devices [4].

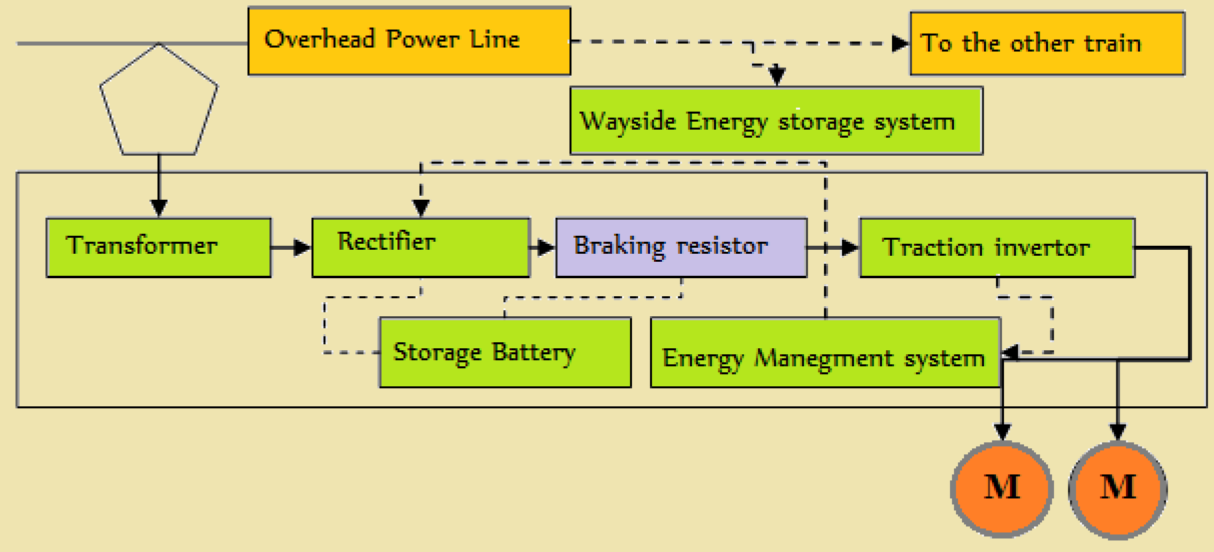

Figure 3-1: Regenerative braking energy concepts in electric traction [5]

Trains with regeneration capability using three phase traction motors are regenerating up to 30% of energy consumed, more so on slow corridor, characterized with stop at all stations [4]. Energy savings up to 17% can be achieved on inter-city routes and much higher (up to 30%) savings on suburban services and metro services owing to frequent starts and stops [5]. AC-motored trains with regenerative braking capability on DC traction have two associated problems: occasional regeneration failure due to lack of line receptivity and inferior braking characteristics at the higher speeds when compared to dynamic braking. These problems can be addressed by introducing on-board and/or wayside energy storage devices [1].

3.2. Regenerative Braking in DC-Electrified Railway

Most electric trains in DC-electrified railways are presently equipped with regenerative braking system. DC trains using inverter-fed AC traction motors have similar torque speed characteristics in powering and braking modes. Braking power in regenerative mode can be around 30% greater than that of powering but inferior to dynamic braking where braking power typically exceeds two and half times that of powering [4]. A DC substation using diode rectifiers cannot pass regenerated energy back into the grid, so it can only be consumed by other accelerating trains in the same feeding section. On a busy suburban service at peak times receptivity can be as high as 15% whereas on long sections with low service frequency it can fall below 5%. Even if enough trains are accelerating, where there is a long distance between the source and the load, the pantograph voltage tends to be high because of the line resistance. In such cases, the regenerating current itself has to be limited so as to avoid excessive voltage on the regenerating train [9].

On braking, traction controller of a train converts kinetic energy to electrical energy during deceleration of the train when other powering trains consume the electrical energy as electrical loads for the regenerating train in the electrical circuit [2]. The braking train must reduce the electrical power following squeezing control of regenerative power when power consumption of powering train is too little because there are typically no devices which absorb the regenerated energy in the electrical circuit. However, some devices have recently introduced in DC-electrified railways for effective usage of regenerative braking [2].

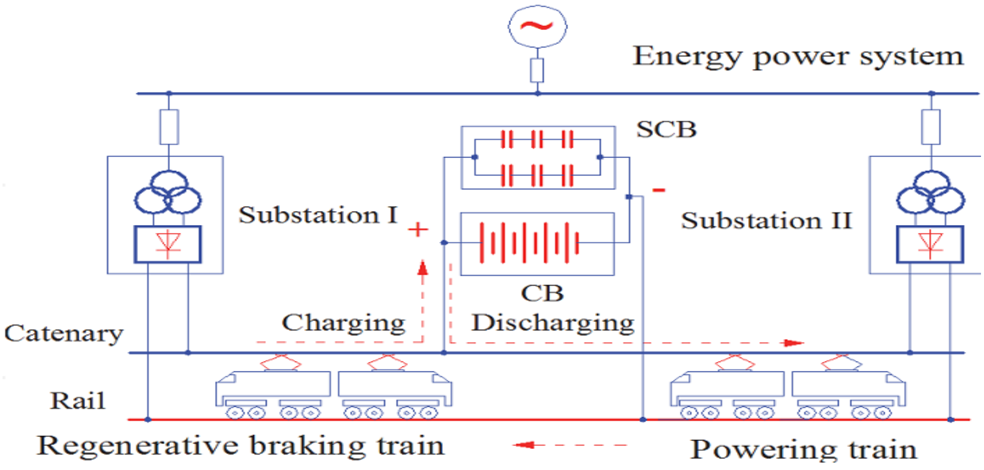

Figure 3-2: Typical power flow on braking [2]

CB- conventional batteries; SCB-super capacitors block

3.3. Efficient use of regenerative electric power

3.3.1. Regenerative braking under light load conditions

The regenerative energy obtained from regenerative braking process is returned to the power supply line so that it can be reused in any other trains on the line that are currently accelerating. However, during off-peak and other times when there are few trains able to take the regenerative energy produced during braking, this energy has nowhere to go. This is called *"regenerative braking under light load conditions" [2].* Absorption of regenerative electric power function is a solution to the problem of regenerative braking under light load conditions [9]. When no other trains are available to make use of the regenerative energy, the energy is collected in an onboard or wayside storage battery so that it can be reused for acceleration as shown in figure 3-3.

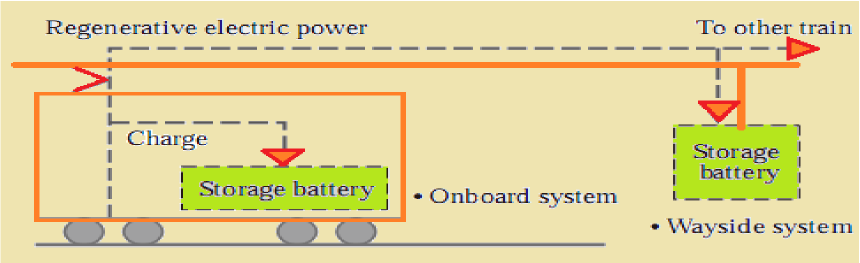

Figure 3-3: Absorption of Regenerative Electric Power [3]

The energy savings are maximized if regenerative braking can provide all of the braking energy needed to decelerate to a halt [3]. At higher speeds, however, the amount of regenerative braking is limited by the motor output characteristics. As the additional required braking not able to be supplied by regenerative braking in this high speed range is provided instead by the air brake, the energy-saving benefits are reduced ("limits on performance due to motor characteristics") [20].

The regenerative brake with effective speed extended function is a solution to the problem of limits on performance due to motor characteristics [12]. This function extends the operating range of the regenerative brake into higher speeds by using the storage battery to boost the DC voltage of the inverter and increase the output of the electric motor, inverter, and so on without changing the level of the current following through each component, thereby shifting upwards the top speed of the V/F (voltage/frequency) range in which full regeneration is possible, as shown in Figure 3-4.

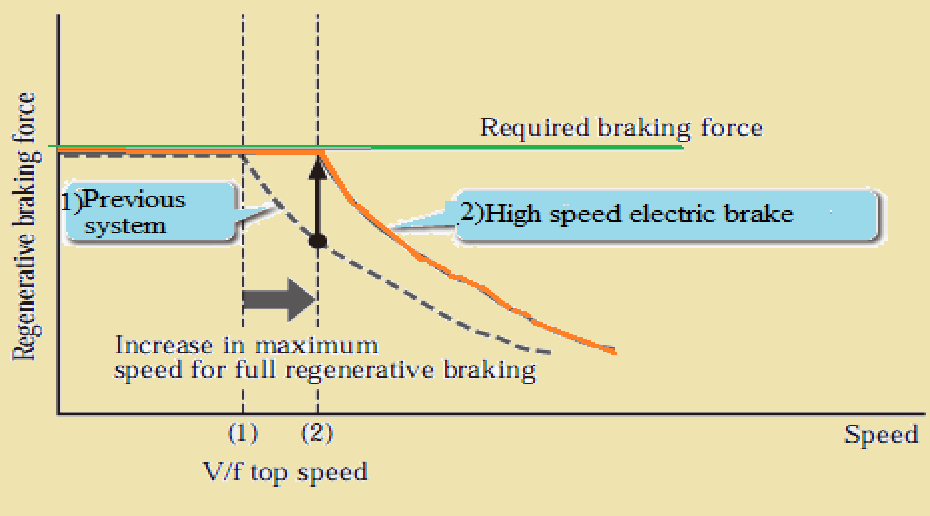

Figure 3-4: Regenerative Brake Characteristics [3]

The storage battery extends the top speed of the operating range for regenerative braking by boosting the DC (direct current) voltage of the inverter and increasing the output of the motor, inverter, and other components [3].

3.4. Benefits of Regenerative Braking

3.4.1. Energy saving potential

About 90% of the energy drawn by a typical urban rail vehicle is used for traction and 10% for auxiliaries. Up to 40% of the total energy consumed is theoretically available to be recovered. Without energy storage, a typical urban rail network might save about 15% of the total energy through regenerative braking. With efficient energy storage, this proportion might rise to 35%, or even 40%, average can be estimated at 24% [17]. Assuming an energy storage unit on train saving 55 kWh per hour for 350 days in 20 hours a day, annual saving would be 385 MWh [23].

3.4.2. Extra peak power

In addition to saving energy, storage units can reduce line voltage fluctuations and provide peak power when it is most needed. This can be used to improve the acceleration of trains during peak periods, especially in situations where traffic has grown and the existing supply can barely cope up [33].

3.5. Braking systems used in Ethiopia AALRT

Brake system for AALRT trams with 70% low floor incorporates advanced, well-proven and reliable products already installed for practical applications. Such brake system is suitable for mounting and operation on vehicles with 70% low floor. Brake system incorporates modular design with simple interface to meet requirements of modern brake system. It is equipped with electric brake (regenerative brake), hydraulic disc brake and track brake, which are independent of each other [1]. Components are concentrated with sufficient spacing in-between for easy replacement and removal. Components requiring frequent maintenance should be mounted close to vehicles. Test connections and interfaces for hydraulic and electrical applications should be easily accessible. Their connection is not requiring removal of pipes or lines on the train [1].

Train brake system is microprocessor based electric regenerative brake system incorporating monitor terminals for self-diagnosis and failure recording. Such system can offer service brake (including blended brake for electric brake and hydraulic brake), emergency brake, safety brake, stopping brake, substitute brake in case of failure of electric brake and parking brake. Each bogie is equipped with an independent brake control device that receives brake command from train control unit.

Regenerative brake is preferably applied as service brake for AART vehicles. Role of regenerative brake is utilized to a maximum extent and return energy back to power network. In case of insufficiency in regenerative braking force or failure of regenerative brake, resistance brake is automatically put into service for compensation. Safety brake is applied by hydraulic friction brake and magnetic track brake.

Emergency brake is applied by electric brake, hydraulic friction brake and magnetic track brake. Brake rigging is disc brake, partially for parking brake. It can conveniently execute manual release of parking brake (including hand pump release and mechanical release).

4. ENERGY STORAGE DEVICE USED IN RAILWAY SYSTEM

4.1. Introduction

The outstanding advances in both power electronics and energy storage technologies have permitted ESSs to become a very promising option to manage regenerated braking energy in urban rail. Energy storage technologies are getting more attention to overcome receptivity issues [4]. In order to maximize the use of the surplus energy, energy storage technologies combining higher power and energy density with acceptable losses and longer life, such as lithium-ion or nickel-hydrogen (Ni-H) batteries and electric double-layer capacitors (EDLC), promise more efficient train operation [42]. Compared to other storage technology, the ultra-capacitor has the advantages of rapid charging and discharging frequencies, a long cycle life and high power density, which highly match the characteristics of urban rail transit, such as short running time between stations, frequent accelerating and braking, booming power within a short time, etc. Thus, the ultra-capacitor becomes a major promising alternative of energy storage technologies in the urban rail system [9].

According to the installation location of ESS, it can be installed either on board vehicles or at specific points along the track. The former option enables rail vehicles to temporarily store their own braking energy and reuse it for subsequent acceleration. In turn, stationary ESSs accumulate energy from any braking train nearby and release it when a power demand is detected [7]. The location for an energy storage system has to be chosen very carefully to ensure maximum efficiency of the measure. The highest energetic benefit of energy storage systems can be realized in parts of the network with a low degree of cross-linking (low probability of direct use by other trains), with slopes and high velocities (high amounts of braking energy) [2]. The energy flows in the system are managed in a way that braking energy is stored only if no other train can use the energy directly [9].

On-board energy storage is an accepted means of conserving energy [12]. On-board ESSs' efficiency is high with low loss in the storing and releasing of surplus energy, but restrictive in terms of vehicle weight and space; in contrast, stationary ESSs have no restrictions of weight and required space, but it is difficult to determine its best location and size, namely, the optimal place for locating and sizing, which has become an important research issue in the application of stationary ESSs [25].

The selection of energy storage technologies for ESSs depends on the particular needs of each case but, in general, urban rail applications will call for the following features [13].

- Large number of load cycles
- High power capacities
- Intermediate energy storage capacity (although it may be high for on-board systems)
- Reduced weight and volume (especially for on-board systems)

The choice of the best storage technology has to take into account the following requirements.

- Sufficient power (during charging and discharging) and sufficient energy content in order to serve as an effective booster for accelerating trains.
- High cycle stability: the storage medium has to allow for 500-1000 charging and discharging cycles a day without undergoing any performance changes.

These conditions clearly favor flywheels and super capacitors. Apart from the storage unit itself, the storage system consists of [5]:

- Power electronic equipment (inverters etc.)
- Cooling unit (peaks of up to ~ 50kW heat generation have to be cooled, with restrictions to be met concerning the noise emission of cooling unit in urban areas)
- Resistor (needed for safety reasons, only used for discharging of storage unit in failure scenario)

An important issue is the layout of the storage system. There is a complex trade-off between technological and economic needs. On the one hand, the storage unit should be dimensioned in such a way that it supplies enough energy and power for a train to accelerate without additional energy supply [23]. Assuming a 50 t light rail vehicle and a maximum speed of 80 km/h, the critical energy is 3.4 kWh. On the other hand, storage systems have high investment costs and no unnecessary storage capacity should be installed.

4.2. Stationary energy storage systems

Trackside stationary ESSs collect the regenerated braking energy that cannot be instantaneously consumed in the system, delivering it when a voltage drop is detected in the line, e.g. when a vehicle is accelerating in its electric section. Therefore, these kinds of systems can be used to reduce the traction energy consumption of the system. In comparison with on-board devices, they have fewer installation restrictions as space and weight are normally not a big issue in trackside facilities. Besides, their maintenance does not affect the service. In contrast, stationary ESSs involve higher transmission losses in the line, which calls for a careful study to determine the optimum position of the storage devices within the network [2]. Different Trackside ESSs developed by international manufacturers are listed in appendix B Table B.1

Figure 4-1 shows an example of a wayside installation of a system for storing regenerative electric power in a storage battery. As with the on-board system, the energy produced by regenerative braking is collected in a storage battery for reuse when accelerating. In addition to benefits that include avoiding loss of regeneration by keeping the feeding voltage stable, a feature of this system is that it provides a way to keep the feeding voltage stable.

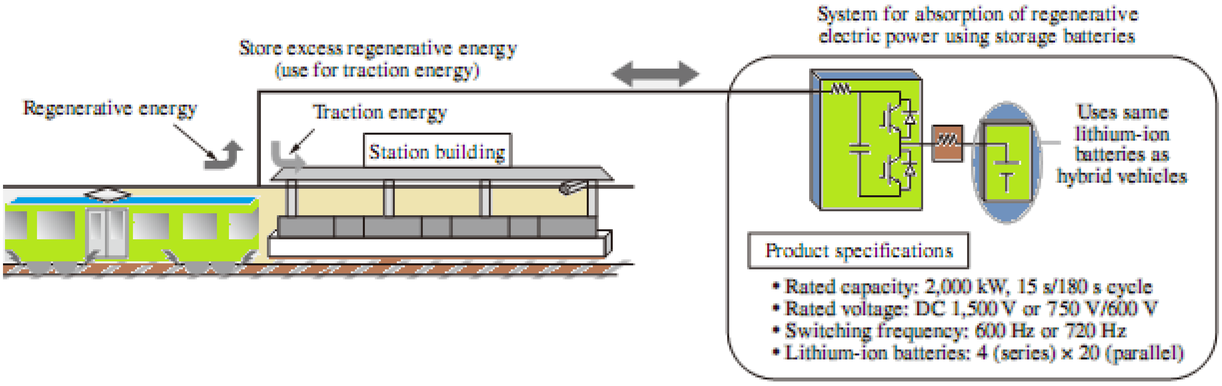

Figure 4-1: System for Absorption of Regenerative Electric Power Using Storage Batteries [2]

To make maximum use of regenerative electric power, it is necessary to undertake an optimization that utilizes the respective characteristics of the wayside and on-board systems, and this in turn requires various types of engineering. This can be supported by variety of ways including investigating the optimum location for the lithium-ion batteries, whether it is on or off the train, the system capacity, interoperation with peripheral systems, and other factors, and also through the use of simulation to verify the results.

4.3. On board energy storage (Sequential Regenerative Brake System)

Modern energy storage devices permit the storage of braking energy on-board for use in subsequent acceleration phase [4]. Especially in DC systems, where energy losses in the distribution network are high, this could be an interesting alternative to feeding back energy into the supply system. Without on-board energy storage much of the potential for brake energy recovery is not exploited because the system is often not able to take up the power [5]. The sequential regenerative brake reduces energy consumption by charging an electric power storage unit with the regenerative electric power that is unable to be returned to the overhead contact line (third rail conductor system) and then reusing this energy in the next acceleration. The step-up/step-down chopper can control the charging and discharging current even if the voltages at the electric power storage unit and inverter differ [2].

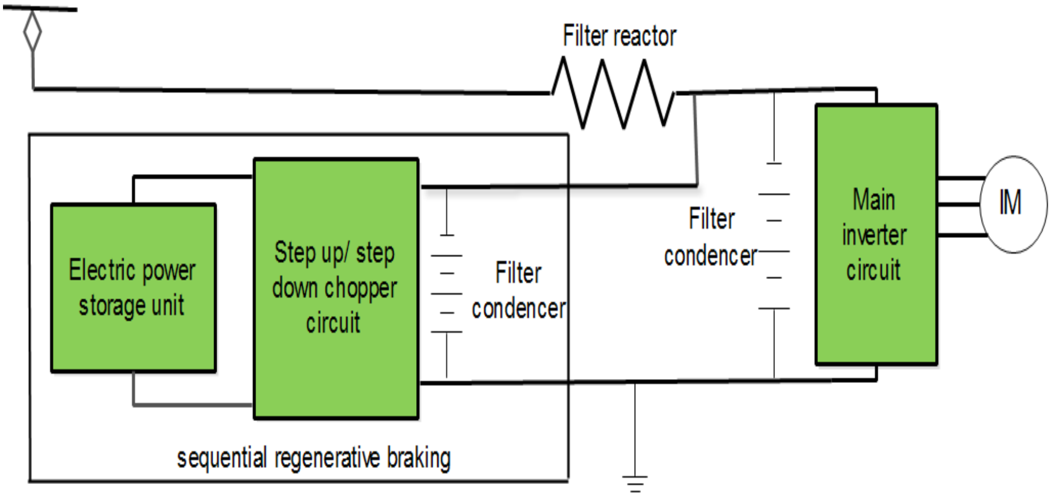

Figure 4-2: Block Diagram of Sequential Regenerative Brake System Equipment [4]

The way charging control works is that, when the voltage across the filter condenser rises because regenerative electric power cannot be returned to the overhead contact line (third rail conductor system), part of the regenerative electric power is used to charge a storage battery so as to prevent the filter condenser voltage from exceeding the designated voltage. Also, discharge control supplies traction power preferentially from the electric power storage unit.

On-board ESSs undoubtedly offer a high energy saving potential for urban rail. In this sense, a few scientific studies have demonstrated that the traction energy consumption could be reduced by approximately 15% to 35% in existing systems [5]. Additionally, on-board ESSs may help minimize power peaks during acceleration of vehicles, which results in reduced energy costs and fewer resistive losses in the distribution line. Furthermore, they may be designed to help stabilize the network voltage or also to provide a certain degree of autonomy for catenary-free services, for instance in lines going through historical city centers.

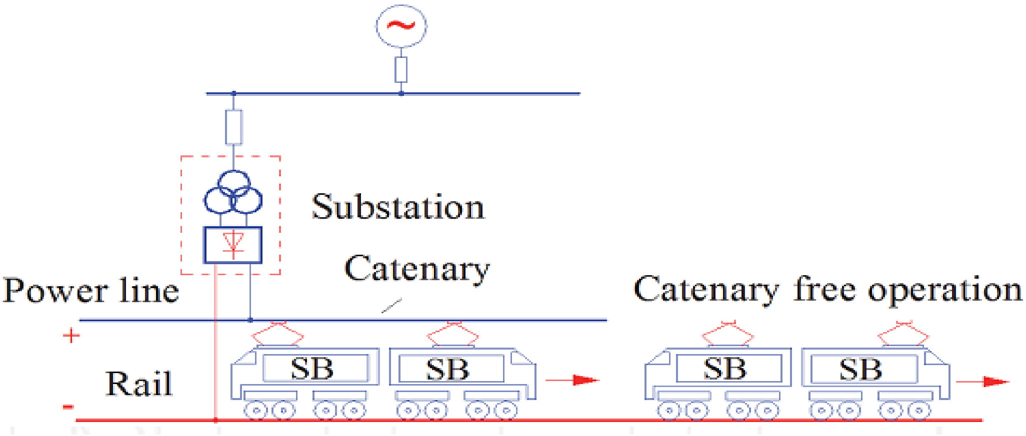

Figure 4-3: Diagram of vehicle's catenary free operation using on board storage battery (SB) [39]

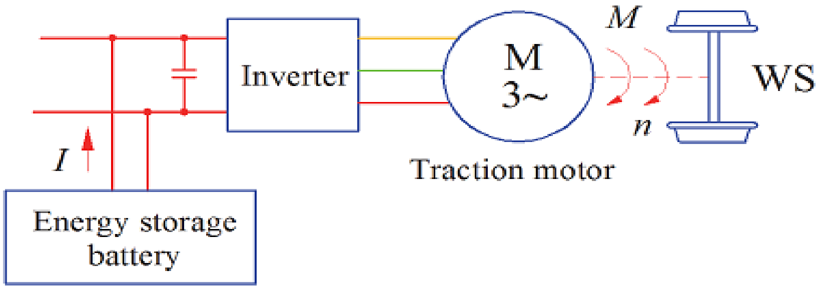

Figure 4-4: Circuit diagram of catenary-free operation of the vehicle (traction mode) [14]

The most challenging operating for storage devises on board of traction vehicle are high number of load cycles during the vehicle lifetime, relatively short charge and discharge times as well as high charge and discharge power values [39]. The battery is charged when line voltage goes up so that it limits the line voltage increase. Trains can unlimitedly generate regenerative braking energy when capacitors super capacitor bank (SCB) block and conventional storage batteries capacitor bank (CB) operate [27].

When compared to stationary systems, on-board ESSs present higher efficiency due to the absence of line losses. Moreover, the management of the recovered energy is simpler as the control is independent of traffic conditions [22]. However, mobile storage devices typically require large spaces on the vehicle and introduce a considerable increase of weight. For these reasons, the installation of on-board ESSs is preferred for brand-new designs rather than for retrofitting of current fleets [9].

4.4. Characteristics of On-board and Wayside Installation of Electric Power Storage Unit

To provide systems to implement the absorption of regenerative electric power function, wayside installation and sequential regenerative brake system for on-board installation should be in parallel [11]. It was done this way because it was important to be able to offer the appropriate system based on the characteristics of the respective systems and on the track and other operating conditions at the railway where the system is to be installed.

Table 4.1 lists the characteristics of the on-board and wayside systems for absorbing regenerative electric power.

Table 4-1: Comparison of Different Electric Power Storage Unit Installation Locations [36]

Parameter	Wayside installation	On-board installation
Absorption of regenerative electric power function	Stores regenerative electric power that is not used by other trains	Stores regenerative electric power that is not used by other trains.
Ease of installation	Installation is comparatively easy if space is available by the wayside	Space for installation in train is restricted. Electric power storage units need to be installed separately in each train
Regeneration can continue when disconnected from power line.	No	Yes

4.5. Electrical energy storage system based on super-capacitors device

4.5.1. Super capacitors basics

A super capacitor (SC), sometimes called ultra-capacitor or electric double-layer capacitor (EDLC)) is a high-capacity electrochemical capacitor with capacitance values up to 10,000 farads at 1.2 volt that bridge the gap between electrolytic capacitors and rechargeable batteries [6]. They typically store 10 to 100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster than batteries, and tolerate many more charge and discharge cycles than rechargeable batteries. They are however 10 times larger than conventional batteries for a given charge [16].

Super capacitors are used in applications requiring many rapid charge/discharge cycles rather than long term compact energy storage: within cars, buses, trains, cranes and elevators, where they are used for recovery energy from braking, short-term energy storage or burst-mode power delivery [13]. Super capacitors don't have a conventional solid dielectric. They use electrostatic double-layer capacitance or electrochemical pseudo capacitance or a combination of both instead [31]. Aging is not an issue for the super capacitor. Provided that it is not subjected to over voltages, too large currents and too high temperatures its lifetime can be up to almost 80 years [36].

4.5.2. Advantages and Limitations of super capacitors

Advantages

- Virtually unlimited cycle life - can be cycled millions of times.
- Low impedance - enhances load handling when put in parallel with battery.
- Rapid charging - super capacitors charge in seconds.
- Simple charge methods - no full-charge detection is needed; no danger of overcharge except life time deterioration.

Limitations

- Linear discharge voltage prevents use of the full energy spectrum.
- Low energy density - typically holds one-fifth to one-tenth the energy of an electrochemical battery.
- Unable to use its entire energy spectrum.
- High self-discharge - the rate is considerably higher than that of an electrochemical battery.

4.5.3. Super-capacitor types

There are many sorts of super capacitor technologies; some examples are carbon double-layer capacitors, utilizing pseudo-capacitance capacitors, metal oxide capacitors, conducting polymer capacitors and hybrid capacitors [45]. Electrical energy is stored in super capacitors via two storage principles: static double-layer capacitance and electrochemical pseudo capacitance; and the distribution of the two types of capacitance depend on the material and structure of the electrodes. There are three types of super capacitors based on storage principle [30].

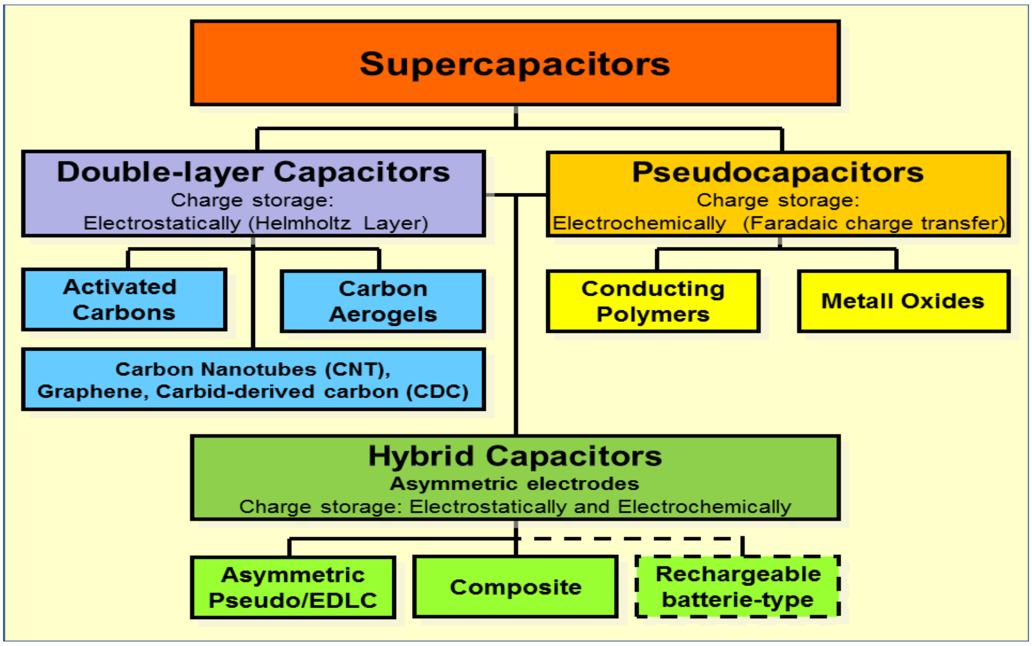

Figure 4-5: Family tree of super capacitor types [17]

Electric Double-layer Capacitors (EDLCs):- use carbon electrodes or derivatives with much higher electrostatic double-layer capacitance than electrochemical pseudo capacitance, achieving separation of charge in a Helmholtz double layer at the interface between the surface of a conductive electrode and an electrolyte [17]. The separation of charge is of the order of a few angstroms (0.3–0.8 nm), much smaller than in a conventional capacitor.

Pseudo Capacitors: - use metal oxide or conducting polymer electrodes with a high amount of electrochemical pseudo capacitance [29].

Hybrid capacitors: - with asymmetric electrodes, one of which exhibits mostly electrostatic and the other mostly electrochemical capacitance, such as lithium-ion capacitors.

4.5.4. Basic design and operation of a super capacitor:

A super capacitor, sometimes referred as an electrochemical capacitor, is an electrical energy storage device that is constructed much like a battery [14]. The goal of the super capacitor bank is to improve the performance of the vehicle, by providing an energy storage that supplies a power boost with low losses and no maintenance. The first step towards constructing a super capacitor bank is to establish the voltage level of the DC – link and the maximum power the train can operate with [11].

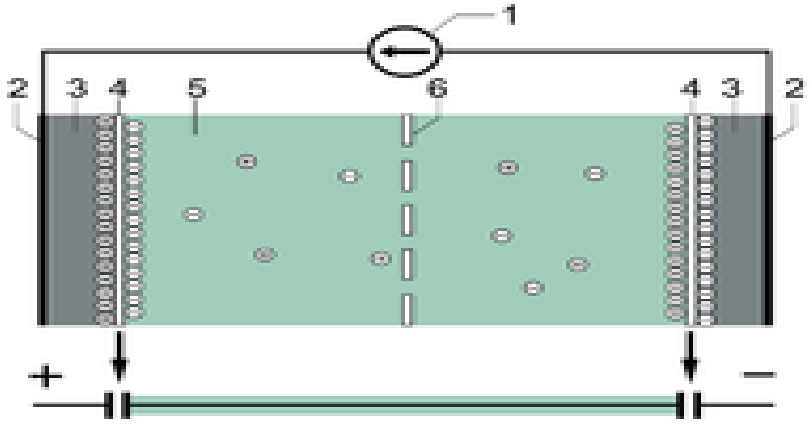

Figure 4-6: Typical construction of a super capacitor [24]

1) Power source, 2) Collector, 3) Polarized electrode, 4) Helmholtz double layer, 5) Electrolyte having positive and negative ions, 6) Separator.

Electrochemical capacitors (super capacitors) consist of two electrodes separated by an ion-permeable membrane (separator), and an electrolyte electrically connecting both electrodes [32]. When the electrodes are polarized by an applied voltage, ions in the electrolyte form electric double layers of opposite polarity to the electrode's polarity. For example, positively polarized electrodes will have a layer of negative ions at the electrode/electrolyte interface along with a charge-balancing layer of positive ions adsorbing onto the negative layer. The opposite is true for the negatively polarized electrode [34].

Additionally, depending on electrode material and surface shape, some ions may permeate the double layer becoming specifically adsorbed ions and contribute with pseudo capacitance to the total capacitance of the super capacitor.

The two electrodes form a series circuit of two individual capacitors C_1 and C_2. The total capacitance C_{total} is given by the formula:

$$\boldsymbol{C_{total}} = \frac{\boldsymbol{C_1 * C_2}}{\boldsymbol{C_1 + C_2}} \text{……………………………………………………………………} \quad 4\text{-}1$$

Electrochemical capacitors use the double-layer effect to store electric energy; however, this double-layer has no conventional solid dielectric which separates the charges [10]. The amount of charge stored per unit voltage in an electrochemical capacitor is primarily a function of the electrode size, although the amount of capacitance of each storage principle can vary extremely. Practically, these storage principles yield a capacitor with a capacitance value in the order of 1 to 100 farad [42].

Capacitance values for commercial capacitors are specified as "rated capacitance C_R". This is the value for which the capacitor has been designed. The value for an actual component must be within the limits given by the specified tolerance [11]. Typical values are in the range of farads (F), three to six orders of magnitude larger than those of electrolytic capacitors. The capacitance value results from the energy W of a loaded capacitor loaded via a DC voltage V_{DC}. This value is also called the "DC capacitance".

$$W = \frac{1}{2} * C_{DC} * V^2{}_{DC} \text{……………………………………………………………………} \quad 4\text{-}2$$

Standard super capacitors with aqueous electrolyte normally are specified with a rated voltage of 2.1 to 2.3 V and capacitors with organic solvents with 2.5 to 2.7 V. Super capacitors rated voltages are generally lower than applications require [45]. Higher application voltages require connecting cells in series. Since each component has a slight difference in capacitance value and ESR, it is necessary to actively or passively balance them to stabilize the applied voltage. Passive balancing employs resistors in parallel with the super capacitors. Active balancing may include electronic voltage management above a threshold that varies the current [14].

Because super capacitors operate without forming chemical bonds, current loads, including charge, discharge and peak currents are not limited by reaction constraints [17]. Current loads are limited only by internal resistance, which may be substantially lower than for batteries. Internal resistance "R_i" and charge/discharge currents or peak currents "I" generate internal heat losses "P_{loss}" according to:

$$P_{loss} = R_i . I^2 \text{……………………………………………………………………} \quad 4\text{-}3$$

This heat must be released and distributed to the ambient environment to maintain operating temperatures below the specified maximum temperature. Super capacitors (except those with polymer electrodes) can potentially support more than one million charge/discharge cycles without substantial capacity drops or internal resistance increases [19]. Beneath the higher current load this is second great advantage of super capacitors over batteries. The stability results from the dual electrostatic and electrochemical storage principles.

Super capacitors occupy the gap between high power/low energy electrolytic capacitors and low power/high energy rechargeable batteries. The energy W_{max} that can be stored in a capacitor is given by the formula

$$W_{max} = \frac{1}{2} . C_{total} V^2{}_{loaded} \text{...} \quad 4\text{-}4$$

However, only part of the stored energy is available to applications, because the voltage drop and the time constant over the internal resistance mean that some of the stored charge is inaccessible. The effective realized amount of energy W_{eff} is reduced by the used voltage difference between V_{max} and V_{min} and can be represented as:

$$W_{eff} = \frac{1}{2} . C . (V^2{}_{max} - V^2{}_{min}) \text{...} \quad 4\text{-}5$$

This formula also represents the energy asymmetric voltage components such as lithium ion capacitors.

Charging/discharging a super capacitor is connected to the movement of charge carriers (ions) in the electrolyte across the separator to the electrodes and into their porous structure. Losses occur during this movement that can be measured as the internal DC resistance [43].

With the electrical model of cascaded, series-connected RC (resistor/capacitor) elements in the electrode pores, the internal resistance increases with the increasing penetration depth of the charge carriers into the pores [37]. The internal DC resistance is time dependent and increases during charge/discharge. The internal resistance R_i can be calculated from the voltage drop ΔV_2 at the time of discharge, starting with a constant discharge current $I_{dischage}$. Resistance can be calculated by:

$$R_i = \frac{\Delta V_2}{I_{dischage}} \text{...} \quad 4\text{-}6$$

The discharge current $I_{dischage}$ for the measurement of internal resistance can be taken from the classification according to IEC 62391-1 [25]. Here R_i determines several super capacitor properties. It limits the charge and discharge peak currents as well as charge/discharge times. R_i and the capacitance C results in the time constant τ

$$\tau = R_i . C \qquad 4\text{-}7$$

This time constant determines the charge/discharge time.

The amount of energy per mass that can be stored in a super capacitor is called specific energy. Specific energy is measured gravimetrically (per unit of mass) in watt-hours per kilogram (Wh/kg). The amount of energy per volume that can be stored is called energy density. Energy density is measured volumetrically (per unit of volume) in watt-hours per liter (Wh/l). Super capacitors can therefore store 10 to 100 times more energy than electrolytic capacitors, but only one tenth as much as batteries [34]. Although the energy densities of super capacitors are insufficient compared with batteries the capacitors have an important advantage, the power density. Power density describes the speed at which energy can be delivered to/absorbed from the load [17]. The maximum power P_{max} is given by the formula:

$$P_{max} = \frac{1}{4} . \frac{V^2}{R_i} \qquad 4\text{-}8$$

Where V = voltage applied and R_i the internal DC resistance.

Power density is measured either gravimetrically in kilowatts per kilogram (kW/kg) or volumetrically in kilowatts per liter (kW/l). The maximum power P_{max} specifies the power of a theoretical rectangular single maximum current peak of a given voltage. In real circuits the current peak is not rectangular and the voltage is smaller, caused by the voltage drop.

$$\boldsymbol{P_{eff}} = \frac{\mathbf{1}}{\mathbf{8}} . \frac{\boldsymbol{V^2}}{\boldsymbol{R_i}} \qquad 4\text{-}9$$

Super capacitor power density is typically 10 to 100 times greater than for batteries and can reach values up to15 kW/kg [11].

Super capacitors do not support AC applications. Super capacitors have advantages in applications where a large amount of power is needed for a relatively short time, where a very high number of charge/discharge cycles or a longer lifetime is required. Typical applications range from milliamp currents or milliwatts of power for up to a few minutes to several amps current or several hundred kilowatts power for much shorter periods [37].

The time t a super capacitor can deliver a constant current I can be calculated as:

$$t = \frac{C.(U_{charge} - U_{min})}{I} \quad \text{4-10}$$

as the capacitor voltage decreases from U_{charge} down to U_{min}.

If the application needs a constant power P for a certain time t this can be calculated as:

$$t = \frac{1}{2P}.C.\left(U^2{}_{charge} - U^2{}_{min}\right) \quad \text{4-11}$$

Where in also the capacitor voltage decreases from U_{charge} down to U_{min}

4.6. Comparison between batteries and super capacitors

Compared to batteries, super-capacitors have higher power density but lower energy density. Super-capacitors store energy in an electric field between two very closely spaced plates [25]. Super- capacitors also have higher cycle life compared to batteries. Therefore, they are able to maintain rapid charge and discharge cycles. The terminal voltage of super-capacitors is only affected by the amount of energy that they store, and they have low internal resistance and are therefore energy efficient. Super-capacitors have a cost per kWh that is lower than batteries. Typical specifications for super-capacitors are given in Table B.3 in Appendix B. Table 4-2 compares characteristics between batteries and super-capacitors.

Table 4-2: Comparison of characteristics between batteries and super-capacitors (Kadhia, 2009) [38]

Battery Type	**Lead Acid**	**Super Capacitor**	**Electrolytic Capacitor**
Charge time	1-5 hrs	0.3-30 s	1ms-1µs
Discharge time	0.3-3 hrs	0.3-30s	1ms-1µs
Specific Energy (Wh/kg)	10-100	1-10	<0.1
Specific Power (W/kg)	<1000	<10,000	<100,000
Lifetime cycle	1,000	>500,000	>500,000
Efficiency charge/discharge	70-85	85-98	>95

5. SYSTEM DESIGN AND MATHEMATICAL MODELING

5.1. Modeling train movement and power consumption system

The light rail train on the Addis Ababa Light Rail transit Line is composed of 3 configurations and 2 power-cars. The length of the configuration is about 30m long and it weighs 44ton. It has the maximum acceleration ability 0.5m/s^2 to 1m/s^2 and the maximum deceleration ability of 2.0m/s^2 when it is applied by the emergency brake.

5.1.1. Train motion model

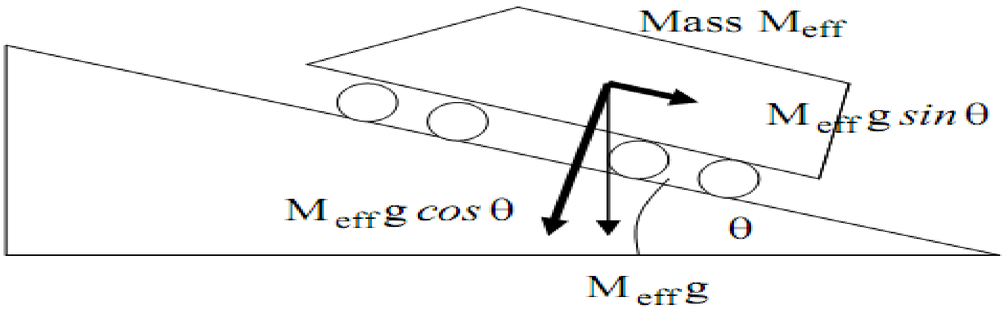

Figure 5-1: Free body diagram of train motion

The basic equation of train motion is based on Newton's Second Law:

$$\boldsymbol{M_{eff}\frac{d^2s}{dt^2} = TE - R - M_{eff}g\ \sin(\theta)} \quad \text{5-1}$$

Where

- M_{eff} is the effective vehicle mass (including rotational inertia);
- g is the acceleration due to gravity;
- R is the vehicle resistance to motion;
- TE is the tractive effort;
- s is the current vehicle distance.
- θ is the angle between the route slope and vertical line.

The vehicle resistance to motion is given by:

$$R = a + bv + cv^2 \quad \text{5-2}$$

Where, a, b and c are resistance force coefficients and v is the train speed.

The constant is a bearing and contact friction and varies with the weight of the train and number of axles. The second term is proportional to velocity, and is mostly due to increased rolling resistance at higher speeds, although it also includes some components of laminar air flow. The last term is proportional to velocity squared, and this aerodynamic drag, or friction with the atmosphere. A typical standard resistance equation for passenger car is:

$$R = 6.4\,T + 129N + 0.033TV + 0.91V^2 \ldots\ldots\ldots\ldots\ldots\ldots \quad 5\text{-}3$$

Where T= weight, N= number of axles

The rated train weight in AALRT including passengers is T=59240*9.81N=581144.4N, number of axles N=6, Average speed 24km/h=6.67m/s, then R=3848.054kN

Given that maximum and Average acceleration of AALRT trains are 1.0m/s^2 and 0.5m/s^2 respectively, effective mass of the train including passengers is $\boldsymbol{M_{eff}} = 59240\text{kg}$, the vehicle resistance to motion is calculated above R=3848.05kN, maximum gradient of the railway line from Mexico square to Torhiloch square is 55‰ $\tan\boldsymbol{\theta} = \frac{55}{1000} = 0.055$, $\boldsymbol{\theta} = 3.15^0$ the maximum and actual traction Efforts are calculated from equation 5-2 as:

$$59240kg * 1.0m/s^2 = TE_{max} - 3848.05kN - 59240kg * 9.81m/s^2 \ \sin(3.15^0)$$

$$TE_{max} = 3939.224kN$$

$$59240kg * 0.5m/s^2 = TE_{actual} - 3848.05kN - 59240kg * 9.81m/s^2 \ \sin(3.15^0)$$

$$TE_{actual} = 3909.604kN$$

5.1.2. Traction system model

The whole traction system for urban railway transportation contained these key components such as: power supply unit, traction motor, driven control unit, super-capacitor unit and Bidirectional DC/DC converter unit etc. [29]. The traction power supply system in general supplied by the city power grid to track traffic through multi-level substation and rectifier devices, converts high-voltage AC to 1500V/750V DC, which is used to feed the inverter to drive AC traction motor [29].

The basic calculation, as shown in equation 5-4, requires line voltage, current and motor combination code, etc. The k value is the number of parallel motor circuits. According to equation 5-4, this method contains an assumption that energy consumption has a linear relationship with the proportion between actual traction and maximum traction [44].

$$\boldsymbol{E_m = \int \frac{1}{3.6*10^4} * V * I_m * k * r_T dt = \frac{1}{3.6*10^4} * k * V * \int I_m * r_T dt} \text{.................. 5-4}$$

Where E_m = main power energy consumption (kWh), V = voltage (V), I_m = motor current (A), k = motor combination code, k ≥ 1, $r_T = \frac{TE_{actual}}{TE_{max}}$, the proportional between actual traction TE_{actual} and maximum traction TE_{max}, $0 \leq r_T \leq 1$,t = operational time (s).

For AALRT trains motor specification the number of parallel motor k=4, motor rated voltage V=3X500V, motor rated current I_m= 210 A, Rated frequency: 71 Hz, Rated rotation speed =1800 r/min, Maximum rotation speed = 4377 r/min, from above equation 5-1 to 5-3 calculation Actual traction $TE_{actual} = 3909.604kN$ and maximum traction $TE_{max} = 3939.224kN$ then $r_T = \frac{TE_{actual}}{TE_{max}} = \frac{3909.604kN}{3939.224kN} = 0.99$, taking the distance between two stations, from station at St. George brewery factory to station at Lideta Church the time taken for train is calculated from average speed and line distance is 139.5 seconds. Energy consumption of the train is calculated as

$$\mathrm{E_m} = \frac{1}{3.6 * 10^4} * 4 * 3\mathrm{X}500\mathrm{V} * \int_0^{139.5} 210\mathrm{A} * 0.99\mathrm{dt}$$

$$\mathrm{E_m} = 4.834\mathrm{kWh}$$

Energy for the railway traction system is used for acceleration, overcoming electrical and mechanical power losses and for work in moving the mass of the train forward against the frictional forces [51].

5.1.3. Energy Model for Regenerative Braking

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, equation 5-5 must be applied to determine the electric braking force first. Then the product of the motor braking force, velocity and regenerative efficiency yields the electric power produced by the regenerative braking, as expressed in equation 5.6.

$$B_T = B_e + B_f \quad \text{5-5}$$

$$P_r = \frac{1}{3.6} * B_e * v * \eta_B \quad \text{5-6}$$

Where B_T = total braking force (kN), B_e= electrical regenerative braking force (kN), B_f= friction braking force (kN), η_B= regenerative system efficiency, P_r= electric power of regenerative braking (kW), v= speed of the train. For AALRT case electrical regenerative braking force is calculated from the data given in tables at Appendix A, rated service braking acceleration $a_B = 1.1 m/s^2$ and effective train mass with passengers $M_{eff} = 59240 kg$, regeneration efficiency =35%

$$\mathrm{B_e} = \mathrm{M_{eff} a_B} = 59240\mathrm{kg} * 1.1 \frac{\mathrm{m}}{\mathrm{s}^2} = 65.164\mathrm{kN}$$

$$P_r = \frac{1}{3.6} * 65164 N * 6.7 \frac{m}{s} * 0.35 = 42.45\mathrm{kW}$$

From this result amount of energy generated $\mathrm{E_g}$ by regenerative braking system of AALRT trains, taking the movement between two stations (from station at St. George brewery factory to station at Lideta Church), is calculated as;

$$\mathrm{E_g} = \frac{1}{3600} \int_0^{139.5} P_r \, dt = \frac{1}{3600} \int_0^{139.5} 42.45 kWh \, dt$$

$$\mathrm{E_g} = 1.645 kWh$$

The vehicle motion model shown below in figure 5-2 begins with a tractive force demand model. An input block specifies the requested tractive effort. For this evaluation, tractive force requests are either 100% braking or 100% acceleration. Acceleration force is derived from maximum force as a function of velocity.

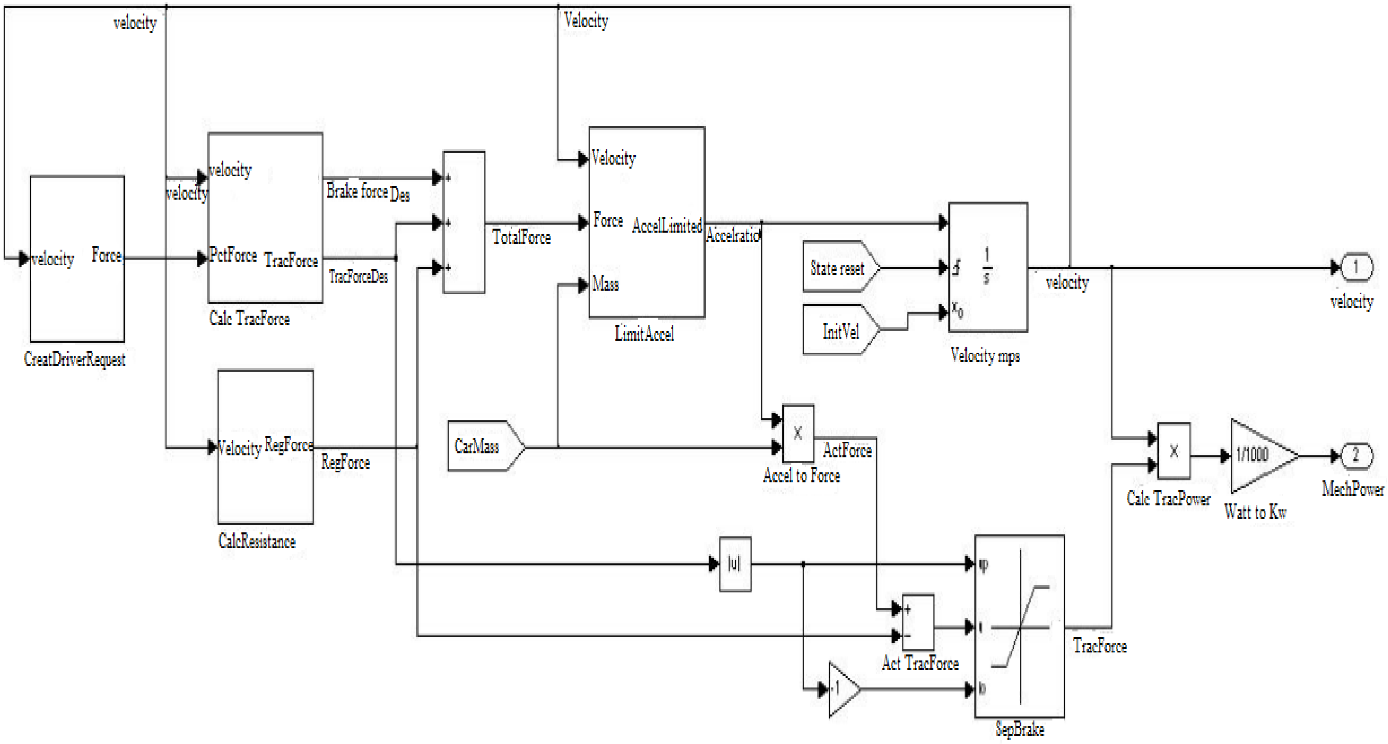

Figure 5-2: Vehicle Motion Model

Deceleration force demand is determined from the maximum friction braking force available, which was constant with velocity. In the case of regeneration, the model then provides as much braking force to electrical regeneration as possible, while applying friction braking force as necessary to ensure the requested deceleration rate is achieved.

The tractive force demand is then added to a drag factor to account for the force lost to wind resistance and rail friction. The force is then limited based on pre-defined maximum acceleration and braking specifications. Finally, the force is applied to an integrator to calculate the instantaneous velocity, which is fed back into the models of available force and drag. The output of the motion model is the mechanical power consumed or generated by the traction drive.

5.1.4. Bidirectional DC/DC Converter Model

The Bidirectional DC/DC converter is designed as high power half bridge configuration which is formed by a buck and a boost circuit in anti-parallel connection. The operation of the DC-DC converter can be divided into two modes, charging mode, and discharging mode. The DC bus is high voltage end and the super-capacitor is the low voltage end.During the charging mode, the bidirectional DC/DC converter is operated as a buck converter and the power flows from the DC bus to super-capacitor. While charging the power switch S1 and the freewheeling diode S2 are at work, as shown in Fugure.5.3 . During the discharging mode, the bidirectional DC/DC converter is operated as a boost converter and the power flows from the super-capacitor to DC bus. While discharging the power switch S2 and the freewheeling diode 1 are at work, as shown in Fugure 5.3.

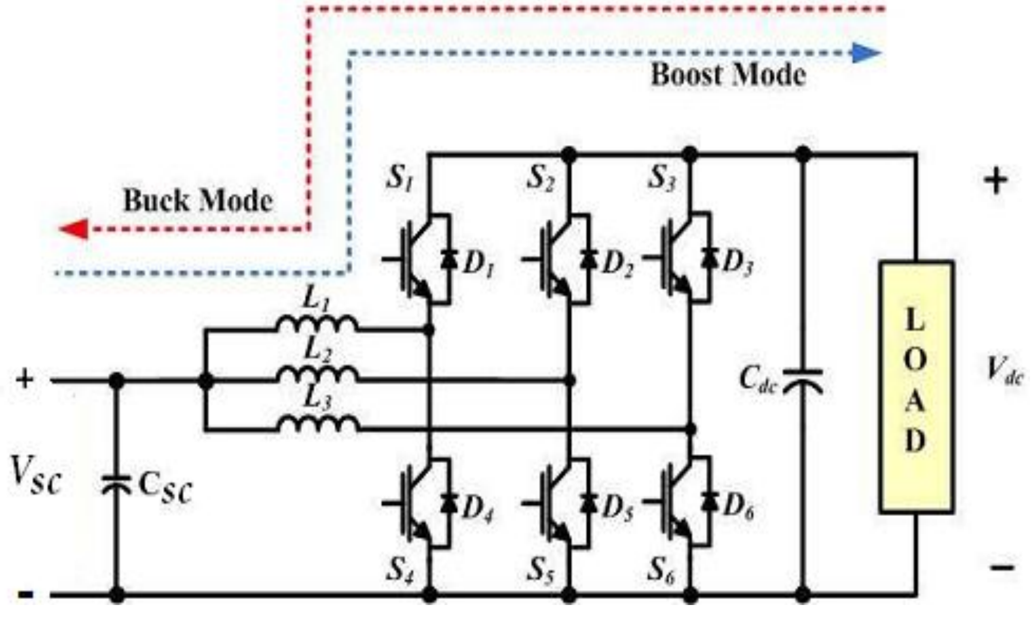

Figure 5-3 Main circuit topology of Bidirectional three leged DC/DC Converter [18]

The converter must be able to charge and discharge the supercapacitor bank. Hence, a bidirectional DC-DC converter is necessary. There are many different solutions that can be used or this purpose, and a lot of literature is available on the subject. The converter will be used in an EV, and properties like weight, volume and dependability are essential to the design. A converter that has several legs for carrying the current has shown promising advantages [14].

The voltage of high voltage end is determined by DC bus voltage (such as 1500V or 750V), and the voltage of low voltage end is determined by the connection structure of super-capacitor cells as it is mentioned before. Gate control signals of power switch S1 and S2 are generated by the controller of bidirectional DC/DC. As for S1, there are two feedback signals (low voltage end voltage and DC bus voltage) and the reference output voltage of the low voltage end. As for S2, there are three feedback signals (voltage of super-capacitor, current of DC bus and high voltage end output voltage) and the reference output voltage of the high voltage end. During braking, the controller of DC/DC will detect the voltage of DC bus and the super-capacitor. If the voltage of super-capacitor lower than the reference voltage and the voltage of DC bus is higher than the threshold setting, the controller generate the PWM control signal of S1 to charge the super-capacitor. While during start-up or accelerations, the controller of DC/DC will detect the voltage of super-capacitor and the mean current of DC bus.

If the voltage of super-capacitor reached the lowest discharging value and the mean current of DC bus higher than the set value, the DC/DC converter operating as a boost converter, generate the PWM control signal of S2 to release of energy stored in the super capacitor.

5.2. Design of the super-capacitor braking energy recovery system

In conventional traction control system, resistance braking is necessary and braking energy is consumed at the braking resistances by means of heat, the regenerative braking will not be achieved. In the system presented in this thesis, the braking energy is saved in the ultra-capacitor by a bidirectional DC/DC converter, the energy flows from the DC bus to super-capacitor.

When the capacity of stored energy components is less than the rated capacity, the energy storage components will not stop being charged through the charging circuit until they reach rated capacity. The function of SCU (switch control unit) is detect the state of super-capacitor, when the super-capacitor cannot accept energy any more for some reason, the TCU (traction control unit) will switch the braking energy recovery system to the braking resistance system to avoid regeneration failure. The charge and discharge of super-capacitor are control by the auxiliary control unit (ACU). During start-up or accelerations, greater currents drawn by trains and imply greater voltage drops on the overhead line.

If the super-capacitor full of energy, then the super-capacitor can supply some currents that will stabilize the voltage of DC-line and reduce the peak power. The ACU detect the capacity of the super-capacitor and determine whether the power has reached the threshold value. If the capacity of the super-capacitor is enough, the super-capacitor will supply the power for inverter by the bidirectional DC/DC converter which works as a boost circuit. The super-capacitor can supply the power to the AC consumers and DC consumers (air-conditioning and lighting etc.) through a DC/DC converter and a DC/AC converter which control by ACU also. The selection of super-capacitor is decided by the charging and discharging time, braking period and output power. The super-capacitor unit is made of many cells and these cells are assembled by series and parallel connection.

There are several problems that need to be addressed when series connecting super capacitors. The main problem is the voltage balancing between the cells, because of differences between each super capacitor. They are given with a +20 % tolerance, i.e. the capacitance of each cell is between 1500 F and 1800 F [20]. The voltage will not be distributed evenly over the whole bank and could destroy the cells after some time. Another problem is connected to the EPR (equivalent parallel resistance) of the super capacitors. If the super capacitor bank is kept charged for longer periods of time, the voltage will divide itself according to the EPR. This can lead to over-voltages and destruction of the cells. Because of these problems, voltage balancing circuits must be implemented between the super capacitors. The voltage balancing does not require any external power source or control.

Let us supposed that a branch were composed of N series cells connected in series, and N parallel branches connected in parallel to form a set of super-capacitor unit. The capacity of the super-capacitor unit described as:

$$C_{sup-C} = \frac{C_{cell} x N_{parallel}}{N_{series}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 5\text{-}7$$

Equivalent resistance of the super-capacitor unit :

$$R_{sup-C} = \frac{R_{cell} x N_{series}}{N_{parallel}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 5\text{-}8$$

Where C_{cell} is capacity of the cell, R_{cell} is resistance of the cell, C_{sup-C} is capacity of the super-capacitor unit, R_{sup-C} is resistance of the super-capacitor unit.

According to the characteristic of the super-capacitor, the energy saved can be expressed as:

$$E = \frac{1}{2} C_{sup-C} ({U^2}_1 - {U^2}_2) = \frac{1}{2} C_{sup-C} ({U^2}_1 - (\alpha U_1)^2) \text{.............} \quad 5\text{-}9$$

Where, U_1 is the final charging voltage, U_2 is the final discharging voltage, α is discharging depth. According to the braking energy which needed to be absorbed by braking unit, the capacity of super-capacitor can be ascertain, and the number and connection mode of cells also can be determined.

5.3. Energy Relationship Model

Let n is the speed of motor(r/min), J and G_D is the moment of inertia of the vehicles which were converted into the motor(kg·m2), then the kinetic energy of the motor and the vehicles is:

$$E = \frac{1}{2} J \omega^2 = \frac{1}{2} J (\frac{2\pi n}{60})^2 = \frac{1}{730} G_D \, n^2 \text{ ....} \quad 5\text{-}10$$

During the braking, speed decrease from n_1 to n_2 and released the kinetic energy：

$$E = \frac{1}{730} G_D \, ({n_1}^2 - {n_2}^2) \text{ ....} \quad 5\text{-}11$$

If supposed that all the kinetic energy of the mechanical system were convert into regenerative energy of the DC side of the inverter, then:

$$E_K = E_g = \frac{1}{2} J \omega^2 = \frac{1}{2} J (\frac{2\pi n}{60})^2 = \frac{1}{730} G_D \, n^2 \text{ ....} \quad 5\text{-}12$$

For the urban railway vehicles, if the maximal DC-line voltage marked as $\boldsymbol{U_{max}}$, and the minimum voltage marked as $\boldsymbol{U_{min}}$, the braking energy should be absorbed by braking unit expressed as：

$$E_S = E_g = \frac{1}{730} G_D \, n^2 - \frac{1}{2} C_{DC-line} ({U^2}_{max} - {U^2}_{min}) = \frac{1}{2} C_{sup-C} ({U^2}_{max} - {U^2}_{min}) \text{.....} \quad 5\text{-}13$$

Where, E_S is the braking energy saved by super-capacitor, E_g is the energy need to be absorbed by braking unit, $C_{DC-line}$ is the filter capacitor of the DC-line, C_{sup-C} is the capacity of the super-capacitor.

Standard super capacitors are specified with a rated voltage DC line of 2.1V to 2.6V, amount of energy generated by regenerative braking system of AALRT trains within the movement between two stations is $\mathrm{E_g} = 1.645kWh$. The capacitance of super capacitor used to store this regenerated energy can be calculated from equation 5-13 as :-

$$E_g = \frac{1}{2} C_{sup-C}(U^2{}_{max} - U^2{}_{min})$$

$$C_{sup-C} = \frac{2E_g}{(U^2{}_{max} - U^2{}_{min})} = \frac{2 * 1.645 * 10^3\ Wh}{\left(2.6^2 - 2.1^2\right) V^2}$$

$$C_{sup-C} = 1.645 * 10^3 \mathrm{F}$$

6. SIMULATION RESULTS

6.1. Train Motion Simulation

The following graphs illustrate the data generated by the motion model of the system during a full stop sequence of simulations.

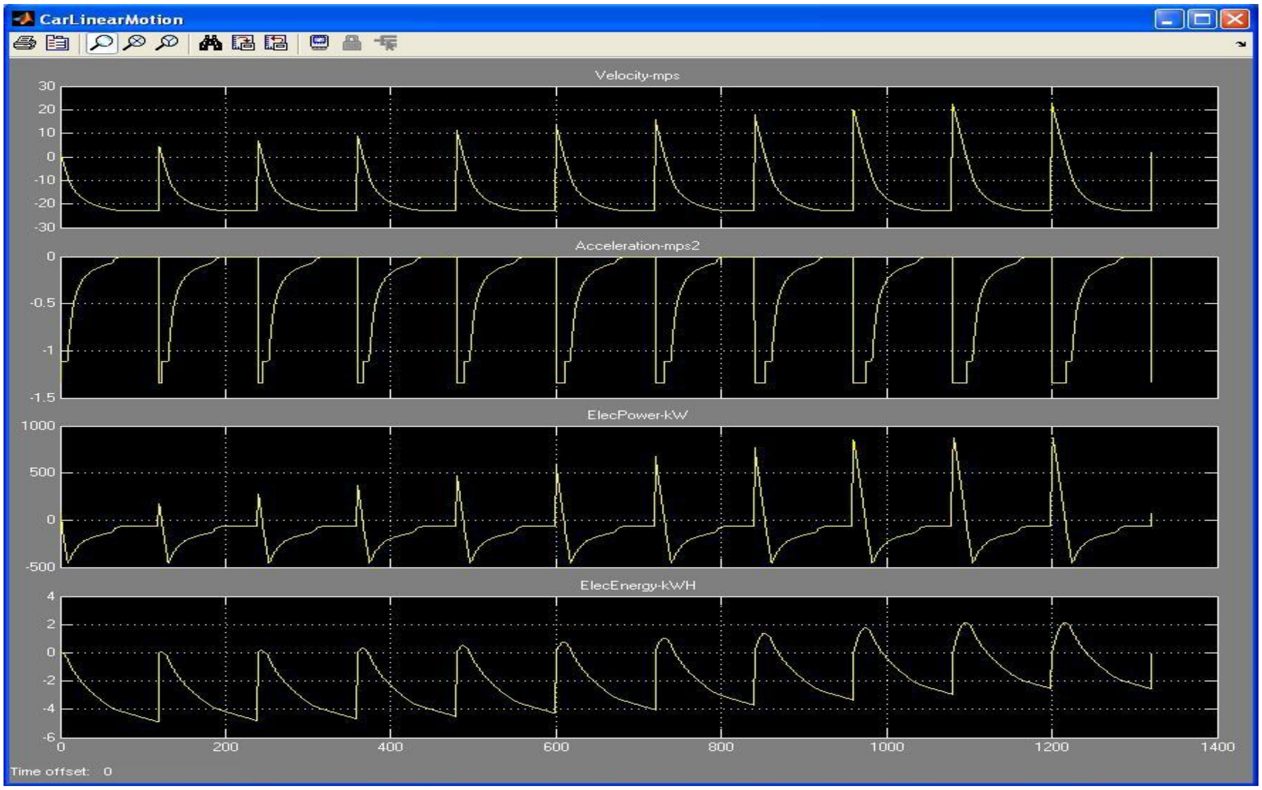

Figure 6-1: Full Stop Motion Model

The top graph shows vehicle velocity (in meters/second) versus time. Each cycle includes starting at an initial positive speed, decelerating to zero speed then accelerating in reverse to the maximum speed (70kmph/19.44mps) and cruising until the next cycle. The first cycle shows deceleration from (8.03kmph/2.23mps) to zero. Subsequent cycles show increments of 8.03kmph in the starting speed up to a maximum of 70kmph.

The second graph shows the acceleration of the train on each cycle. The third graph shows electrical power available from the traction drive on each cycle. The negative halves of the cycles (acceleration from zero speed) look very similar. The positive halves of the cycle show peaks of increasing power and duration as the initial velocity increases.

The bottom graph shows the net electrical energy of the traction drive, starting at 0 kWh on each cycle. The positive hump is the energy recovered from regeneration, the negative peak is the energy used to propel the vehicle in reverse. The magnitude of the positive humps increases on each consecutive cycle as the initial velocity increases.

6.2. Energy Storage System Simulations

The value of an energy storage device is gauged by the amount of energy that it returns to the traction drive system on the subsequent acceleration cycle. An energy storage system with a sufficient number of cells to receive the entire regenerative energy of the car will never return 100% of that energy to the traction system due to resistive losses in the cell.

The following graphs illustrate the results of simulating four consecutive stops from 70kmph, followed by acceleration back to 70kmph and cruising, run with the EDLC ultra capacitor cells.

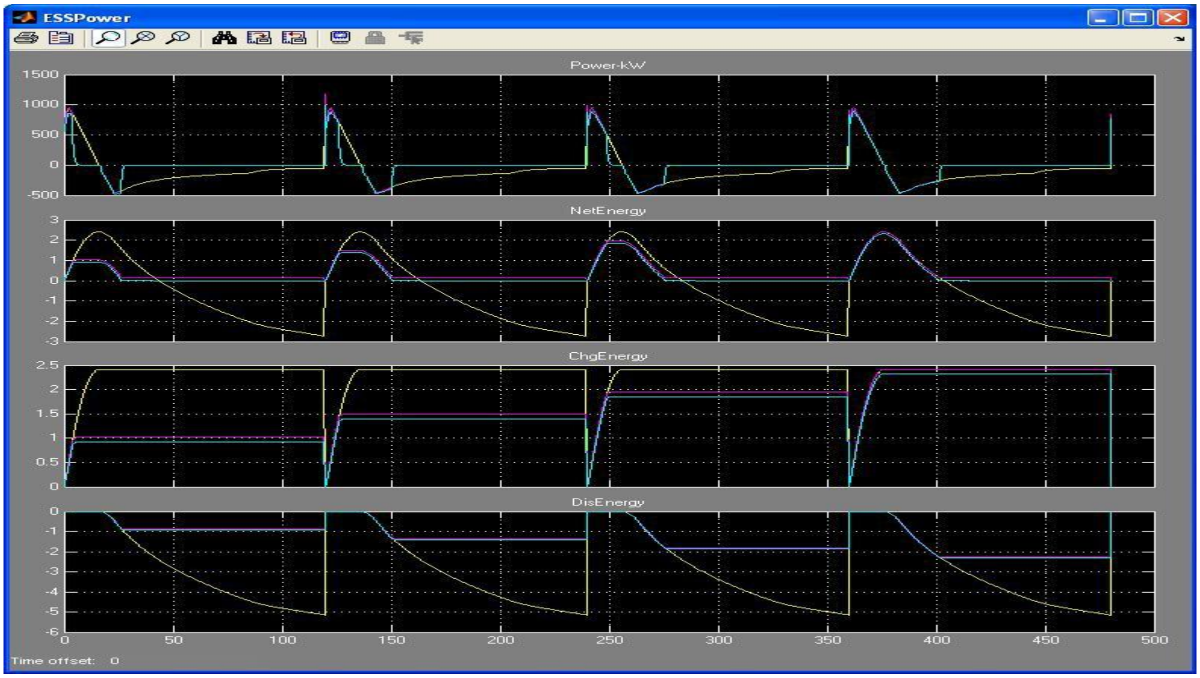

Figure 6-2: Model of Energy Storage with EDLC Ultra capacitor

In the first three cycles, the peak power at the terminals (purple line) matches that of the traction inverter (yellow line). However, the charge cycle is cut short as the energy storage system becomes fully charged. On the fourth cycle, there is finally enough energy storage available to absorb the complete stop cycle. Note that this is close to the maximum energy storage requirement for one car because it illustrates a complete stop from maximum speed to zero speed.

In accordance with the models built in above chapters, a simulation model was set up by using Matlab script program software. Figure 6-3 displays the peak to peak ripple in the super capacitor bank for one to four legs in a bridge configuration.

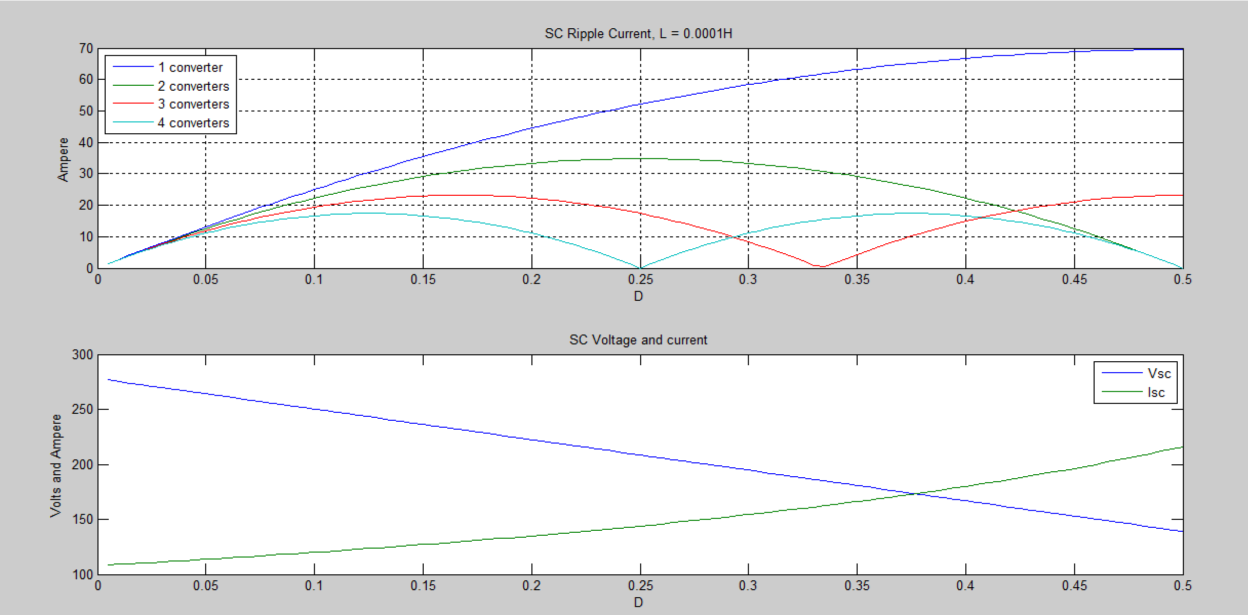

Figure 6-3: Peak to peak ripple and approximate voltage of the super capacitor bank, for different duty ratios

The Matlab code is presented in appendix C. As can be seen from the figure, the maximum ripple is in inverse ratio to the number of converters. If the battery voltage is stiff during energy transfer, the duty ratio will vary between 0.15 and 0.5. Examining Figure 6-3, it seems like the best option is to connect as many legs as possible in parallel.

There are of course other factors to take into account. With increasing number of converter legs the system complexity increases. Each leg needs its own set of switches and each switch needs their own signal. Although the size of the inductors can be reduced, a trade off must be done between the losses in the inductor and the capacitance and the size. Another problem to consider is that the inductors have some tolerance. This limits the effect of interleaving a large number of phases. This effect can be reduced by proper control of the phases, but it still will have a significant effect.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

- Electrical regenerative braking is the main braking technique used for AALRT train driven locomotives.
- The use of regenerative braking of electric locomotives for trains under the conditions of heavy railway traffic allows 25–40 % of electric power to be returned to the power system.
- This thesis presents on board super capacitor system design capable of receiving regenerated energy from Addis Ababa light rail transit train.
- The use of super capacitors in the locomotives with electric drive expands the regenerative braking range to full stopping. This creates the conditions for full use of kinetic energy of the train.
- MATLAB simulation results noticed that maximum energy storage is possible within complete stop of trains from maximum speed to zero speed using super capacitor energy storage device.

7.2. Recommendations

- Based on the result of this thesis work, it is strongly recommended that Ethiopian railway corporation has to consider the installation of super capacitor bank to its traction power system to save the regenerated braking energy of train system and to improving overall system power consumption performance.
- The models developed takes approximation and some datasheet from international railway standards and railway manufacturing companies. Thus, after full operation of AART system by taking actual information and analyzing cost of using super capacitors the result obtained in this thesis will be improved.

REFERENCES

[1] *Addis Ababa light rail transit project study report of east-west and north-south lines, china railway group limited, 2009.*

[2] *A.González-Gila,*, R. Palacina, P. Battya, J.P. Powella, "**Energy-efficient urban rail systems: strategies for management of regenerative braking energy",** Transport Research Arena Paris, 2014.*

[3] *Myung-Jin Chung, Sangidaehak-ro, Siheung-si, Gyeonggi-do, "**Design Method Using Thermal Analysis in the Development of Electric Braking Resistor for Railway Carriage",** Department of Mechatronics Engineering, Korea Polytechnic University, 237, Republic of Korea,(2014),*

[4] *Yuruki OKADA[1], Takafumi KOSEKI[2], Kohei HISATOMI[3], **"Power Management Control in DC-electrified Railways for Regenerative Braking Systems of Electric Trains",** The University of Tokyo, Japan Shin-Keisei Electric Railway, Japan, (2007).*

[5] *Motomi Shimada, Ryoichi Oishi, Daijiro Araki, **"Energy Storage System for Effective Use of Regenerative Energy in Electrified Railways",** Yasushi Nakamura*

[6] *Shimada, Yoshihiro Miyaji, Takashi Kaneko, Keita Suzuki (2012), **"Energy-saving Technology for Railway Traction Systems Using Onboard Storage Batteries",** Hitachi Review Vol. 61, No. 7-31*

[7] *M. Tulbure, R.Both, R. Festila, (May 17-19, 2012),**"Analysis of the induction railway traction motor in regenerative braking",** International Conference on development and application systems, Suceava, Romania*

[8] *J.M. ORTEGA, METRO DE BILBAO;S:A: H. IBAIONDO, A. ROMO. INGETEAM TRACTION, S.A. may, (2011), **"Kinetic energy recovery on railway systems with feedback to the grid"**, 9th world congress on railway research]*

[9] *Mahendra ChandraJoshi, **"Modeling and Control of Bidirectional DC DC Converter Fed PMDC Motor"**,National Institute of Technology Rourkela Rourkela, Odisha, 769008, India*

[10] *Yuruki Okada, TakafumiKoseki, Satoru Sone, "**Energy Management for Regenerative Brakes on a DC Feeding System International Symposium on Speed-up and Service Technology for Railway and Maglev Systems",**(STECH'03) 2003.8.19-22 Tokyo JAPAN, 2003..*

*[11] Tosaphol Ratniyomchai,**"Recent development of energy storage devices for electrified railways",** University of Birmingham, (2013).*

*[12] Jacques Poulin, Andrew Gillespie, Kevin Morelock, Jim McDowall, Brian Inniss, **"Recycled Energy Optimization Project with Regenerative Braking Energy Storage"**, (2010)*

*[13] M. Chymera, A.C. Renfrew, M. Barnes, **"Analyzing the Potential of Energy Storage on Electrified Transit Systems", University of Manchester,** 2009.*

*[14] Hanmin Lee, Gildong Kim, Changmu Lee **"Development of ESS for Regenerative Energy of Electric Vehicle"**, Korea Railroad Research Institute, Uiwang-City, Gyeonggi-Do, Korea, 2010.*

*[15] YeJing-Jing, LiKe-Ping, JinXin-Min, **"Simulating train movement in an urban railway based on an improved car-following model"**Beijing Jiaotong University,Vol.22,No.12-120206 Beijing 100044,China, 2013.*

*[16] Lars Abrahamsson **"Optimal Railroad Power Supply System Operation and Design",** Doctoral Thesis, Stockholm, Sweden 2012.*

*[17] Nicklas Sundberg, **"Efficiency Improvements with Super Capacitors in Mechatronic Systems"** Master of Science Thesis Stockholm, Sweden 2007.*

*[18] A. STEIMEL, Senior Member, IEEE, **"Power-Electronics Issues of Modern Electric Railway Systems"** 10th International Conference on DEVELOPMENT AND APPLICATION SYSTEMS, Suceava, Romania, Ruhr-University Bochum, Germany, May 27-29, 2010.*

*[19] Shaofeng Lu **"Optimizing Power Management Strategies for Railway Traction Systems"** Doctoral thesis, University of Birmingham, UK October 2011.*

*[20] S.Lu, S.Hillmansen, and C.Roberts, **"A Power-Management Strategy for Multiple-Unit Railroad Vehicles",**Vehicular Technology, IEEE Transactions on,vol.60,pp.406-420,2011*

*[21] S.Lu, S.Hillmansen, and C.Roberts, **"Power management strategy study for a multiple unit train,"** IET Seminar Digests, .2010, pp.29-29, 2010.*

*[22] S.Lu, D.H.Meegahawatte, S.Guo, S.Hillmansen, C.Roberts, and C.J.Goodman,**"Analysis of Energy Storage Devices in Hybrid Railway Vehicles",** International conference on railway engineering, IET 2008 Hongkong,2008*

*[23] Mahendra Chandra Joshi, **"Modeling and Control of Bidirectional DC-DC Converter Fed PMDC Motor"**, National Institute of Technology Rourkela, IndiaMay 2013*

*[24] Tobias Andersson, Jens Groot, **"Alternative Energy Storage System for Hybrid Electric Vehicles",** Master Thesis in, CHALMERS UNIVERSITY OF TECHNOLOGY GÖTEBORG, SWEDEN October 2003*

*[25] Jarrad Cody, ÖzdemirGöl, ZoricaNedic, Andrew Nafalski, Aaron Mohtar, "**Regenerative Braking in an Electric Vehicle"** University of South Australia ZeszytyProblemowe – MaszynyElektryczne Nr 81/2009 113*

*[26] Flavio Ciccarelli, Diego Iannuzzi, PietroTricoli**"Control of metro-trains equipped with onboard super-capacitors for energy saving and reduction of power peak demand** "Trans portation Research Part C 24 (36–49), University of Birmingham, United Kingdom 2012*

*[27] Jyh - Cherng JONG, En-Fu CHANG, **"Models for Estimating Energy Consumption of Electric Trains"** Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp. 278 - 291, 2005*

*[28] Dayton T. Brown, Inc., Keith Cummings, **"Feasibility Study of On-Car Regenerative Braking System (RBS) for Electric Rail Applications",** Energy Research and development center, New york city, 11 January 2013.*

*[29] HengLi, JunPeng, Weirong Liu and Zhiwu Huang, **"Stationary Charging Station Design for Sustainable Urban Rail Systems",** A Case Study at Zhuzhou Electric Locomotive Co.,China2015*

*[30] CHEN Xiao-li, LIANG Da-qiang, and ZHANG Wei-dong, **"Braking Energy Recovery for Electric Traction Based on Super-capacitor and Bidirectional DC–DC Converter",**IEEE 7th International power Electronics and Motion Control Conference - ECCE Asia, Harbin, China, June 2-5, 2012*

*[31] Iannuzzi, D.; Lauria, D.; Tricoli, P. **"Optimal design of stationary supercapacitors storage devices for light electrical transportation systems**". Optim. Eng. 2012, 13, 689–704.*

*[32] Teymourfar, R.; Asaei, B.; Iman-Eini, H. **"Stationary super-capacitor energy storage system to save regenerative braking energy in a metro line".** Energy Convers. Manag. 2012*

*[33] Barrero, R.; van Mierlo, J. "**Stationary or onboard energy storage systems for energy consumption reduction in a metro network".** J. Rail Rapid Transit 2010*

[34] *L. Latkovskis, U.Sirmelis, L.Grigans, "**On-Board Super-capacitor Energy Storage Sizing Considerations",** Latvian journal of physics and technical sciences Institute of Physical Energetics, Latvia 2012*

[35] *JianfengLiu, QingYan, XiaohuiQu, FeiJiang, WeirongLi, ZhiwuHuang, **"Explicit Model Predictive Control of Bidirectional DC/DC Converter for Ultracapacitors Energy Storage Unit Applied to Light Rail Vehicle"**19th World Congress The International Federation of Automatic Control Cape Town, South Africa. August 24-29, 2014*

[36] *Karl BA. Mikkelsen, **"Design and Evaluation of Hybrid Energy Storage Systems for Electric Powertrains",**University of Waterloo, Ontario, Canada, 2010*

[37] *Diego Iannuzzi and DavideLauria**"A New Super-capacitor Design Methodology for Light Transportation Systems Saving",** University of Naples Federico II, Electrical Engineering Department Italy 2010*

[38] *Ogasa, M. **"Energy saving and environmental measures in railway technologies: Example with hybrid electric railway vehicles"**, IEEJ Trans. Electrical Electr. Engin. 2008, 3, 15–20.*

[39] *Takafumi KOSEK, Yuruki OKADA, Yuzuru YONEHATA, Satoru SONE "**Innovative Power Supply System for Regenerative Trains"**, The University of Tokyo, Japan 2011*

[40] *ThanatchaiKulworawanichpong, **"Optimising Ac Electric Railway Power Flows With Power Electronic Control"**Doctoral thesis, University of Birmingham November 2003*

[41] *T.K. Ho1, Y.L. Chi, L.K. Siu, and L. Ferreira"**Traction Power System Simulation in Electrified Railways"** Queensland University of Technology, Australia 2005*

[42] *Leon C Rosario, **"Power and Energy Management of Multiple Energy Storage Systems in Electric Vehicles"**PhD Thesis, Cranfield University, United Kingdom June 2007*

[43] *R.J.Hill,"Electricrailwaytraction:Part2tractiondriveswiththree-phaseinductionmotors," PowerEngineeringJournal,vol.8,pp.143–152,Jun.1994.*

[44] *C.W. Lander, "Power Electronics." McGraw-Hill Publishing Companies, 3rd ed., 1993.*

[45] *Jyh - Cherng JONG, En-Fu CHANG, " Models for Estimating Energy Consumption of Electric Trains", Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp. 278 - 291, 2005*

APPENDIX

*APPENDIX A:-*TRACTION SYSTEM AND ELECTRICAL BRAKE SYSTEM OF AALRT

A.1. Railway system in Addis Ababa Ethiopia

Table 0-1 Main parameters of lines

S.No	Parameters	units
1	Track gauge:	1435mm
2	Minimum radius of horizontal curve:	
	Mainlines between sections	50m
	Yard line	30m
3	Minimum radius of vertical curve:	1000m
4	Maximum gradient	55‰
5	rails :	
	Type of rails for main lines and depot:	50kg/m
	Maximum super elevation:	120mm
	inclination at rail bottom:	1/40
6	Axle load:	≤11(1+3%)t
7	Platform parameters	
	Platform height:	300mm
	From platform edge to centerline of the line:	1420mm

Table 0-2: Main dimensions of vehicle

S. No	Length of car body:	≤30000 mm
1	Height of vehicle roof from top of rail (excluding pantograph):	≤3700 mm
2	Maximum width of car body:	2650 mm
3	Height of vehicle floor from top of rail (low floor area, new wheels and empty load)	≤380 mm
4	Height of vehicle floor from top of rail (exit and entry areas, new wheels and empty load)	≤350 mm
5	Height of vehicle floor from top of rail (raised floor area, new wheels and empty load)	≤900 mm
6	Wheelbase (power bogie)	1900 mm
7	Wheelbase (unpowered bogie)	1800 mm
8	Clear height of passenger compartment	≥1980 mm
9	Wheel diameter (new wheel)	≤660 mm
10	Wheel diameter (Max. wear)	≤600 mm

Table 0-3 Rated passenger capacity of vehicles

S. No	Number of passengers (persons)	Seated	Standing	Total
1	Seats (AW)	65	0	65
2	Rated passenger capacity (AW2) (standing: 6 persons/m)	65	189	254
3	Overload capacity (AW3) standing: 8 persons/m2)	65	252	317

Table 0-4: Vehicle weight

S. No	Loads	Car body weight	Passenger weight	Total weight
1	Empty vehicle (t)	44	0	44
2	Rated passenger capacity (t)	44	15.24	59.24
3	Overload capacity (t)	44	19.02	63.02

Table 0-5: Main technical indicators

S. No	Indicators	
1	Speed	
	Maximum operation speed:	70 km/h
	Average travelling speed (average dwelling time of 30 seconds at each station)	≥24km/h
	Operation speed during car wash:	3~4 km/h
2	Average acceleration	
	Vehicle speed from 0km/h to 40 km/h	≥1m/s2
	Vehicle speed from 0km/h to 70 km/h	≥0.5m/s2
3	Average braking deceleration	
	Maximum service brake deceleration:	≥1.1m/s2
	Emergency brake deceleration:	≥2.0m/s2

Table 0-6: Power supply

S. No	Parameters	Amount
1	Rated voltage:	DC 750V
2	Range of voltage variation:	DC 500～900V
3	Height of contact line for ground sections from top of rail is generally	4500 to 5400mm.
4	Height of contact line for underground sections from top of rail is generally	4040mm

Table 0-7: Capacities of External Power Sources for Substations in East-west Phase (I) Project

No.	Substation	Near term		Long term		**In current phase**	
		Number of power circuits	Capacity for a circuit (kVA)	Number of power circuits	Capacity for a circuit (kVA)	Number of power circuits	Capacity for a circuit (kVA)
1	EW22	1	2160	2	2660	1	2660
2	EW20	1	3150	2	4400	1	4400
3	EW18	1	320	2	320	1	320
4	EW16	1	3250	2	4500	1	4500
5	EW13	1	2126	2	2626	1	2626
6	EW10	1	2250	2	2750	1	2750
7	Interval Traction Substation 1	1	2160	2	2660	1	2660

8	Interval Traction Substation 2	1	2126	2	2626	1	2626
9	EW2	1	2126	2	2626	1	2626
10	EW1	1	2160	2	2660	1	2660
11	Ayat Depot	2	3000	2	3500	2	3500

Table 0-8: Capacities of External Power Sources for Substations in North-south Phase (I) Project

No.	Substation	Near term		Long term		**In current phase**	
		Number of power circuits	Capacity for a circuit (kVA)	Number of power circuits	Capacity for a circuit (kVA)	Number of power circuits	Capacity for a circuit (kVA)
1	NS27	2	3000	2	3500	2	3500
2	Interval Traction Substation 1	1	2160	2	2660	1	2660
3	NS22	1	2160	2	2660	1	2660
4	NS14	1	2126	2	2626	1	2626
5	Interval Traction Substation 2	1	2100	2	2600	1	2600
6	NS10	1	2200	2	2700	1	2700
7	NS7	1	2126	2	2626	1	2626
8	NS6	1	2160	2	2660	1	2660
9	Kality Depot	2	4860	2	5360	2	5360

Note:

Traction rectifier unit used in the project shall meet the requirements of Class VI load:

100% of rated load — continuous,

150% of rated load —2h,

300% of rated load —1min, 0922276343

Table 0-9: Capacities of 0.4kV Municipal Power Supply in East-west Phase (I) Project-

No.	Location of substation	Capacity
1	EW22	80 kVA
2	EW20	200 kVA
3	EW18	160 kVA
4	EW16	250 kVA
5	EW13	63 kVA
6	EW10	125 kVA
7	Interval Substation 1	80 kVA
8	Interval Substation 2	63 kVA
9	EW2	63 kVA
10	EW1	80 kVA

Table 0-10: Capacities of 0.4kV Municipal Power Supply in North-south Phase (I) Project

No.	Location of traction substation	Capacity
1	Interval Substation 1	80 kVA
2	NS22	80 kVA
3	NS14	63 kVA
4	Interval Substation 2	50 kVA

5	NS10	100 kVA
6	NS7	63 kVA
7	NS6	80 kVA

Specific requirements for the 0.4kV municipal power supply:

(1) The 0.4kV municipal power supply shall be stable and reliable.

(2) Under normal conditions, the allowable deviation (in % of rated voltage) at the connecting position of 0.4kV municipal power supply should comply with the allowable deviation of supply voltage: ±5%.

(3) Under normal conditions, the allowable frequency deviation at the connecting position of 0.4kV municipal power supply shall be 50Hz±1%.

Table 0-11: Number of passengers and weight:

Condition	Number of Passengers	Approximate car body weight (t)	Passenger weight (t)	Total (t)
AW0	0	44	0	44
AW1	64	44	3.84	47.84
AW2	254	44	15.24	59.24
AW3	317	44	19.02	63.02

Note: Take 60 kg as average weight of each passenger; tare weight of vehicles ≤44t.

APPENDIX B: - ENERGY STORAGE DEVICE USED IN RAILWAY SYSTEM

Table 0-1: Trackside ESSs developed by international manufacturers

Brand name	Company	Technology	Main features	Application in urban rail	Reference
MITRACTM	Bombardier	EDLC	PC: 300 kW SC: 1 kWh W: 450 kg D: 1700 x 680 x 450	Commercially available. Examples in Mannheim LRV, in service 2003–2007; Rhein-Neckar-Verkehr GmbH tramway, 2013.	(Steiner et al., 2007)
Sitras MES	Siemens	EDLC	PC: 288 kW SC: 0.85 kWh W: 820 kg D: 2000 x 1520 x 630	Commercially available. Examples in Innsbruck tramway.	(Siemens, 2012a)
ACR	CAF	EDLC	PC: N/A SC: 0.8 kWh W: 800 kg D: N/A	Commercially available. Examples in Seville, Saragossa and Granada tramway systems, in service.	(CAF, 2012)
STEEM	Alstom	EDLC	PC: N/A SC: 0.8 kWh W: 800 kg D: N/A	Prototype testes Paris tramway, tested from 2009 to 2010.	(Moskowitz & Cohuau, 2010)
Citadis flywheel	Alstom & CCM	Flywheel	PC: 325 kW SC: 4 kWh W: 1600 kg D: N/A	Prototype tests in Rotterdam in 2004– 2005	(Lacôte, 2005)

LRV Swimo	Kawasaki	NiMH	PC: 250 kW SC: 120 kWh W: 3200 kg D: N/A	Prototype tests in Sapporo Municipal Transport network, 2007 – 2008.	(Ogasa, 2010)
LFX-300 streetcar	Kinki Shayro	Li-ion	PC: N/A SC: 40 kWh W: 3200 kg D: N/A	Prototype tests in Charlotte, 2010.	Railway Gazette (News, 2011)
Sitras HES	Siemens	EDLC + NiMH	PC: 288 + 105 kW SC: 0.85 + 18 kWh W: 820 + 826 kg D: 2000 x 1520 x 630 1670 x 1025 x 517	MTS light rail system in south Lisbon, in service since 2008.	(Meinert, 2009)

Table 0-2: On-board ESSs developed by railway manufacturers

Brand name	Company	Technology	Main features	Application in urban rail	Reference
Sitras SES	Siemens	EDLC	SV: 600/750 V PC: 700 kW SC: 2.5 kWh	Madrid and Cologne, in service since 2003; Beijing metro, in service since 2007; Toronto rail transit, in service since 2011	(Siemens, 2012b)
Ener Gstor TM	Bombardier	EDLC	SV: 600, 750, 1500 V PC: 650 kW SC: 1 kWh	N/A	(Bombardier, 2010)

Neo Green Power	Adeneo (Adetel)	EDLC	SV: 750 V PC: 300–1000 kW SC: 1–4 kWh	Lyon tramway, pilot project in 2011	(A deter, 2011)
Envistor	Envitech Energy (ABB)	EDLC	SV: 500–1850 V PC:750–4500 kW SC: 0.8–16.5 kWh	Warsaw metro, to be implemented; Philadelphia transit system, pilot project in 2012 (battery-based).	(ABB, 2012)
Capapost	Meidensha	EDLC	SV: N/A PC: 2000 kW max SC: N/A	Hong Kong metro, to be delivered.	(Railway Gazette News, 2012)
Power bridge	Piller Power Systems	Flywheel	SV: 400, 1000 V PC: 1000 kW SC: 5 kWh	Hannover and Rennes metro systems, pilot project in 2004 and 2010, respectively.	(Boizumeau et al., 2011)
GTR system	Kinetic Traction Systems	Flywheel	SV: 570–900 V PC: 200 kW SC: 1.5 kWh	London metro, pilot project in 2000; New York City transit system, pilot project in 2002; Lyon metro, pilot project in 2003-2004.	(Tarrant, 2004)
Regen - system	Vycon	Flywheel	SV: N/A PC: 500 kW SC: N/A	Los Angeles metro, to be delivered	(V ycon, 2013)
Giga cell BPS	Kawasaki	NiMH	SV: 600, 1500 V PC: N/A SC: 150–400 kWh	New York City Transit network, pilot project in 2010; Osaka City Subway, tested in 2007.	(Ogura, 2011)
B-CHOP	Hitachi	Li-ion	SV:600/750, 1500V	Kobe transit system, pilot project in 2005 and regular	(Shimada et al., 2010

			PC: 500–2000 kW SC: N/A	service since 2007; Macau metro system, to be delivered	
Intensium Max	Saft	Li-ion	SV: 700 V PC: 900–1500 kW SC: 600–400 kWh	Philadelphia transit system, pilot project in 2012.	Poulin, (2012)

Table 0-3: Summary characteristics of different super-capacitor manufacturers

Super Capacitor type	Rated voltage (V)	Capacity C (F)	Specific Energy (Wh/kg)	Specific Power (W/kg)	Weight (kg)	Volume (L)
Maxwell	2.5	2700	2.55	784	0.7	0.62
Ness	2.7	5085	4.3	958	0.89	0.712
Asahi Glass	2.7	1375	4.9	390	0.21	0.151
Panasonic	2.5	2500	3.7	1035	0.395	0.328
EPCOS	2.5	2790	3.46	2055	0.57	0.377
Montena	2.5	2800	3.33	858	0.525	0.393
Okamura	2.7	1350	4.9	650	0.21	0.151

APPENDIX C: - SUPER CAPACITOR

C.1. Matlab Programs SC current ripple dependent on duty cycles

This programs display a graph over the SC current ripple

```
Vbatt = 278;%Battery Voltage
Ts=0.0001;  %Switching time
L=0.1e-3;   %Inductance
Isc0=108;    %Current at battery voltage

for i= 1:100;

    D(i)=0.005*i;
    Vsc=Vbatt*(1-D(i));
    Vscplot(i)=Vsc;
    deltai=Vsc*Ts/L*D(i);
    Isc(i)=Isc0*1/(1-D(i));
    Peaktopeak2(i)=deltai*(2-1/(1-D(i)));

    if (D(i) <= 0.25)

        Peaktopeak3(i)=(3*deltai-2*deltai/(1-D(i)));
        Peaktopeak4(i)=deltai*(4-3/(1-D(i)));

    elseif (D(i) >= 0.25) & (D(i) <= 0.3333)

        Peaktopeak3(i)=(3*deltai-2*deltai/(1-D(i)));
        Peaktopeak4(i)=deltai*(4-1.5/(1-D(i))-1/(2*D(i)));

    else

        Peaktopeak3(i)=deltai*(1-2/(3*(1-D(i)))+2*(D(i)-1/3)/D(i));
        Peaktopeak4(i)=deltai*(4-1.5/(1-D(i))-1/(2*D(i)));

   end

    DIsc(i)=deltai;
end
%plot properties
subplot(2,1,1);plot(D,DIsc,D,Peaktopeak2,D,Peaktopeak3,D,Peaktopeak4)
title (['SC Ripple Current, L = ',num2str(L),'H'])


legend ('1 converter','2 converters','3 converters','4 converters',2)
xlabel ('D')
ylabel ('Ampere')
grid on

Subplot(2,1,2);plot(D,Vscplot,D,Isc)
title ('SC Voltage and current')
legend ('Vsc','Isc',1)
xlabel ('D')
ylabel ('Volts and Ampere')
```