UTILISATION OF LOCOMOTIVE FOR MID-TERM ENERGY STORAGE

by

ANDILE NQODI

Submitted in accordance with the requirements for
the degree of

MAGISTER TECHNOLOGIAE

in the subject

ELECTRICAL ENGINEERING

at the

UNIVERSITY OF SOUTH AFRICA

SUPERVISOR: PROF. ADEDAYO A. YUSUFF

CO-SUPERVISOR: MR THAPELO C. MOSETLHE

December 2020

Declaration

Name: **Andile Nqodi**

Student number: **46542817**

Degree: **MAGISTER TECHNOLOGIAE: ELECTRICAL ENGINEERING**

UTILISATION OF LOCOMOTIVE FOR MID-TERM ENERGY STORAGE

I declare that the above dissertation is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

I further declare that I submitted the dissertation to originality checking software and that it falls within the accepted requirements for originality.

I further declare that I have not previously submitted this work, or part of it, for examination at Unisa for another qualification or at any other higher education institution.

December 2020

Acknowledgement

I would like to acknowledge and thank Prof. Adedayo A. Yusuff for his valuable assistance, encouragement and effort during this research, without which this study might not have been a success. In the same word, I would like to thank Mr. Thapelo C. Mosetlhe for all his guidance and lastly, I offer my sincere gratitude to my beautiful wife Mokgadi and my children Siphesihle and Wandile for their relentless love, encouragement and help in completing my dissertation.

Abstract

The idea of a mid-term energy storage system (ESS) is becoming a popular option for improving the performance of energy conservation, power efficiency and the power grid. The goal of this research is to explore the possible benefits of utilisation of locomotive for mid-term energy storage. Various technologies are available in the market, including the Flywheel energy storage system (FESS), which is more appealing due to energy storage capacity, regular discharge cycles, reduced discharge costs for a few minutes, long lifespan and ongoing research and development. In this work, the efficacy of integration of FESS onto a locomotive power system for energy harvesting is evaluated. First, the model of the railway power network is presented. Based on the data available from the locomotive, the sizing of the FESS is done. The proposed scheme absorbs the braking energy generated. The benefits of feeding the recovered energy back into the railway power network when the train moves from a plane horizontal surface to steep gradient are investigated. The contribution of the evacuated power from the FESS to the catenary line is also appraised. The effectiveness of the proposed scheme is technically feasible for trains operating between Ermelo Coalfields to Ports of Richards Bay (RCB). The network is hampered by limitations on the power supply and regular faults, resulting in service delays. Feasibility to use FESS will potentially improve energy on-time delivery between traction stations. The results show that the use of flywheel energy storage technology would save the rail operators 25 % of their energy on class 19E locomotives. Therefore, for feasibility validation, this scheme may be feasible for implementation at a prototype level. This scheme will unburden the supply systems as the stored energy can be evacuated into the distribution networks. Furthermore, the effectiveness of this scheme will augment the supply during the irregular peak power that is often experienced in the railway connected system.

Table of Contents

List of Table

List of Figures

Acronyms

AC	Alternating Current
DC	Direct Current
ESS	Energy Storage System
OES	On-board Energy Storage System
SESS	Stationary Energy Storage System
TE	Tractive Effort
RBCT	Richards Bay Coal Terminal
RCB	Richards Bay
FESS	Flywheel Energy Storage System
CAES	Compressed Air Energy Storage
DMU	Diesel Multiple Unit
EMU	Electric Multiple Unit
NiCd	Nickel Cadmium
Pb-Ac	Lead-Acid (Battery)
Li-ion	Lithium-ion
SC	Super-capacitor
APS	Advanced pumped storage
SA	South Africa
OEM	Original Equipment Manufactures
RBS	Regenerative braking system
RPN	Railway Power Network

EMU	Multiple Electrical Units
ITM	Induction Traction Motors
IGBT	Insulated Gate Bipolar transistor Control
ERU	Event Recording Unit
OTMR	On-Train Monitoring Recorder
ERS	Event Recording System
OTDR	On-Train Data Recorder
ER	Event Recorder
FRA	Federal Rail Road Administration
TCMS	Train Control Monitoring System
CPU	Central Processing Unit
SRAM	Static RAM
PRASA	Passenger Rail of South Africa
ESKOM	Electricity Supply Commission

Chapter 1 : Introduction

1.0 Introduction

In many parts of Africa and the Indian sub-continent, as well as some other parts of Asia, energy deficiency is a problem. This is a result of inefficiencies in energy conversion systems, transmission losses, and inefficient consumer behaviour. In railway systems, energy is distributed in rail infrastructure then transferred to railways. Electrical energy is transferred to running trains along the rails through a sliding pantograph. Various supply voltages and frequencies are used by different countries depending on the need and the technology used. In order to generate adequate tractive effort for train motion, the energy consumed by traction motors is utilised. This is where the bulk of the gross energy usage of electric trains is. Electric locomotives use their traction motors to transform kinetic energy into electromagnetic force. A train decelerates throughout regenerative braking system (RBS). Typically, in modern electrical train network, by changing the polarity of its induction traction motors. During braking, kinetic energy is usually dissipated as waste, but the recovered power is directed to the energy storage at train deceleration through the power electronics control system. The recovered regenerated energy is stored until the train needs it again, turning it back into kinetic energy using the train power electronic control system [1]. According to [2], there are various energy storage systems that could be deployed to capture the braking energy once disposed of as heat. Energy storage systems are classified as chemical, electrochemical, mechanical, hybrid and electrical by their storage type [3]. Batteries, super-capacitors and FESS are popular energy storage devices used in the railway sector [4]. The energy storage system and a converter are the two main components of regenerative breaking to control energy transfer between a train and storage system. This study proposes the utilisation of FESS to provide means of mid-term energy storage in locomotives. The FESS absorbs the energy produced during regenerative braking. At peak power demands (during uphill), less power can be extracted through pantographs with augmentation from the FESS. The excess power could then be returned back to the grid to reduce traditional public grid reliance. Compared to other traditional energy storage technologies, FESS has several benefits, such as fast power response, high power density, high number of operating cycles over its lifespan, higher than other energy storage technologies, versatile power/energy ration as it depends on the dimensions of the motor and flywheel and high performance when charging and discharging energy [5].

1.1 Motivation

An increasing energy cost in our society, especially in the railway industry has become a serious concern. The most important goal of railway system operators is a reduction in power usage and improves energy efficiency. The utilisation of energy storage devices is one of the prospects for energy efficiency in the railway industry. The railway's power consumption in South Africa (SA) is 41 % diesel,59 % electric, while traction energy is 19 % diesel and 81 % electric [6]. The financial benefits of the system of harvesting regenerated energy are investigated in order to decide if energy savings obtained warrants the investment needed. This will be achieved by means of calculating average annual energy costs versus energy regenerated.

1.2 Problem statement

During the locomotive regenerative braking system, energy is being omitted in the form of heat, not being utilised and dissipated as waste. Locomotives do not have on-board energy storage systems to capture this wasted energy during regenerative braking. Locomotives are originally designed without the energy storage system. Due to global scarcity of electricity, harvesting of energy by utilisation of locomotives is inevitable. Integration of on-board energy storage technologies into locomotives will minimize energy cost and dependency from power utilities which are currently constrained and experiencing unimaginable load shedding and energy shortage.

1.3 Research objectives and aims

This research work will focus on assessing the amount of energy that is wasted during braking system and a suitable range of FESS using mechanical transmissions. The objectives are summarised as:

- To quantify the amount of energy that is dissipated in the braking system of a locomotive.
- To determine the amount of energy that could be recovered by the integration of FESS on-board the locomotive.
- To determine the economic feasibility of energy recovery based on flywheel energy storage system.

1.4 Research/Core Questions

The following are the research questions relevant to this work:

- What is the amount of energy which can be generated from the locomotive regenerative braking system per trip?
- How much energy could be recovered by the integration of FESS in a locomotive?
- What is the effect of feeding back the energy into the railway power network?

1.5 The benefit of the study

This study provides scientific evidence towards the possibility of energy recovery through FESS in a locomotive. The implementation of this scheme will result in reduced energy demand of the locomotive and thus, increase cost savings. The successful operation of this system, in effect, would increase the efficiency of the locomotives power system.

1.6 Delimitation of the study

- The study will only focus on a fraction of Ermelo coal-mines to the Ports of Richards’s Bay, limited to class 19 Electric locomotives.
- The study will not evaluate the impact of FESS on the operation of the traction stations and the overall power distribution system.

1.7 Layout of the Dissertation

In this study, the subsequent research layout is followed to achieve the set goals:

- Chapter 2 presents the literature review conducted on certain aspects of energy storage systems (ESS) used on electric and railways vehicles. The chapter outlines the various types of ESS based on their energy formation, compositional material, and technique of power delivery over their potential, overall efficiencies and life expectancy.

- Chapter 3 presents a modelling and theoretical background of conceptual model on each component of regenerated braking system (RBS) and integration of these subsystems. A system is defined and acts as a framework when the theoretical model is developed.

- Chapter 4 presents the model approach used for analysing the conceptual method for recovery of regenerated energy on class 19E locomotives. The modelling method and technique are discussed and results are presented.

- Chapter 5 presents the summary, conclusion, and suggestions for future work. The chapter summarises the technological viability for recovery of regenerated energy using FESS and uses available data to draw up a conclusion along with suggestions for future work.

Chapter 2 : Literature Review

2.0 Introduction

Electricity plays an essential role in the health of humans and it is a contributor in countries economic developments. Due to existing being insufficient to meet the country energy demands, saving initiative are receiving considerable attention in various electrified applications [1, 2]. In railway vehicles with regenerative braking capability, a portion of the energy used to power a train is regenerated during braking [4]. To avoid overvoltage in pantographs, this energy is normally dissipated in a form of heat. In recent times, there is a growing interest to harness and store the energy for future utilisation. These developments in railway vehicles have the potential to offer a substantial reduction in energy consumption [7]. In [7], the effective collection of regenerated energy and its subsequent storage led to about 30 % energy consumption reduction. The advantage of storing regenerated energy could be divided into three broad categories; (1) peak demand shaving, (2) voltage stabilization and (3) possibility of catenary free operation. The peak demand shaving is managed by optimally evacuating the energy stored by the energy storage system (ESS) to augment the traditional supply [8]. Voltage stabilisation is accomplished by limiting voltage drops in the system supply network, which could theoretically allow a higher traffic density without further modification in the existing supply infrastructure [9]. Possibility of catenary-free vehicles service in a certain emergency situation such as upstream power failure, certain parts of the railway and or in deports operation [8]. Catenary free operation is a method of operation whereby the energy from an energy storage system is used by a train on an area where the installation of overhead lines is an impracticable or non-electrified track [10][11][12]. The precise length of free catenary operation depends on lots of variables e.g. the capability of an on-board energy storage system, not only providing high peak power but also high energy capacity. There’s several kinds of energy storage system that are completely matured and used in public transportation like batteries, flywheel, super-capacitors and hybrid energy storage system (HESS) [7]. Good use of energy storage systems may be a useful solution for regenerated energy harvesting. This could also help to address the unresolved issues of energy management in electric vehicles [7]. In [5], “name of the ESS listed above” allowed for abrupt energy transfer between railway vehicles as a result of its ability to dispatch the energy quickly. Previously, numerous researches have contributed significantly to the analysis of several aspects of the energy storage system (ESS) in electrical vehicles (EV) and railway vehicles (RV). Majority of RV’s fitted with energy storage system are still at prototype stage [13]. In [14], a detail review of ESS has been presented with pros and cons for EV implementation their classifications, specifications, constructions and energy conversion. Additionally, the study outlines various types of ESS based on their energy formations, compositional materials, and technique of power delivery over their capacity and overall efficiencies within their life expectancies. An illustration of a system that store energy during braking and reuse the stored energy during traction was presented [15].

2.1 Overview of Energy Storage Systems

Electrical energy storage is accomplished by converting electrical energy into another form, namely: mechanical, electrochemical, chemical, and electrical [16]. A wide array of energy storage systems are discussed and compared in this section. Batteries, flywheel, and super-capacitors receive special attention. Power and energy density, response time, weight, volume and operating temperature would depend on the choice of energy storage technology for a system [17][18]. Batteries and super-capacitors are highly energy-efficient and can be recharged from any source using electricity. Both batteries and super-capacitors face low power output and energy density. While the super-capacitor can easily achieve the desired output power, but they do not store enough power for more than a few kilometres of propulsion. Batteries suffer from a lower power density, a flywheel is perhaps the most direct energy storage, as there is no conversion of energy between flywheel and transmission, storage and conversion are thus efficient, which makes mechanical storage excellent for harvesting of regenerative braking energy [18].

2.1.1 Types of Energy Storage System for Regenerated Energy in EV's and RV's

Energy storage system (ESS) for electrical and railway vehicles applications can be divided into five groups tailored to their individual storage technologies of electrical energy with particular shapes and designs: mechanical energy storage, electrochemical energy storage, electrical energy storage, hybrid energy storage and chemical energy storage [14][16]. In terms of operation, discharge time, discharge loss, energy density and wattage rating [16][19], each device has distinguished characteristics. Figure 2.1 presents in detail the energy storage classifications where the specific energy storage for the application of EVs, diesel and electric trains is boxed in grey.

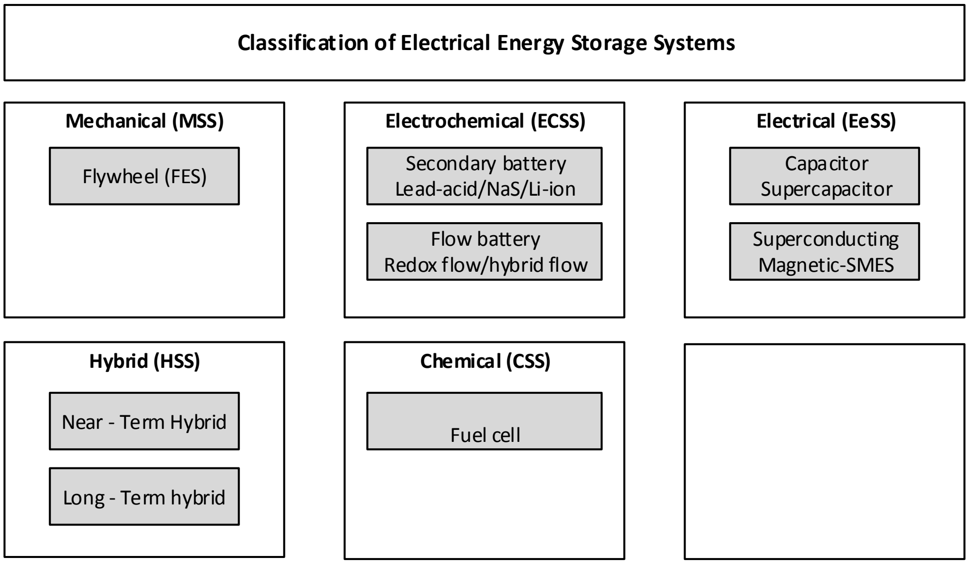


Figure 2.1: Classification of ESS technologies [14][16]**.**

2.1.1.1 Mechanical storage systems

Mechanical storage systems (MSSs) are widely exploited worldwide for generating electricity. Pumped hydro storage (PHS), compressed air energy storage (CAES), and flywheel energy storage (FES) are three MSSs [20]. PHS is used in hydro power stations and is the most popular MSS. High-head reserved water is used and pumped to an electric turbine with a generator to produce electricity. This storage system account for about 99 percent of the world electricity storage capacity, about 3 % of world supply generation [14][21]. In CAES, compressed air is mixed with natural gas, expanded, and further transformed into refined gas for feeding into gas turbine shafted with an electricity generator [14][22]. CAES is appropriate to generating huge capacity of electricity.

2.1.1.1.1 Flywheel storage systems

Flywheel energy storage system (FESS) is older than batteries and super-capacitors. In Japan, flywheels have been in operation since 1970 as the stationary energy storage system (SESS) with energy savings of 12 % [23]. Reports show that the United Kingdom and the United States have placed 300 KW and 1 MW flywheels in-service for DC metro lines, respectively [23]. The tests result shows that the recommended flywheel is capable of switching in both generation and motoring mode within 5 ms and needs a minimal maintenance [23]. A latest report on the use of flywheels in heavy-duty locomotives indicates that such storage systems are more effective for on-board energy storage system compared to batteries due to strength, costs, lifetime limitations [23]. In short-term application up to several MW, Flywheels are suitable ESS [24]. FESS is a mechanical energy storage device consisting of a rotor that is mounted inside a helium-filled vacuum chamber, thereby reducing air friction losses and supported by magnetic bearings for stable operation [25]. To discharge the stored energy, the FESS is connected to a motor-generator assembled on a stator by means of power electronics that interacts with the grid [26]. In the advancement in power electronics and material engineering [14][27], it makes FESS a great option for the use in EVs and RV’s. FESS efficiency and rated power are estimated to be between 90 to 95 percent and 0 to 50 MW respectively [14][27][28][29][30][31][32][33][34]. A conventional high speed flywheel system has five key components, a collection of special bearings, electrical motor/generator, power electronics unit and confinement that provides high vacuum containment as shown in Figure 2.2 [35][16]. In accordance with the rule of conversation of energy in discharging process, a system should operate as a generator by releasing the kinetic energy stored in the flywheel back to electrical energy with rotor deceleration

[36][16]. The total energy which could be retained in a flywheel depends on the moment of inertia of the rotor as well as the speed at which it could be rotated, along with the thermal conductivity and stress limitations.

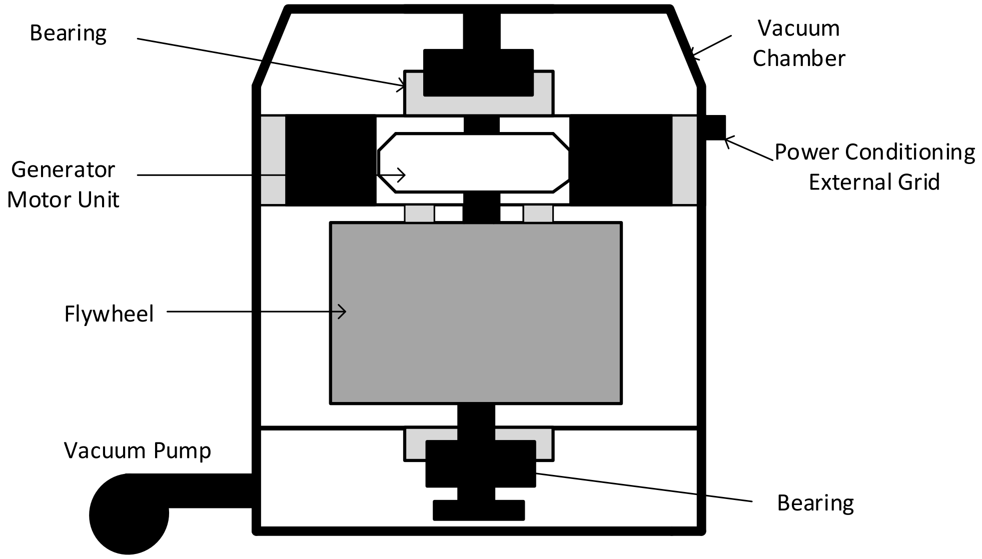


Figure 2.2: Structure and component of a FESS system [37]

2.1.1.2 Electrochemical storage systems

Electrochemical energy storage systems (EcSS) are the earliest known technologies used to store energy [16]. According to [38][14], EcSSs are used for all traditional rechargeable batteries, specifically, flow batteries (FBs) and rechargeable secondary battery energy storage systems (BESS). Through EcSSs, energy is converted from electrical to chemical energy and vice versa with energy efficiency and low physical changes [38][14]. Nevertheless, a chemical response can however decrease cell life and energy [14][39]. Such battery types have a double purpose of absorbing and releasing electrical energy by adjusting the phases of changing and discharging without harmful emission and with little maintenance [14][40]. EcSS is the biggest collection of available electrical energy storage systems with a wide range of energy densities ranging from 10 Wh/kg up to 13 kW/kg having an efficiency of 70 to 80 percent for different methods [41][42][14].

2.1.1.3 Hybrid Energy storage systems (HESS)

Power and energy capacity are certainly, the key criteria to be taken into consideration when selecting energy storage systems for electric vehicle applications, in particular as far as the regenerated energy storage is concerned. In some applications a single ESS might not be adequate to satisfy the peak load times and intermittent load power fluctuations for electric vehicles, researchers have suggested a different variation of hybrid energy storage systems over the last decade [16][43][17]. Hybridization is the method of creating a super device by integrating two or more ESSs electronically with complementary characteristics to provide optimal power for loading [14][44]. The combination of different storage systems assists in meeting desirable technical requirements like high energy density, power rating, operating temperatures, discharge rate, efficiency, costs and life cycle, taking into account the harsh working environment, economy and real-time application. HESSs are categorized as follows, hybrids of batteries and SMES and batteries, hybrids of batteries and ultra-capacitor, hybrids of batteries and batteries, hybrids of CAES and batteries, hybrids of CAES and UC, hybrids of FC and UC, hybrids of batteries and flywheel, hybrids of FC and ultrahigh-speed flywheels [14][17]. Because of its diversification and unique capabilities, batteries can be used for HESS applications in high power and high energy regions, short-term high power requirements will be supplied by high power devices, while long-term energy needs can be satisfied by high energy devices. Interestingly, HESS appears to be a promising option for electric vehicle energy storage. HESS apparently performs better than single energy storage devices, especially for energy savings and catenary free operations. Hybrid ESS such as NiMH and Zn-Air, Zn-Air and Li-ion, FC and Li-ion, Zn-Air and VRLA, FC and NiMH, FC and VRLA exhibit relatively high specific energy and high specific power combinations. Low and high power demands combination are supplied by UC and li-ion, NiMH and UC, VRLA and UC hybrids. The following are the long-term application; SMES and Li-ion, FC and UC, CAES and UC, FC and UHSF hybrids. HESS has the capability to recharge energy from regenerative braking and even from a specific sub-station rapid charging unit [15].

2.1.1.4 Chemical storage systems (CSS)

CSS store energy in molecular compounds and are the key to long-term energy storage systems. CSS uses electricity to generate hydrogen which is subsequently stored [45]. In addition, fuel cells transform the stored energy back into electricity, using hydrogen as a fuel. Power is created by means of chemical reactions and electron transfer by molecular rearrangement. CSS focuses primarily on secondary energy carriers, such as hydrogen and synthetic gas, of which hydrogen is electrolyzed, and it can also be synthesised with carbon dioxide into natural gas [46]. Hydrogen-based chemical energy storage technologies employ two distinct methods for storing and releasing energy. With an electro-chemical reaction to produce electricity, hydrogen and oxygen gases are pumped into a fuel cell (FC). The anode and the cathode are separated by a membrane, the electrolyte. Electrolyser is the common way of producing hydrogen from water, hydrogen is stored in high pressure vessels and or transmitted by pipelines for later use [16]. This technology is environmentally friendly, zero emission, with more than 100 GWh storage capacity. The hydrogen-based in particular are popular and available in the market, FC vehicles will have the least environmental impacts as their by-products are only heat and water [16][46]. However, it has low energy conversion efficiency problems, only 4 to 50 per cent, high cost, lack of existing infrastructure, large investment and low safety measures which makes it unsuitable for large scale fundamental energy system [46].

2.2 Comparison and Evaluation of ESS

It seems none of the single electrical energy storage systems may fulfil all technical requirements for applications of electrified railways (ER) and electrical vehicles (EV). Tables 2.1, 2.2 and 2.3 provide a detailed matrix indicating a performance and characteristics of each ESS. The data in this section were extracted from a comprehensive literature review, academic research and industry application areas. An appropriate selection of ESS for ER and EV applications is based on their characteristics, capacity, power rating, discharge time, DOD, self-discharge, life cycle, efficiency, size and cost. The total amount of energy available which is stored after a full charge is described as the capacity of ESS. The capacity utilisation will vary from ESS to ESS with respect to self-discharge, DOD, and response time [14]. Every energy storage system has unique performance parameters that make it optimally suitable for certain network applications versus the others.

Table 2.1: Technical characteristics of Energy Storage Systems

Technology	Energy Density (Wh/Kg)	Power Density (W/Kg)	Power Rating (MW)	References
Lead Acid (Pb-Acid)	20-35, 25-50, 30-50	75-300,200-400	0-20, 0-40, <70	[47][48][49]
Nickel Cadmium (Ni-Cd)	45-80, 50 -75	150-300,150-350	0-40, <40	[47][48][49][50]
Nickel Metal hydride (Ni-MH)	60 - 80, 60-120	80 - 300, 200 - 1200, 700-756	<0.03	[47] [51][48][49]
Lithium-Ion (Li-Ion)	100-250	230-340	0.1-5	[47][48][49]
Sodium-sulfur (NaS)	150-240	90-230	0.5-50	[47][48][49]
Vanadium redox (VBR)	10-30,25-35	80-150, 166	0.03-3, 0.01-10	[47][48][49]
Electro Chemical Double Layer Capacitor (EDLC)	2.5-15,<50	4000, 500-5000, 5000 - 10000	0.01-1	[47][48][49]
Hydrogen Fuel Cell (FC)	800-10,000	500 – 3000, 500+	<50	[47][48][49]
Zinc-Bromine (Zn-Br)	60-80	50-150	0.05-2	[47][48][49]
Flywheel Energy Storage (FESS)	10-30, 5-80, 5 - 100, 5-130	400-1500, 400-1600	0.01-0.25, <20	[47][48][49][52]

The energy and power density are important indices which represent the total energy and power per unit weight. At a given amount of energy, high power and densities signify that smaller ESSs are feasible. In comparison, lower energy or power densities for a given amount of energy may mean that an ESS will need larger volumes and footprints and, thus, unsuitable for volume-constrained applications.

Table 2.2: Additional technical characteristics of Energy Storage Systems

Technology	Daily-self Discharge (%)	Lifetime (Years)	Cycling times (Cycles)	Discharge efficiency (%)	Cycle efficiency (%)	Response time	References
Lead Acid (Pb-Acid)	0.05-0.3	5-15	500-1000	85	70-80,80-90	ms	[53]
Nickel Cadmium (Ni-Cd)	0.2-0.3, 0.2-0.6	10-20	2000-2500,2000-3000	85	60-70, 60-83	ms	[52][51]
Nickel Metal hydride (Ni-MH)	1-2	15-20	1500-3000	70-75	50-80	ms	[51]
Lithium-Ion (Li-Ion)	0.1-0.3	8-15	1000-10000	85	90-98	ms	[47][48][49]
Sodium-sulfur (NaS)	15-20 zero	10-15	2000-4500	85	75-90	9h	[54][55]
Vanadium redox (VBR)	Small, very low	10-20	>12000, >16000	75-82	75-85	¼ cycles	[47][48][49]
Electro Chemical Double Layer Capacitor (EDLC)	10-20	10-30	100.000+	95	90-97	ms	[47][48][49]
Hydrogen Fuel Cell (FC)	Almost zero	5-15	1000+	59	20-50	Sec	[49]
Zinc-Bromine (Zn-Br)	0-1	5-10	>2000	70-75		<1ms	[47][48][49]
Flywheel Energy Storage (FESS)	1.3-100	15-20	20.000+	90-93	90, 95	Sec-min	[49][56]

The discharge of ESS depends on the system response and demand. Therefore, the delivery rate determines the time needed to extract the stored energy and to deliver to the load as required [14]. The discharge time of ESS is the maximum-power discharge duration, $\tau(S) = \frac{Wst}{Pmax}$. It depends on the depth of discharge and operational conditions of a system, constant power or not. The self-discharge characteristic is the total lost energy that was initially stored and dissipated over a period of time when an ESS is idling not operational. Lifespan represent the number of time that the ESS could deliver the energy level it was built for after each recharge. The lifespan relies on the material that forms the ESS, and all ESS are prone to wear and tear by use; this is typically the main reason of aging, due to temperature degradation [14][40]. Efficiency is the ratio between delivered and stored energy, $\eta = \frac{\mathrm{Wut}}{\mathrm{Wst}}$. Therefore, in order for the storage device to be genuinely attractive, it must have excellent overall efficiency, which implies that the ESS possesses minimal losses in terms of power storage and self-discharge.

Table 2.3: Other technical and economical characteristics of Energy Storage Systems

Technology	Suitable storage duration	Discharge time at a power rating	Power capital cost ($/KW)	Energy capital cost ($/KWh)	Operating and maintenance cost	Maturity	References
Lead Acid (Pb-Acid)	Minutes-days	Seconds-hours	175-600, 300-600	150-400, 200-400	50$/KWh/Year	Mature	[47][48][49][57]
Nickel Cadmium (Ni-Cd)	Minutes-days	Seconds-hours	500-1500,	600-2400,800-1500	20$/KWh/Year	Commercialized	[47][48][49][50][57]
Nickel Metal hydride (Ni-MH)	-	Hours	120% of NiCd	120% of NiCd	-	Mature	[47] [51][48][49][57]
Lithium-Ion (Li-Ion)	Minutes-days	Minutes-hours	1200-4000	400-2500	-	Demonstration	[47][48][49]
Sodium-sulfur (NaS)	Long-term	Seconds-hours	1000-3000,3200-4000	300-500	80$/KWh/Year	Commercialized	[47][48][49][57]
Vanadium redox (VBR)	Hours-months	Seconds-24h+	1400-3700	500-800	70$/KWh/Year	Developing	[47][48][49]
Electro-Chemical Double Layer Capacitor (EDLC)	Seconds-hours	Milliseconds-1h	100-300	300-2000	0.005$/KWh/Year	Developing	[47][48][49][57]
Hydrogen Fuel Cell (FC)	Hours-months	1-24h+	500-1500, 400-2000	1-15	0.0019-0.0153$KW/h	Developing	[47][48][49]

Zinc-Bromine (Zn-Br)		s-10h			Medium		[47][48][49]
Flywheel Energy Storage (FESS)	Seconds-minutes	15s-15min	250-350, 100-300	1000-5000	0.004$/KWh/Year	Commercialized	[47][48][49][52][57]

The objective of the study is to integrate the railway electricity grid with a near-load energy storage network. Energy storage system rate of discharge should be quick, under 10 minutes based on braking times of the locomotive. Figure 2.3 shows the energy and the power densities of various technologies with red solid lines reflect a time-by-definition relationship between energy and power. This Figure provides a perfect view of the greatest technology with quick discharge times between 1 to 10 minutes and puts flywheel on top position.

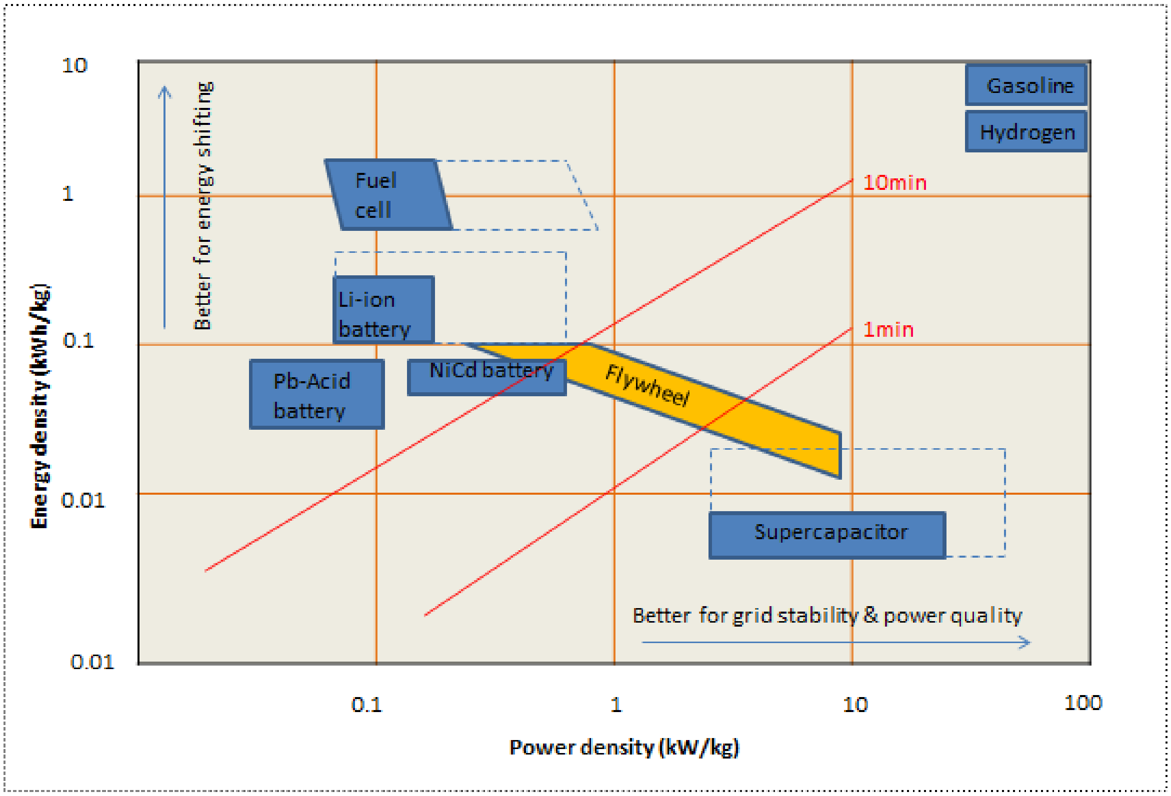


Figure 2.3: Energy and power density of different technologies [58]**.**

For many applications, the size of ESS is a key feature for ER's and EV's [14]. The size determines high energy density in small mass as well as the volume of the device.

Figure 2.4, displays a summary of power density and energy density of various ESS. For a given amount of energy, the greater the power and energy densities are, the lesser the volume of the desired energy storage system will be [14][25]. Extremely compact energy storage is ideal for space-limited application and thus can be observed mostly in the top-right corner and high volume storage systems in the lower-left corner. It has been shown that most batteries, flywheels and fuel cells possess fairly low energy and power densities. A super-capacitor and capacitor have quite high densities of power and low densities of energy. The flow battery densities are typically smaller than those of traditional batteries. The Li-ion batteries has both high energy capacity and high power efficiency, resulting in wide spread in handheld devices and exciting transportation industry and other small-scale ESS applications with potential. Specific energy and specific power are crucial parameters per unit weight reflecting total energy and power. The ESS cost is closely related with the size, the total costs over the whole lifetime of the facility, including the storage unit in terms of sustainable profitability [40].

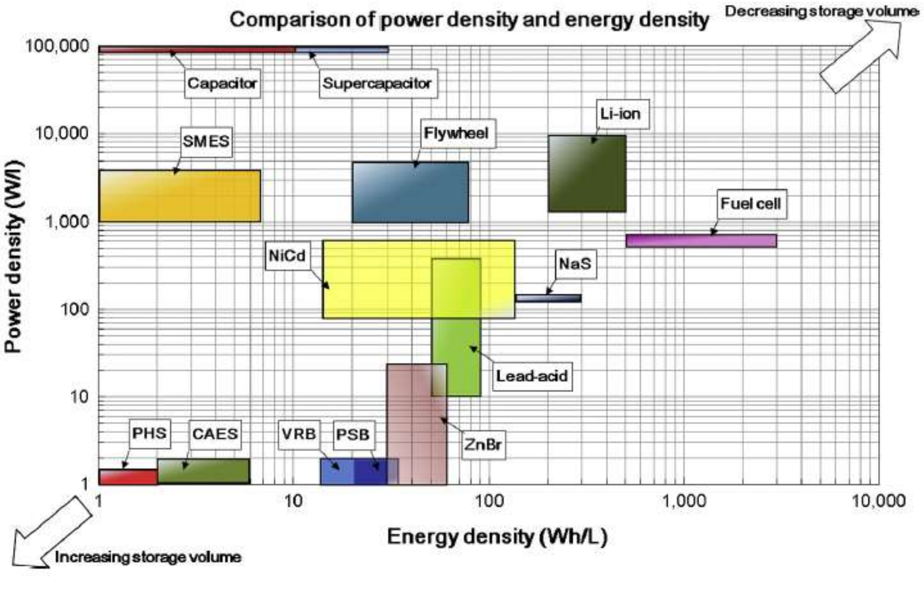


Figure 2.4: Comparison of specific energy and power densities [25]**.**

Figure 2.5, compares the energy-specific and the power specific of energy storage technologies. The lighter the weight of ESS would be to get a specific amount of energy, the higher the actual power and the actual energy are. At the top right corner of the figure, you will find ideal ESS devices appropriate for light weight functionalities. It can be observed that capacitors and EDLC's have high specific power and low specific energy, due to their quick response time, refer to Table 2.2, they are more effective electrical (current) delivery applications in power quality. With low specific strength, the fuel cells and TES have a high specific energy. In terms of basic power and basic energy, flywheel, flow batteries and most traditional batteries are located at the middle stage, which can serve for different ESS domain. Li-ion batteries are excellent, due to both high potential energy and potential strength, which provides a fair justification for a current wide range of Li-ion battery production and application.

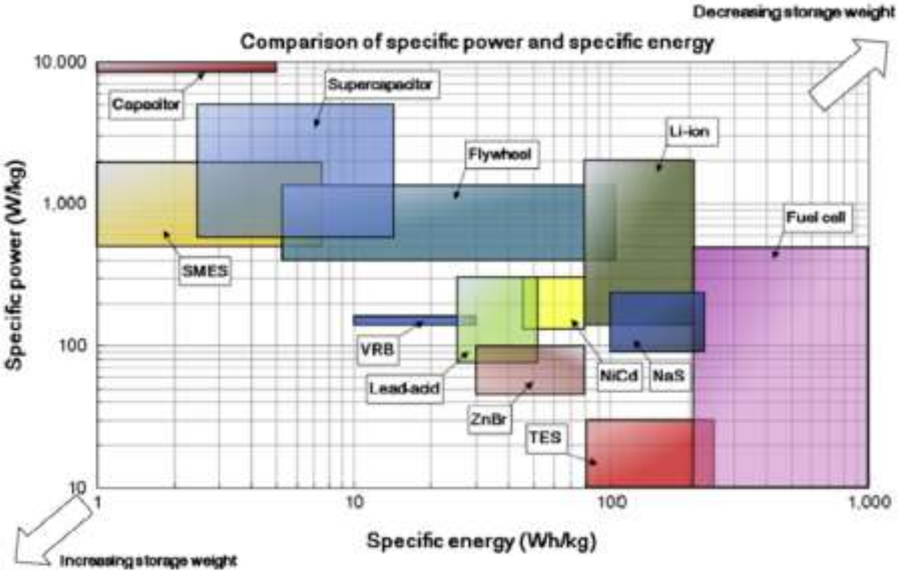


Figure 2.5: Comparison of specific energy and specific power [25]**.**

Figure 2.6 shows a comparison of the power and energy-specific of energy storage technologies. The nominal time of discharge at rated power is also shown within the range from seconds to months. This illustrates the features of energy storage systems. A figure demonstrates a general area of operation on current ESS and also provides guidelines for possible future implementations. From Table 2.3 and Figure 2.6 energy storage systems are listed by average discharge time at rated power: (a). discharge time less than 1 hour: Flywheel, Super-capacitors and SMES; (b). discharge time up to about 10 hours: CAES, Lead-acid, Li-ion, NiCd, ZnBr and PSB; (c) discharge time longer than 10 hours are not considered on this study. Cycle efficiency, also called round-trip efficiency is the ratio of electricity output of the whole device to the electricity input.

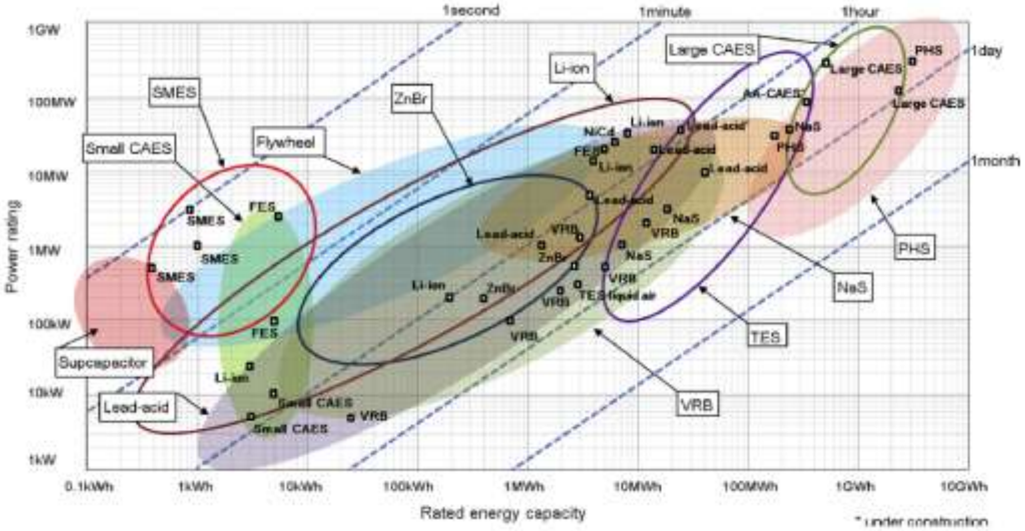


Figure 2.6: Comparison of specific energy and specific power [25]**.**

2.3 Application of Energy Storage System

Application-wise, ESS used in the transport sector can be classified into two groups; on-board energy storage system (OESS) and stationary energy storage system (SESS). SESS also known as a sideway ESS is typically installed in established substations or on the side of the track where a feeding line has substantial voltage fluctuation. The on-board are installed inside the vehicles. OESS is primarily used to store regenerated energy of a single vehicle, power and storage efficiency needed is less than SESS. However, they should be in a position to fulfil the peak energy regenerated during braking and energy requirements. Although FESS is on-board a vehicle, the limitations on its size and weight are more stringent. OESS can be used for three purposes: reduction of energy consumption, peak power reduction and catenary free operation [11]. Both techniques have been widely used, depending on different characteristics and requirements.

2.4 Integration of Flywheel Energy Storage System

FESS is interfaced with power electronics and vehicle software for easy communication. The software distributes train power demand by taking into consideration three sources and sinks: the power grid, brake resistors and energy storage system. Power grid serves as a grid or a sink. Brake resistors only function as sink, which converts surplus energy into heat. FESS act as a source if discharged, or as a sink if charged. FESS operates in two distinct modes. Normally, FESS works in a charging mode while the regenerative braking energy (RBE) is consumed. Once the terminal voltage of the FESS increases above a certain amount, the FESS ceases charging and saves the energy extracted for later usage. FESS works in a discharge mode as it transfers accumulated energy to the traction vehicle before the voltage level decreases below a certain value. When a train power is positive, the discharge mode is activated “Consumption Dominant”. Figure 2.7 (a) shows FESS supplying power to a train (1). When the power of the train reaches the energy capacity of the FESS or the level of charge becomes too small, the electricity from the power grid is drawn with the secondary priority (2) to compensate the additional energy requirements. When a train power is a negative Figure 2.7 (b), the train serves as a source; the charge mode is activated and charges FESS (1) “Regeneration Dominant”. If the power of the train exceeds the charging power, or the FESS is fully charged, the train supplies power to the grid (2). As the power supply of the grid is limited to one constant value, the power of a train may exceed the power limit of the FESS and the grid. In this case, the power remaining is converted to heat by the use of braking resistors (3).

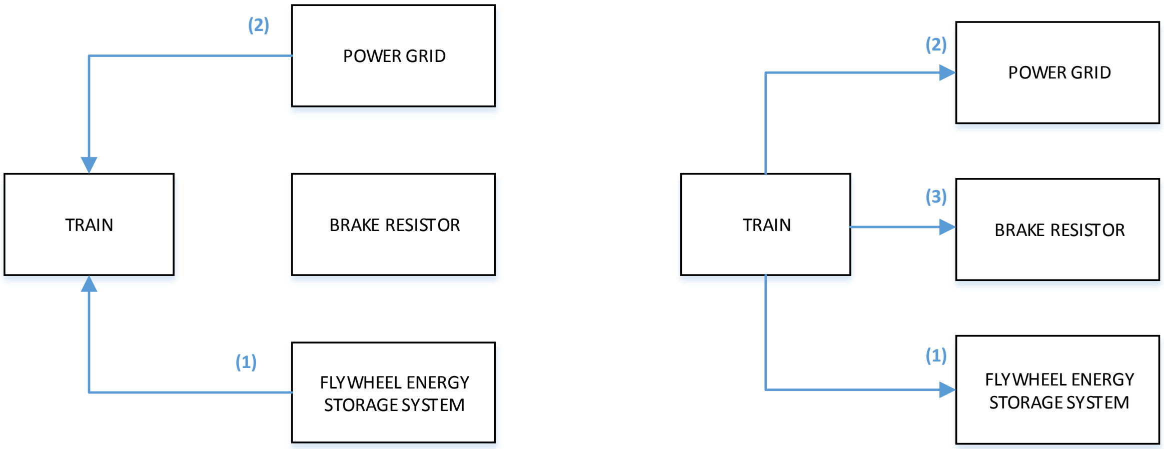


Figure 2.7: Illustrate the power flow between the two operating modes a and b respectively.

(a) Consumption Dominant (b) Regeneration Dominant

2.5 Discussion

This section provides a detailed analysis on three main types of storage systems i.e. batteries, super-capacitors, and flywheels which are used as OESS. These technologies are categorized according to their storage capability, respectively. From the summary, we infer that several countries embrace ESS as a viable solution for the harvesting of regenerated energy. But their facilities are primarily based in Europe and North America, as pioneers of International Energy Agency (IEA) storage program. Hence they have advanced storage system research and development. China and Japan in Eastern Asia are also making strides, while African countries are behind with the introduction of regenerated ESS; however progress is made with research and development. Based on the literature reviews conducted, it is obvious that the use of energy storage for the harvesting of regenerative energy is more prevalent in light weight trains or tramps versus the heavy haul trains. State-owned corporations in South Africa, like Transnet and Passenger Rail Agency of South Africa, are however in a stronger position to make use of strategic alliances to push for these new technologies. We also observed an increasing number of EV's using the different techniques to optimize ESS. Currently, the electric vehicle market, such as BYD, VW, Renault-Nissan, Telsa model 3, Mitsubishi, Toyota, Audi, Porsche, Ford, Fiat, Hondai, and so on, continues to perform well, with pure-electric car registration topping 2,500 marks for February 2020 and selling more than 2,000 PHEV’s. According to the latest figures from the Society of Motor Manufacturers and Traders (SMMT), growth for pure EV’s is an incredible 243 % compared to the previous year, and PHEV’s saw a healthy rise of plus 50 per cent compared to February 2019. It is expected that the trend will continue to grow to improve reliability while reducing net costs.

2.6 Conclusions

An energy storage system is key for energy efficiency improvements, particularly in EV’s and railway transportation. The energy-savings policies could also improve economic growth and reduce dependence on public grids. Rail transport is known as the high energy consumers. Ideally, the transport system should be run with minimum energy consumption. Indeed, ESS will improve railway operating efficiency, but advance studies are still needed on weight and sizes reduction to get more compact and lighter ESS while improving performance features on these technologies. In future, designing new technologies to achieve high-performance storage equipment, high energy efficiency, good charge/discharge rate and low size at reasonable prices is inevitable.

Chapter 3 : Modelling and Theoretical Background

3.0 Modelling and Theoretical Background

Railway Power Networks (RPN) in South Africa are electrified using three methods 3 kV DC, 25 kV AC and 50 kV AC. Approximately 5700 km of power supply infrastructure uses 3 kV DC. In comparison, roughly 2500 km of feeding sections use 25 kV AC, 50 Hz and 861 km of feeding section use 50 kV AC, 50 Hz, which is very uncommon in the world. The South African map of the three core networks are shown in Figure 3.1 and only Iron Ore line uses the 50 kV AC network from Sishen to Saldana. The 3 kV DC power supply system is primarily used by Passenger Rail Agency of South Africa (PRASA) in the suburbs of big cities. Coal Line use 25 kV AC electrification and the long distances between the cities. Rail Operators have different types of rolling stock being utilised including non-electrified diesel-electric locomotives, and multiple electrical units (EMU). The dc traction motors are primarily used in old locomotives and passenger coaches, however, the AC induction motors which is the world standard today is used on the latest locomotives e.g. Toshiba class 15E and 19E, CRRC 20E, 21E, 22E, 45D, Bombardier 23E and GE Class 43D and 44D locomotives. Table 3.1 outlines three types of electrification systems. The 3 kV DC electrification system is used by various countries around the world and has merits such as low power losses on a long distance between substations. The 25 kV AC is also a common electrification system used by many countries around the world. The freight trains for the Black Mesa-Lake Powell Railroads in the United States use 50 kV electrification system to carry the coal for the Navajo steam plant [59][60]. This supply system has the merits of being able to move heavy loads with large axle loads using low load currents.

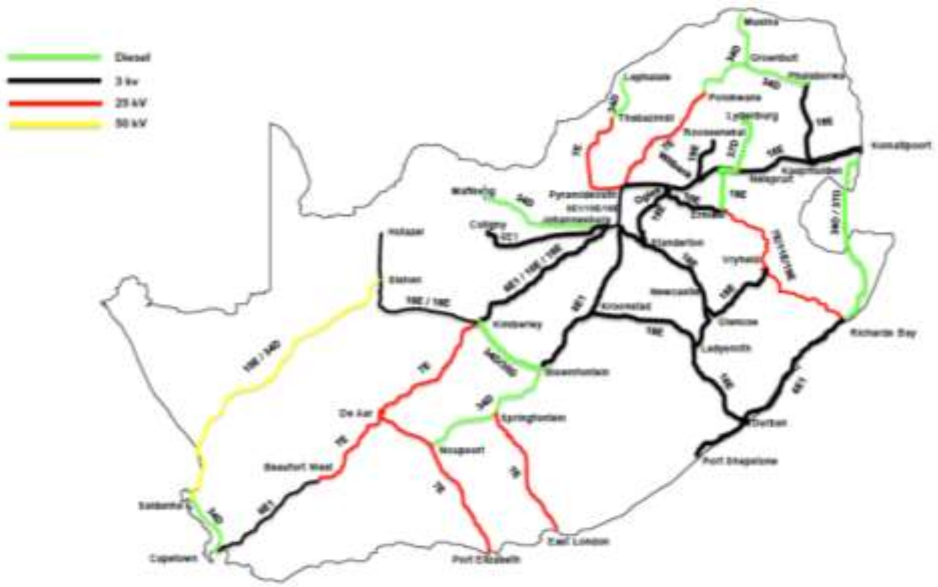


Figure 3.1: South African Electrification Network System [61].

Table 3.1: Overview of Various Feeding Systems [61].

Item	**DC Substation**	**AC Substation**	**AC Substation**
Supply System	3 kV DC	25 kV AC	50 kV AC
No-load Voltage	3.3 kV DC	27.5 kV AC	55 kV AC
Receiving Voltage	88-132 kV	88-132 kV	275-440 kV
Continuous output current	1500 A	800 A	800 A
Supply System Transformer	4.95 kVA	20 MVA	40 MVA
Rectifier	4.5 MW	None	None
Distance between substations	8-21 km	20-30 km	140 km

3.1 Locomotive under Study

In this study, the dual-voltage class 19E locomotive with the ability to operate on both catenary lines of 3 kV DC and 25 kV AC 50 Hz is used for investigations. In the overhead lines feeding the train, an electrical circuit is automatically activated as either AC or DC mode. The train is fitted with on-board voltage sensors to simplify the automatic and trouble-free transition on the track while the overheard cable is equipped with two wooden insulators and neutral wire 3 m long to separate the AC and DC feed. The neutral section is attached to the rails which are used on electrified lines as the return conductor. During the changeover process, the train automatically switched off before it enters the isolators and unpowered overhead cable section. It automatically picks up under the unpowered cable after exiting. The pair of track magnets one on each side of the neutral overhead cable and spaced 45 meters apart to achieve this. The two magnets are mounted in relation to each other with their polarities reversed to activate magnetic relay located below the train to switch off and restart. Class 19E is a heavy haul electric locomotive which was put in operation in 2009 for 450 km from Ermelo Coalfields to Richards Bay Coal Terminal (RBCT). This locomotive is a BoBo with four AC induction traction motors and a tractive effort (TE) of 392 KN at the start and continuous 311 KN at 34 km/h and an axle load of 26000 kg. The locomotive is equipped with electro-pneumatic, electrical and rheostat braking systems. The total weight of the locomotive is 104000 kg, six locomotives are coupled together in consists to pull 200 Jumbo wagons [62]. The class 19E locomotive is shown in Figure 3.2 operate on the Coal Line Network and used in this study.

Figure 3.2: Class 19E dual locomotive of Transnet, (OEM) – Toshiba [62]**.**

Table 3.2: Technical Specification of class 19E locomotive (courtesy of Transnet Engineering).

Technical details	Parameters
Service speed	120 km/h
Power output	2940 kW
Tractive Effort	Maximum 392 kN
	Continuous 311 kN
Track Gauge	1067 mm
Bogies fully equipped	18400 kg
Length	18300 mm
Width	2890 mm
Weight	104000 kg
Height	Over the pantograph – 4120 mm
	Over the roof – 3887 mm
Brake Force	251 KN
Electric Braking System	Blended Regeneration/Rheostat – 3490 kW

Table 3.3 presents the efficiencies of various components of the locomotive. These efficiencies will be used to evaluate the locomotive power flow.

Table 3.3: Efficiencies of the locomotive

Components Description	**Efficiencies**
Main transformer	0.97
Converter	0.98
Traction inverter	0.985
Traction motor	0.93
Gear	0.98
Auxiliary inverter	0.95 (Power factor 0.85)

The train network is 1700 m above sea level from Ermelo to Vryheid and 1200 m from Vryheid to Richards Bay. The route from Ermelo to Richards's Bay is about 450 km. It comprises of a single and double network lines of which one is primarily for down direction and the secondary is for uphill. The difference between the gradients of the two lines permits the loaded trains only to run on the “down” line, Figure 3.3 and 3.4. There is quite number of diesel and electric locomotives running on this network.

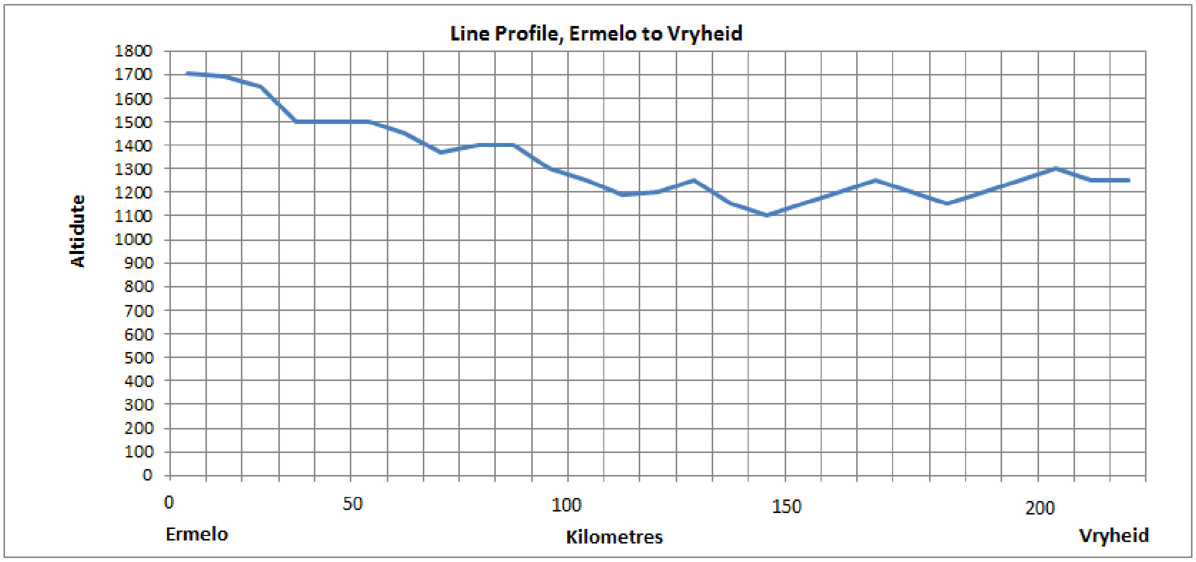


Figure 3.3: Line Profile Ermelo Coalfields to Vryheid (courtesy of Transnet Freight Rail).

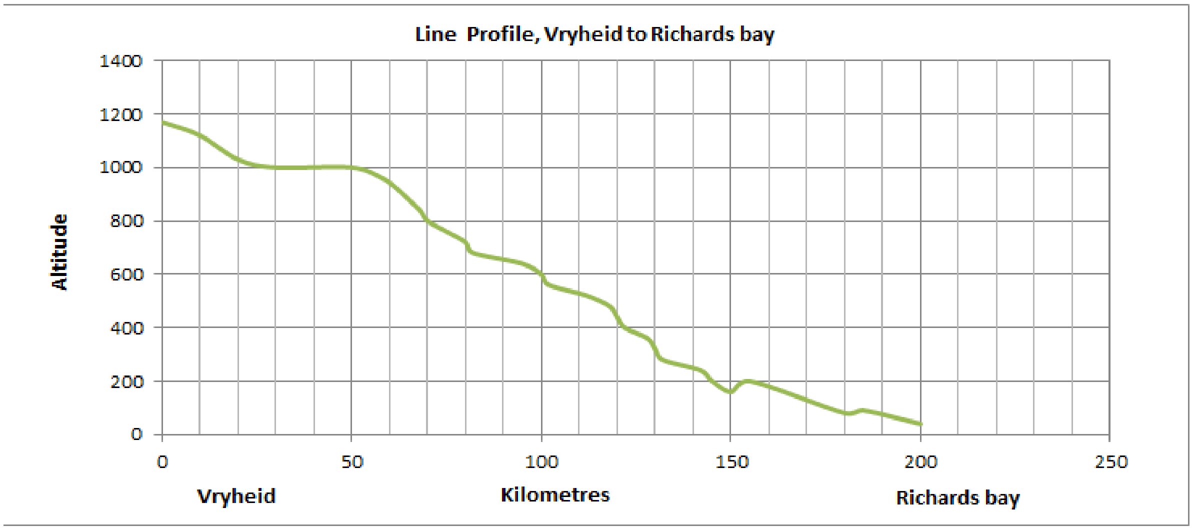


Figure 3.4: Line Profile Vryheid to Richards Bay (courtesy of Transnet Freight Rail).

Transnet Freight Rail’s (TFR) core market consists of freight logistic solutions planned for sectors such as mining, heavy and light manufacturing industries. Minerals, grain and fuel are transported on the Mpumalanga to the Richards Bay Line. In this line, coal is a crucial export product, producing billions of rands in income generation for South Africa and gaining the nickname “Black Gold”. Figure 3.5 shows a map indicating a route in South Africa for coal exports from Ermelo to Richards Bay coal terminal.

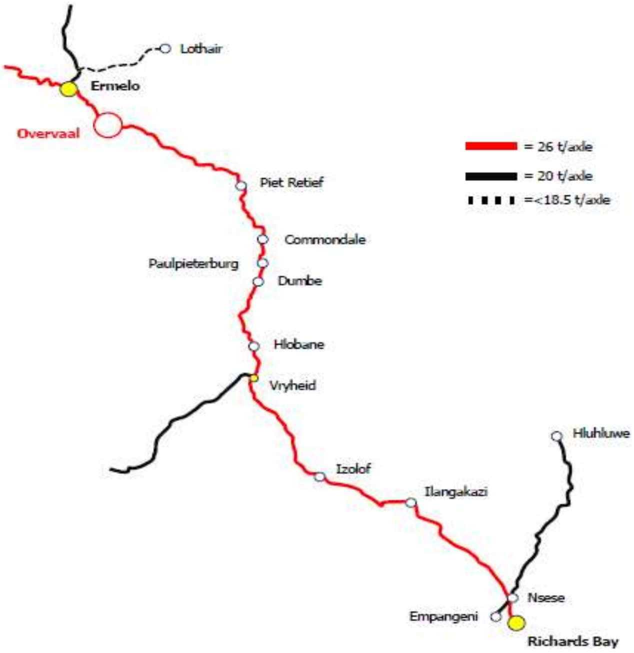


Figure 3.5: Map indicating the route from Ermelo Coalfields to RCB [63]**.**

A locomotive TE is a force that is produced by the locomotive to transport the load. The tractive effort of a locomotive should be sufficient to move a train at the maximum permissible speed. In general, the tractive effort is equal or slightly greater than the locomotives hauling power [64][65]. The wheels of the locomotive will slip if the tractive effort is greater than what is needed to haul the train. A tractive effort and braking curve of class 19E is shown in Figure 3.6 and 3.7.

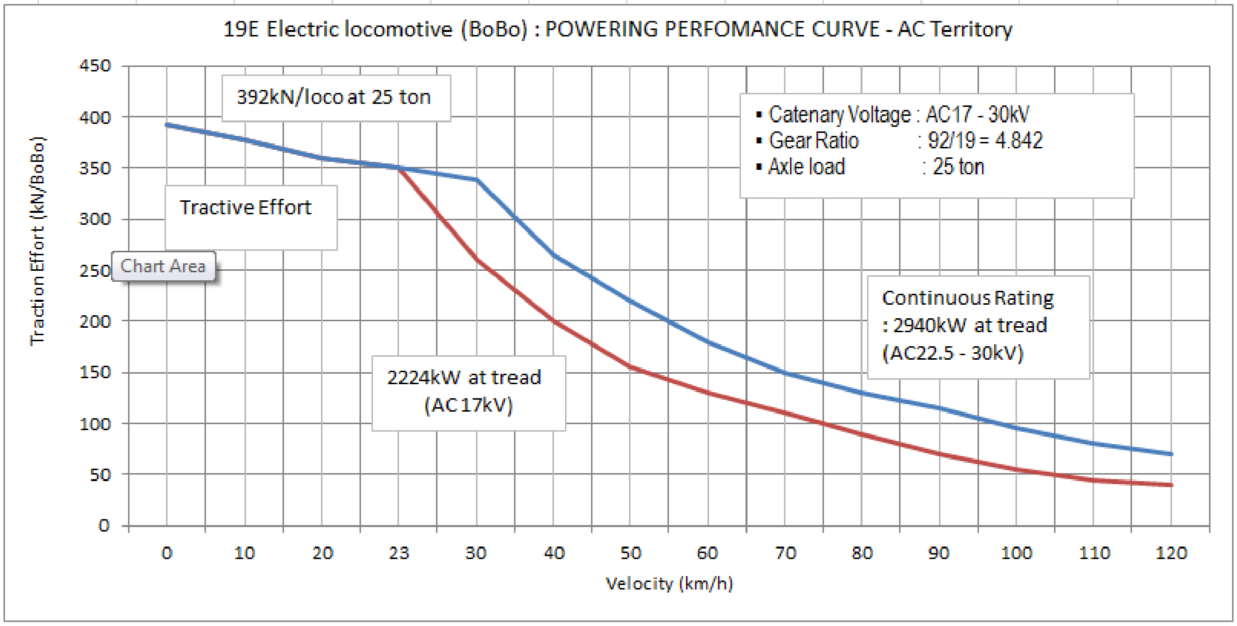


Figure 3.6: Locomotive powering performance curve [66]**.**

The locomotive braking characteristics must comply with the specifications set out in Figure 3.7.

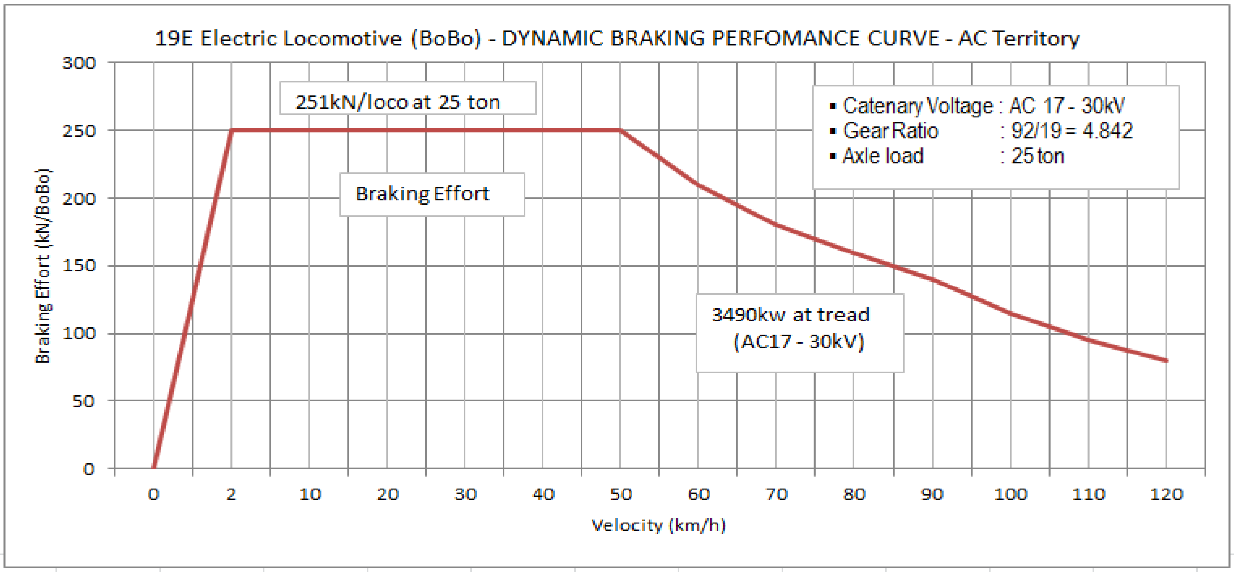


Figure 3.7: Locomotive Regenerative braking Characteristic Curve [66]**.**

3.2 Transmission Line Model

There are three methods of modelling the transmission lines in general practice. A model consists of a short, medium and long line. The short lines are less than 80 km long, medium lines are estimated to be approximately 240 km long. Anything longer than 250 km is known as a long transmission line [67] [68]. The length of the power line must be taken into consideration when choosing the model, but in this case, the distance from the power supply to the load shall not exceed 80 km [68] [67]. Figure 3.8 shows the equivalent circuit of the short transmission line.

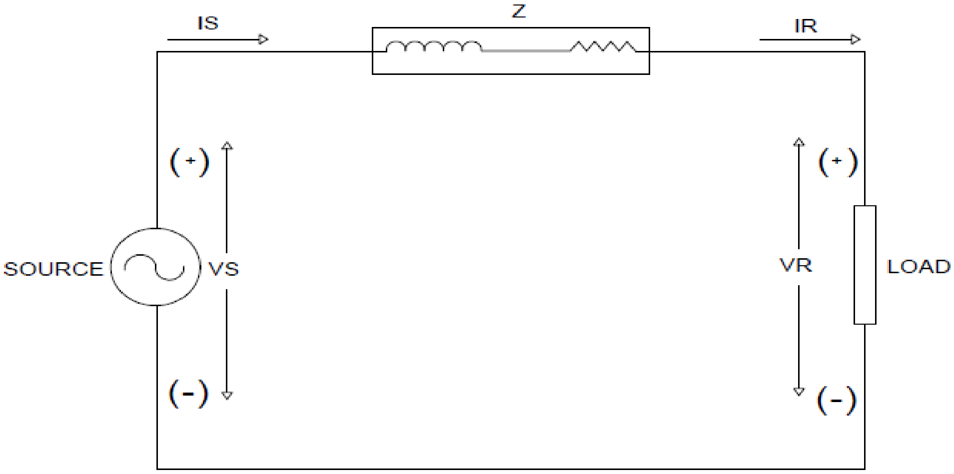


Figure 3.8: Short transmission line model [68]**,** [67]**.**

3.2.1 Power Flows in the train line

In general, for train systems, there are three types of busses and are presented in Table 3.4.

Table 3.4: Bus type in calculation of power-flow

Bus type	Voltage (V)	Voltage angle θ	Active power	Reactive power
Slack bus	known	known	to be calculated	to be calculated
PV bus	known	to be calculated	known	to be calculated
PQ bus	to be calculated	to be calculated	known	known

PV bus is normally a generator and PQ bus is normally a load. For this study, the train is treated as a PQ bus when the catenary voltage is within limits conforming to European standard EN 50163:2004. If the voltage values in Table 3.5 of the line are under the set acceptable limits then the train is regarded as PV bus. Substations are regarded as slack bus with a voltage source of 25 kV at a phase angle of 0 degrees. A schematic line model diagram with line impedances is shown in Figure 3.9. It is worth noting that, the double line between Ermelo and Richards Bay consists of two separate single lines. These tracks are bi-directional signalised enabling trains to travel in both paths on a single track.

Table 3.5: Nominal Voltage and their Permissible Limits in Traction System [69], [70]**.**

Electrification system	**Nominal voltage and their permissible limits**				
	Lowest non-permanent voltage Umin2 (V)	Lowest permanent voltage Umin1 (V)	Nominal Voltage Un (V)	Highest permanent voltage Umax1 (V)	Highest Non-permanent voltage Umax2 (V)
AC(r.m.s value)	17500	19000	25000	27500	29000

The value of the knee point factor is shown in Table 3.6

Table 3.6: Value of factor a [71]

Power supply system	**Value of *a***
AC 25kV 50 Hz	0.9
AC 15kV 16,7 Hz	0.95
DC 3000 V	0.9
DC 1500 V	0.9
DC 750 V	0.8

In any case, the current values must not exceed 800 A. The value of the knee point factor a = 0.9, Umax2 = 29 KV, Un = 25 KV and Umin2 = 17.5 KV.

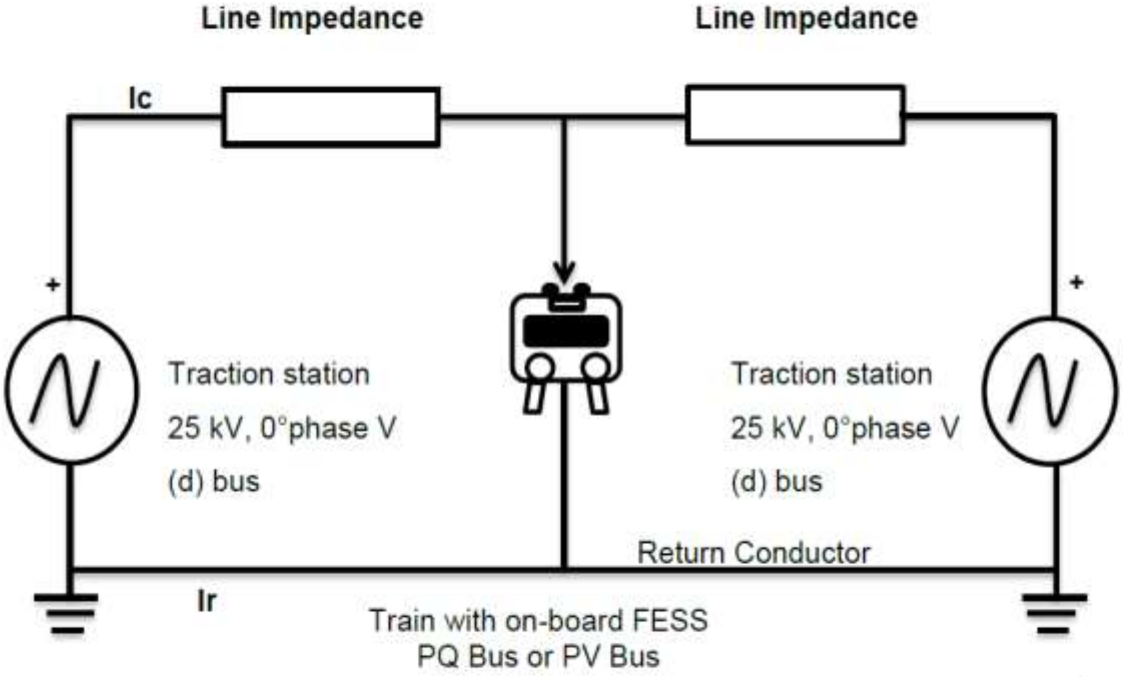


Figure 3.9: AC single line model diagram with line impedances [72]**.**

The train simulation model was designed as a rail return circuit. Any power system transmission line would have resistive, inductive and capacitive components. The voltage magnitude and phase angle will result from these attributes. Typically, the impedance of the line is defined per kilometre, so a model, can be used in such a way that the impedance is a function of the distance (d) from the substation. Most recent locomotives are equipped with innovative on-board control electronics and have an estimated unit power factor.

3.2.2 Single-train Model Calculation (PQ)

[Iteration 1]

If Cos θ = 1, VLoco = 25 kV and PLoco = 3.68 MW. The locomotive current can be computed as:

$$\mathrm{ILoco} = \frac{\mathrm{PLoco}}{\mathrm{VCos\theta}} \qquad 3.1$$

$$Z = \frac{\text{VLoco}}{\text{ILoco}} \tag{3.2}$$

$P = [I^2] R$ and $(Q = 0)$

$SL = [JXI] I$ and $(PL = 0)$

[Iteration 2]

According to Transnet Freight Rail (TFR), infrastructure electrical specification a loop impedance and line reactance for the heavy haul freight is 0.18 - 0.27 Ω/km and resistance of 0.05 - 0.1 Ω / km.

Note: If Cos θ = 1 and PLoco = 3.68 MW.

$$\text{SLoco} = \frac{\text{PLoco}}{\text{PF}} \tag{3.3}$$

$$\text{QLoco} = \text{PLoco Sin } \theta \tag{3.4}$$

3.2.3 Line Electrification System

The Coal Line electrification system uses 25 kV AC, 50 Hz. It has an overall length of 450 km and a distance of approximately 20 – 30 km between substations. The train has a length of 2.496 km and runs at a top speed of 80 km/h with an average speed of 60 km/h. Each day, 16 trains travel one direction, and the entire journey takes 10 hrs. In this scenario, the train cycle is 90 minutes. Due to the train taking 20 min to reach the substation each substation operates for 20 min and stops for 70 min. When the transport capacity is twice the current level the rail operator expects a 1.5 time increase, so the substation will have a period of 45 minutes, run for 20 min and stop for 25 min. Although the Coal line is a double-track line time table of the train is designed to allow only one train to operate at one substation.

3.2.4 Values for U mean useful at the pantograph Table 3.5

The basic requirements for mean useful voltage of the pantograph throughout the normal working conditions shall be as set out in Table 3.7. The minimum value for mean useful pantograph voltage is 22 kV for a line speed of less than or equal to 200 km/h and 22.5 kV for a line speed of greater than 200 km/h calculated in accordance with the method set out in clause 8.2 and 8.4 of EN 50388:2012.

Table 3.7: Minimum U mean useful at pantograph [71]

	Minimum mean useful voltage U mean useful at the pantograph	
Power supply system	**Category I, II, III HS TSI lines**	**Category IV, V, VI, VII CR TSI lines and Classical lines**
	Zone and train	Zone and train
25000 V AC 50 Hz	22 500	22 000
15000 V AC 16.7 Hz	14 200	13 500
3000 V DC	2 800	2 700
1500 V DC	1 300	1 300
750 V DC	N.A.	675

This line is classified as category IV, V, VI, VII CR TSI lines and classical lines, Umean useful is equal to 22000 V. Values below 22000 V shall not be accepted during the calculations [71]. In normal operating conditions the catenary line voltage level is different from the nominal voltage for AC 50 Hz system as set out in EN 50163 [69] and reported in Table 3.7. The catenary voltage usually ranges from Umin1 to Umax1 or can be as low as Umin2 or as high as Umax2 for a short period of time (i.e. 2 to 5 minutes). The voltage is impacted by changes in the voltage supply side of the Traction Substation (TS). This is partly related to the mechanism for voltage regulation and caused by traffic overload [70].

3.3 Locomotive Main Supply

The Railway Power Network (RPN) consists of three main mechanisms. The first is the distribution network, the second is the traction substations that includes converter traction transformer with rectifiers and if necessary, the frequency converters. The last component is the traction distribution system used for the transfer of power to the train. Power is transferred from catenary by means of pantograph or the third line by means of current collector shoes. The class 19E dual locomotives operate on 3 kV DC and 25 kV AC 50 Hz depending upon the overhead main supply. The pantographs connect the supply to the locomotive through pantographs isolators mounted on the roof. This option is triggered by the Train Control and Monitoring System (TCMS) and does not require input from the driver. Pantograph selection is done by means of the pantograph selector switch located on the Low Voltage Cubicles (LVC). A pressure switch measures the air pressure in the main reservoir when the TCMS system is started and provides the TCMS with digital feedback. If there is ample air in the tank when the pantograph control switch is selected the TCMS will direct the compressed air to the pantograph cylinder by means of a valve which in turn lifts the selected pantograph. The auxiliary compressor will automatically start and fill the auxiliary reservoir if there is insufficient air available to lift the pantograph. In the same manner, as the main reservoir, the air is then diverted to the pantograph. The dc input arrestor and the ac input arrestor are mounted on the top of the locomotive to avoid damage to the locomotive circuit caused by high voltage spikes to earth. Based on the main supply the electricity is channelled through the roof insulators and the bursars to the locomotive. Figure 3.10 summarizes the power flow of both the ac and dc main supply networks.

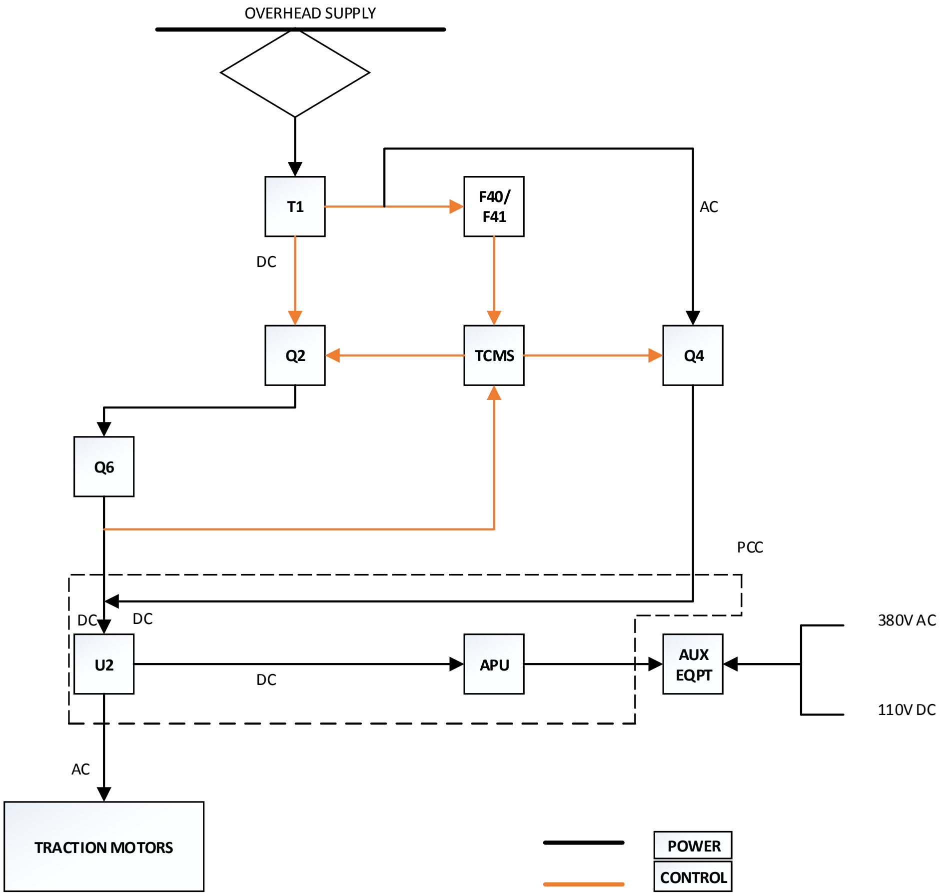


Figure 3.10: Simplified diagram of the main supply system.

3.3.1 AC Circuit Operation

The F40 and F41 relays send a signal to the TCMS when the Potential Transformer (T1) senses that the voltage input is ac. The TCMS then switch over Q2 to ac and the power is routed to the Power Conversion Cubicle (PCC) automatically through the Vacuum Circuit Breaker (VCB) Q4. The traction inverter U2 inverts the dc supply to ac for the traction motors. Voltage and frequency are regulated in accordance with the speed of the train and the necessary power as defined in Figure 3.10. The dc power is then converted and inverted into auxiliary supplies as described in Figure 3.10.

3.3.2 Main Transformer

The main transformer is mounted between the two bogies (base frame of the locomotive), at the centre of the locomotive underframe. The transformer weighs approximately 9800 kg with its associated cooling system and transforms the main 25 kV AC electrical input supply into the various supplies required by the traction motors and the auxiliary equipment. Table 3.8 gives the transformer parameters.

Table 3.8: Main Transformer Design Parameters

Winding	Primary	Secondary
Rating	Continuous	
Power (kVA)	3700	3700
Voltage (V)	25000	2x1792
Current (A)	148	1032

3.3.3 AC Traction Motor

Class 19E locomotives have two bogies (BoBo), each fitted with two pairs of wheels. Each pair of wheels has a traction motor mounted on it that drives a fixed axle via the main gear connected to one of the wheels in the pair. The traction motors continuous voltage rating is 2200 V, 3-phase ac squirrel cage induction motor. The dc supply is inverted to ac while the locomotive works from the dc main input voltage to feed the traction motors through the traction inverter U2 in Figure 3.10. If the voltage to the traction motors increases the output power is increased allowing the traction motors to run and the locomotive to increase the speed. Variation in voltage and frequency is used to adjust the speed of the locomotive up and down. Figure 3.11 presents the diagram of the wheel-set, traction motor, pinion, main gear and the locomotive underframe.

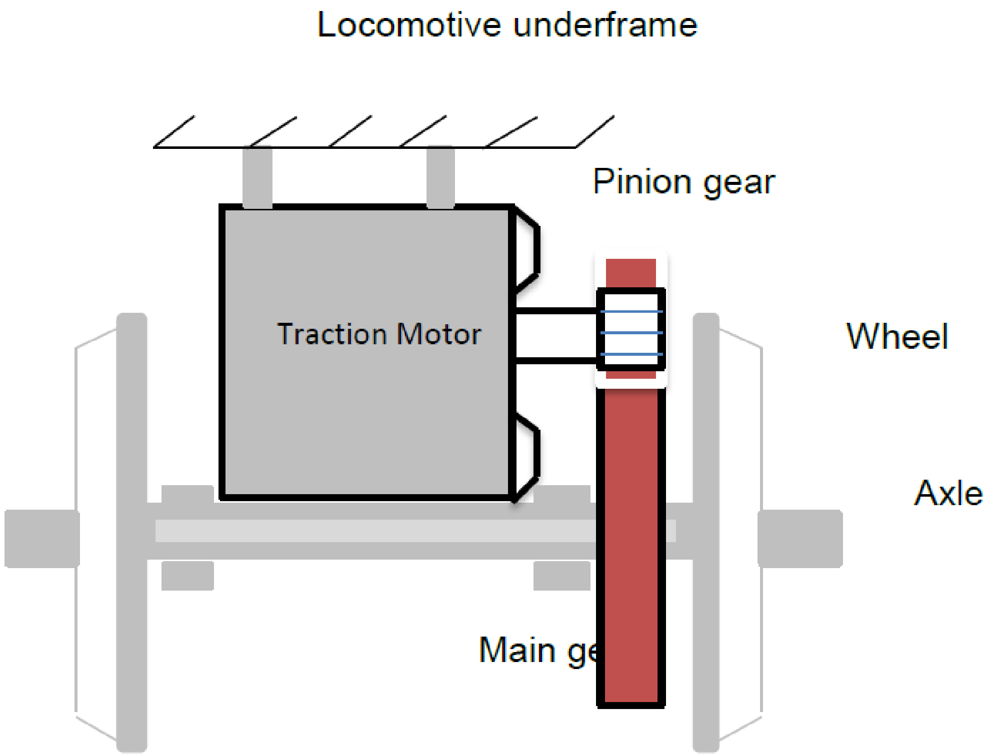


Figure 3.11: Wheel-set Diagram [73]**.**

3.3.4 Traction Control Unit (TCU)

Both the Power Conversion Cubicles (PCC) has a Traction Control Unit (TCU) as a component. The TCU's primary task is to regulate the electrical power supply to the traction motors based upon inputs from the TCMS and to protect the components of the main power circuit from excessive variables such as voltage, currents, and temperatures.

3.3.5 Power Converter Cubicle (PCC) Cooling

In addition to the cooling air supplied by traction motor blowers, each PCC has a waterborne cooling system. A mixture of water flowing within a cooling block cools all components that produce excessive heat in the PCC due to their power conversion function. The hot liquid is then moved to the radiator by means of heat exchanger circulation pump using cooling air extracted from outside the locomotive by means of traction motor blowers.

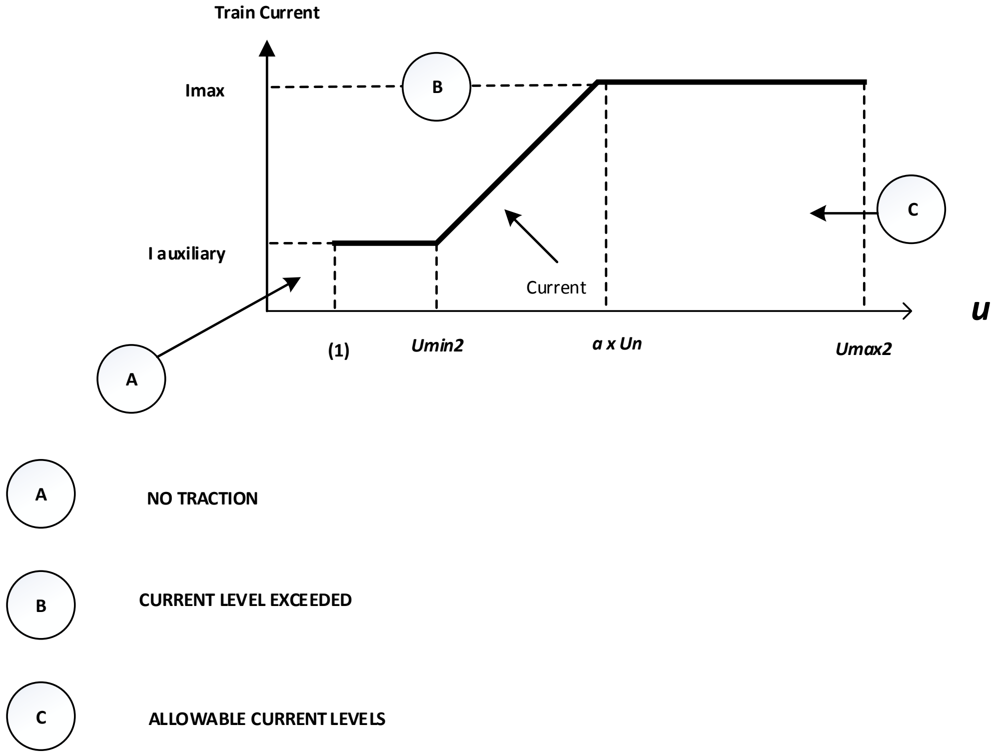
3.3.6 Braking Resistor Cooling

A bank of resistors located in a single cubicle is used in the electric braking function. The Braking Resistor Cubicle (BRC) contains two columns each with its own fan and bank of resistors. Electric braking uses the traction motors to produce braking effort. High temperatures are produced in these processes which are dissipated. In order to cool the resistors, the air is sucked into the resistor cubicle from the outside of the locomotive through the air inlet. A grid blower motor drives an impeller that forces the air through ducting and into the resistor bank. Heated air is automatically ventilated into the atmosphere through the roof of the air outlet.

3.4 Locomotive Current Limitations

In order to allow a stable operation under irregular operating conditions, the train is fitted with an automatic system that regulates the level of maximum power consumption depending on the steady-state contact line voltage [71]. The maximum permissible train current is defined in BS EN 50388: 2012. During regenerative braking system (RBS), the voltage increased to 30 050 V and this value may be surpassed. In tractive mode, the maximum current limit is 800 A at 25 kV AC. The train only accepts higher current values in braking mode. In South Africa, rolling stock follows the International Electro-technical Commission (IEC) initiated by the British Standard (BS) EN 50388:2012. Figure 3.12 shows the maximum permissible current of the train as a function of the contact line voltage [71].

In order to meet the traction requirements, trains usually receive enough energy from the traction power grid. However, whenever the traction network is weak the traction power demand cannot be completely supplied because of the network voltage. On-board devices will change the demand for the train power in order to protect the train traction devices and the power networks. An extensive representation of the train system is necessary to research the train, network and load efficiency. In railway applications for power supply and rolling stock, the British Standard EN 50388:2012 implemented the maximum permissible train current against train voltage, as shown in Figure 3.12. In accordance with the pantograph voltage levels, the train traction phases can be classified into three sections (A, B and C). The train voltage in section A is lower than the lowest non-permanent voltage, Umin2. The train is only supplied with power to operate the auxiliary system, not the train traction system. The train voltage in section B is between Umin2 and axUn, where Un is the system nominal voltage and a is the knee factor between 0.8 and 0.9. Below traction voltage mode is triggered in this area. The traction current of the train is restricted, which implies that the train could not obtain the full traction power. The train voltage in section C is greater than that of Un, where the train is in normal traction phase. The train overall traction power can be entirely supplied by the power network. According to EN 50388:2012, for AC railway systems, the voltage characteristics, including under-voltage levels, are defined in Table 3.5. In this study, the voltage drops on traction mode may be augmented by evacuation power from a flywheel energy storage system.



KEY

U contact line voltage according to EN50163

Imax is the maximum current consumed by the train at nominal voltage

With regard to the setting values of the under-voltage releases , see EN50163:2004, 4.1, Note 2

Figure 3.12: Maximum current of the train against voltage [71]**.**

3.5 Substation Parameters

The infrastructure for the railway supply consists of a substation linked to the national grid that supplies electricity to the catenary line. The railroad tracks serve as a return conductor to the substation. The continuous ratings of various types of traction substations are single units 3.0 MW, 4.5 MW or 5.0 MW and double units 6.0 MW, 9.0 MW and 10.0 MW.

Table 3.9: Traction Substation Design Parameters

Parameter	25 kV AC
Continuous Power Rating	20 MVA
30 minute rating	1 x continuous
2 minute rating	2 x continuous
Continuous output current	800 A @ 25 kV
Nominal Output Voltage	25 000 V
No-load Voltage	27 500 V
Busbar voltage range at substation during load conditions	23000 -27500 kV
Maximum Over-voltage (due to regeneration)	30 050 V
Average substation spacing	15 - 30 km

3.6 Electrical Braking

At 50 km/h or lower the constant brake effort is 251 KN. Over the speed of 50 km/h, a power of 872.5 kW per axle is generated. When 872.5 kW per axle is generated the regenerated power of a locomotive is calculated as: Let Pgen per axle = Paxle

$$\mathrm{Pgen\ (kW)} = \mathrm{Paxle} * 4 \qquad 3.5$$

If the speed of the locomotive is 50 km/h and 100 km/h, the tractive effort Fv (KN) is calculated as:

$$\mathrm{FvKN} = \frac{\mathrm{Paxle} * 4}{\mathrm{v}} * 3.6 \qquad 3.6$$

The locomotive should not generate less than 95 % of the braking effort.

3.6.1 Regenerative Braking System

A locomotive with a dynamic mass of 104 tonnes in 5 km at an altitude of 1000 m above sea level. The assumption would be that the train will retain a same speed (80 km/h) all the way down, and the energy that the locomotive will dissipate is equal to the potential energy.

$$\mathrm{E[MJ]} = \frac{\left[\mathrm{m[kg]} * \mathrm{g}\left[\frac{\mathrm{m}}{\mathrm{s}^2}\right] * \mathrm{h[m]}\right]}{10^6} \tag{3.7}$$

The frictional forces are strongly dependent on the speed:

$$\mathrm{FN[KN]} = 12.07 + 0.07722 * \mathrm{V}\left[\frac{\mathrm{km}}{\mathrm{h}}\right] + 0.003735 * \mathrm{V}\left[\frac{\mathrm{km}}{\mathrm{h}}\right]^2 \tag{3.8}$$

Energy loss is determined by multiplying the force by the distance of the gradient, immediately after frictional losses have been calculated.

$$\mathrm{Elosses[MJ]} = \frac{\left[\mathrm{FN[kN]} \; * \; \mathrm{d[m]}\right]}{10^3} \tag{3.9}$$

The energy that the locomotive will recover while breaking is the energy that the train requires to dissipate. The process requires the removal of the energy losses and multiplies by the efficiency of traction motors and control system to transform mechanical power into electrical power.

$$\mathrm{Ebraking[MJ]} = [[\mathrm{E[MJ]} - \mathrm{Elosses[MJ]}] * \eta] \tag{3.10}$$

The estimated energy that the locomotive is capable of returning to the power system is 752.82 MJ. According to the class 19E locomotive design specification, there would be a restriction of 251 KN as the theoretical maximum electrical braking effort. Other methods for dissipating energy are used if the train needs more effort than the specified design value. In order to ensure that all energy to be wasted is regenerated, the breaking effort shall be less than 251 KN. An effort needed to stop the train within a reasonable braking distance is the braking effort. It does have safety implications. In order to counter the kinetic energy of the moving train, braking effort is needed.

$$\mathrm{Fbraking\ Effort[kN]} = \frac{\mathrm{Ebraking[MJ]}}{\mathrm{d[m]}} * \ 10^3 \qquad 3.11$$

For the slide not to occur, the effective braking effort is limited by adhesive weight. A class 19E locomotive has 104 T, the braking effort shall not exceed 251 KN spread over all axles where appropriate. In order for the energy to be safely transferred back to the overhead line as regenerative energy, the calculated braking effort must be less than 251 KN.

3.7 Energy Storage System Model

Flywheel energy storage system (FESS) is a rotating mass which stores kinetic energy with minimal frictional losses. In order to eliminate drag losses, the flywheel is normally contained in an enclosed vacuum cylinder as a high speed rotating mass. The magnetic levitation devices are used to reduce frictional losses in the bearings. Unlike other storage systems, flywheels are known to offer an efficiency of 90-95% [74][75]. It can easily charge and discharged depending on a design and application and is not impaired by Depth of Discharge (DoD). A power transfer is carried out by a combination of motor/generator that charges and discharges the flywheel. Depending on the manufacture, several types of motors are used in the FESS but due to high efficiency, low rotor losses and power density, permanent magnet synchronous motors (PMSM) are the most common type used [76]. Actually, within a few seconds FESS may go from full discharge to fully charge. The amount of energy that can be stored is proportional to the moment of inertia and the square of its angular velocity [74]. This is shown in 3.12.

$$\mathrm{KE} = \frac{1}{2}\mathrm{I}\omega^2\mathrm{max} \qquad 3.12$$

Where:

E	is the amount of kinetic energy stored
I	is the moment of inertia
ω	is the angular velocity

The moment of inertia I rely more on the design of the rotating mass which is defined by 3.13 [74].

$$\mathrm{I} = \frac{1}{2}\mathrm{mr}^2 \qquad 3.13$$

Where:

m	is the mass of the solid cylinder
r	is the radius

In order to ensure that the speed of the flywheel is not too low or too high, the speed should be regulated between ωmin and ωmax, this also means that the flywheel has the reasonable voltage level with a low fluctuation. This is represented by 3.14

$$\Delta\mathrm{E} = \frac{1}{2}\mathrm{I}(\omega^2\mathrm{min} - \omega^2\mathrm{max}) \qquad 3.14$$

The KEmax specific energy that can be stored as per unit mass in a flywheel is given by 3.15.

$$\mathrm{KEmax} = \mathrm{K}s(\sigma\mathrm{max}/\rho) \qquad 3.15$$

Where:

σmax	is the flywheel maximum material tensile strength
ρ	is the flywheel material density

Ks is the shape factor which depends on the geometry of the rotor

In flywheels 3.6 % of the storage capacity every day is projected to be energy loss and is the maximum tolerable loss due to other forms of energy losses [77].

$$\text{PLosses} = \text{FESS Capacity} * 3.6\ \% \qquad 3.16$$

The flywheel energy storage capacity:

$$\text{Ptotal} = \text{FESS Capacity} - \text{Plosses} \qquad 3.17$$

3.7.1 Sizing the FESS

The overload transformer has a rating of 22 MVA and the continuous power level is 20 MVA.

Table 3.10: Feeder station and transformer rating at traction substations

Continuous	Overload
800 A@25 kV	800 A@27.5 kV
20 MVA	22 MVA

Therefore, the flywheel energy storage must provide 2.5 MVA to supplement 20 MVA during the peak hour. The FESS theoretical continuous service duration is 10 minutes charging and 10 minutes discharging at a 2.5 MW power level, equivalent to 416.667 kWh realizable energy value. The locomotive can act as a power source instead of a power load when enters regenerative braking mode. This can be achieved by actually reversing the locomotive current value (- I_{LOCO}). For temporally storage, FESS will consume energy regenerated by the locomotive and supply it later when the locomotive needs it. In particular, during periods of irregular traffic with trains on closer routes or in special cases, voltages below 19 kV are possible.

[Iteration 3]

Flywheel = 2.5 MW

$$\mathrm{SFESS} = \frac{\mathrm{PFESS}}{\mathrm{Cos\theta}} \tag{3.18}$$

The locomotive regenerated energy is 3.490 MW according to (3.10) is equivalent to 581.667 kWh. In this study, the difference between energy that is regenerated and the energy that can be retained by the flywheel would cater for the losses.

$$\mathrm{PDifference} = \mathrm{PReg} - \mathrm{PFESS} \tag{3.19}$$

Because of limited space on-board the locomotive, choosing heavier FESS that requires lots of space is not recommended. Locomotive size and weight constraints are more stringent.

3.8 Summary

Railway Power Network (RPN) in South Africa is electrified using three methods 3 kV dc, 25 kV ac and 50 kV ac. The 25 kV ac electrification system is used by the Coal Line and the long distances between the cities. The line between Ermelo to Richard bay uses 25 kV ac 50 Hz. This RPN has a total length of 450 km and a distance of approximately 20 – 30 km between traction stations. The continuous ratings of the various types of traction stations are single units 3.0 MW, 4.5 MW, or 5.0 MW. The class 19E train has a length of 2.496 km and runs at a top speed of 80 km/h with an average speed of 60 km/h. In South Africa rolling stock follows the International Electro-Technical Commission (IEC) initiated by the British Standard (BS) EN 50388:2012. This chapter provides some useful calculations on energy consumption, auxiliary energy and regenerative energy on class 19E locomotive. For traction system, this locomotive consumes 3.680 MW and regenerate 3.49 MW power. A short line model was adopted for this study; the train simulation model was designed as a rail return circuit. According to EN 50388:2012 overhead line voltages below 19 kV are possible particularly during periods of abnormal traffic with trains on a closer path. The flywheel could be a remedy and alternative if more energy is needed by the train and cannot be supplied from the power grid since the traction stations are far away. Integrating FESS on-board the locomotive will increase the efficiency of the supply network by balancing the energy savings. A 2.5 MW FESS would result in peak reduction of loads by offering more versatility and complementing the power system at a shorter distance.

Chapter 4 : Results and Discussion

4.0 Results and Discussion

New model locomotives are equipped with Regenerative Braking System (RBS), the power regenerated is given back to the transmission line to be used by various trains. If regenerated power cannot be used by other trains in the same traction sub-station it exceeds energy needed by other trains, the excess energy flows into the public power grid [78] [79]. Nevertheless, energy regenerated into power grids can cause harmonic pollution and drop the quality of power [79] [80]. At the same time, the existing tariff policy do not reimburse electricity fees to the railway operators for regenerated energy, thus, failing to achieve the objective of decreasing the costs of coal transport [79]. The recent technological solution to prevent braking energy feedback to the public grid is an integration of Flywheel Energy Storage System (FESS). The FESS will absorb energy from regenerative braking and discharges to the train when more power is needed. In the event of a sudden change in the gradient, FESS will control the power flow from a closer distance compared to the traction sub-station which will result in an increase in locomotive efficiency and energy savings. A train set was used to evaluate regenerated energy of class 19E electric locomotive on route from Ermelo to Richards bay coal terminal. The details of the train are shown in Figure 4.1.

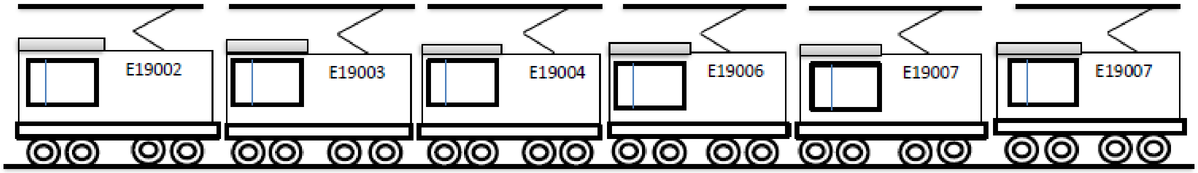


Figure 4.1: Loaded class 19E Locomotive from Ermelo to Richards Bay Coal Terminal

The regenerative braking energy analysis of class 19E heavy-haul locomotives on the route from Ermelo to Richards Bay Coal Terminal will serve as the project profile for this study. The class 19E locomotive uses 3-phase AC Induction Traction Motors (ITM) with an output power of 750 kW. The ITM was developed by Toshiba International Corporation and operated by Insulated-Gate Bipolar Transistor Control (IGBT) on-board the locomotive. This is a dual voltage locomotive running on either 3 kV DC or 25 kV AC 50 HZ with 26-ton axle load.

Table 4.1: Class 19E Locomotive trip information from Ermelo to Richards Bay

Ermelo to Richards bay	
Empty or loaded	Fully Loaded Train
Total load	20800 Tonnes of coal
Locomotives setup	6 Locomotives in consists
Wagons Setup	200 Wagons
Trip distance	450 km
Train Length	2.496

4.1 Train Movement between Substations

In particular for those high resistance lines investment on FESS may be worthwhile when two traction stations are far away from each other, fluctuations in the lines and drop in voltage occur when the train demands more power e.g. train accelerating or driving uphill. One solution is to add FESS on-board the locomotive to allow the train to be supplied from a closer power supply and control the voltage drop. The power losses in the line are proportional to the square of the current, charging the flywheel at a constant current rate and supplying the energy to the train whenever is required instead of running the train from a traction station. Energy savings and improved efficiency are the driving force behind the study. This approach is a solution to enhance the fraction of power lines.

4.2 On-board Event Recorder

The train is equipped with an event recorder. The train event recorder is often referred or known as the On-Train Monitoring Recorder (OTMR), On-Train Data Recorder (OTDR), Event Recording System (ERS), Event Recording Unit (ERU), or Event Recorder (ER). It records data on the operation of train control and outputs in response to the controls and other train control systems. This is identical to the flight data recorder found on the air crafts. In many European Countries locomotives operating faster than 30 mph (48 km/h) are mandated by the Federal Rail Road Administration (FRA) to be fitted with incident recorders, in particular, to aid in the investigation of accidents. Among the items to be recorded, the event recorder records the given set of locomotive characteristic e.g. Throttle position, Air supply, dynamic braking, speed, direction and distance. The class 19E locomotive event recorders are integrated with the Train Control and Monitoring System (TMCS) software. The focus of this study is the potential regenerative energy recovery of class 19E locomotive and a model that could provide a close approximation of actual energy regenerated by the train.

4.2.1 TCMS Software Analysis

The first step is to analyse the recorded data and compare the actual results with the calculated results. The data has been exported from the Train Control and Monitoring System (TCMS) software, the TCMS is a dual redundant system to achieve the highest mission reliability for the Coal link service operation.
The TCMS has the following functions:

1) Locomotive and train control.
2) Monitor operating conditions of the locomotives and their on-board equipment.
3) Data recording and self-test for maintenance.
4) Interface with other systems and peripherals.

The class 19E locomotives are equipped with TCMS technology as shown in Figure 4.2 and 4.3. When the TCMS detects that locomotive is within 500 meters from one of the

GPS coordinates, an automatic transmission of all energy counters and auxiliary data will be transferred into a server. Data recording is stored in a Static RAM (SRAM) mounted on the Central Processing Unit (CPU) board of the TCMS unit. All recording data shall be stored in both TCMS1 and TCMS2 at any time. Some recording data will be sent to the Event Recorder via a serial interface to be stored on the Compact Flash Card. Various tools are available to transmit data from the locomotive to the outside world. It can be usually classified as an on-board download, memory card removal and remote access. On-board a person must go to the locomotive physically or optically attach a note-book computer to the system which then transfers the data to the note book. Normally it is achieved via a serial interface. The key benefit of this approach is that it is an interpretation of real operating data and therefore it takes the operational constraints that were present at the time into consideration. Such restrictions may include traffic or track maintenance delays as well as locomotive driver's behaviour. Analysis of data from TCMS also enables theoretical approach validation. The event data recorders are only available for trips that have already been made; the use of this tool does not necessarily allow predictions as to how trains will run on different routes or even on the same track. Also event recorders do not automatically make it possible to predict how changes in operating conditions, such as different locomotive numbers in consist would affect the energy available for recovery.

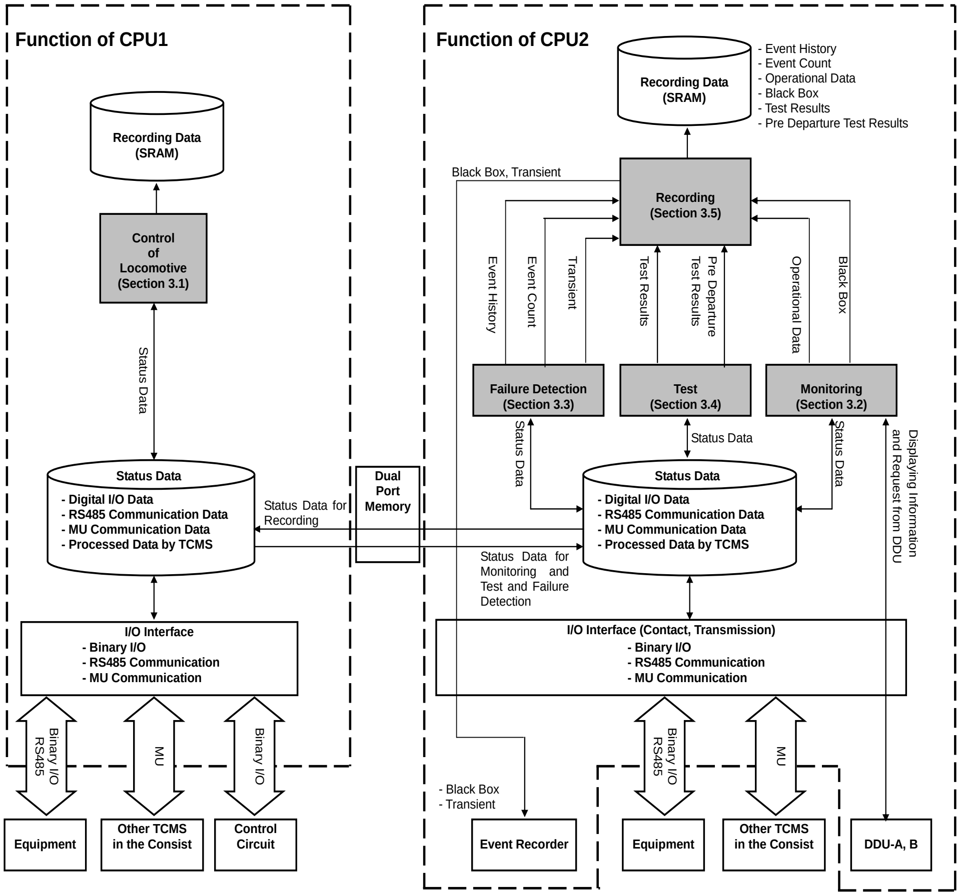


Figure 4.2: TCMS Software Monitoring Function Overview

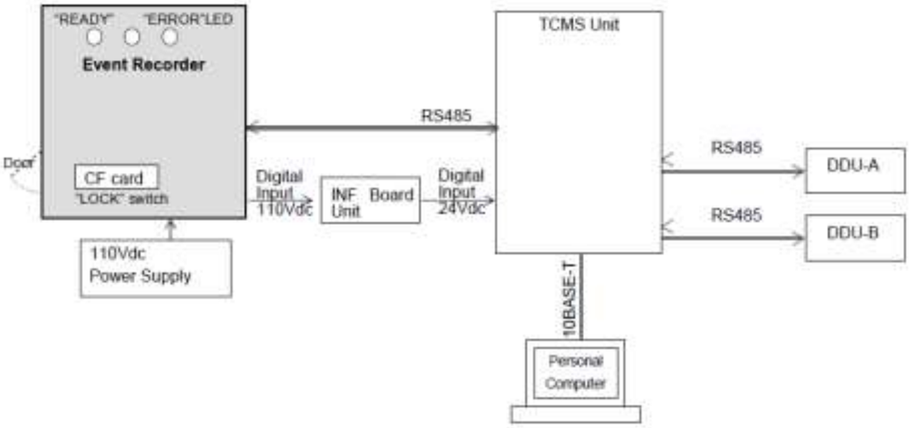


Figure 4.3: Event recorders and TCMS Configuration

The event recorder contains an enormous amount of information related to each locomotive critical parameters in a form of Table similar to Table 4.2. Event recorders are installed in all class 19E locomotives making it possible to select specific locomotive for review.

Table 4.2: TCMS Recorder Data Sample

LOCOMOTIVE_NUMBER	MESSAGE_DATE	AC Consumed kWh	AC Regen kWh	AC Dissipated kWh
19002	18-03-2020 14:09:06	10933712	2835068	1133378
19002	18-03-2020 14:09:07	10933712	2835068	1133378
19002	18-03-2020 14:09:09	10933712	2835068	1133378
19002	18-03-2020 14:09:16	10933712	2835068	1133378
19002	19-03-2020 02:03:58	10933712	2835068	1133378
19002	19-03-2020 02:03:59	10933712	2835068	1133378
19002	19-03-2020 02:04:07	10933712	2835068	1133378
19002	20-03-2020 04:04:07	10933712	2835068	1133378
19002	20-03-2020 09:41:09	10933712	2835068	1133378
19002	21-03-2020 04:04:10	10933712	2835068	1133378
19002	21-03-2020 05:15:09	10933712	2835068	1133378

19002	21-03-2020 08:57:58	10944061	2835489	1133383
19002	21-03-2020 09:00:16	10944061	2835489	1133383
19002	21-03-2020 21:57:05	10944061	2835489	1133383
19002	21-03-2020 21:59:23	10944061	2835489	1133383

It should be noted that only related potential energy recovery data will be analysed to determine the energy consumed and regenerated. The train journey from Ermelo to Richards bay Coal Terminal normally takes approximately 10 hours to rich the ports excluding where there is line maintenance.

Table 4.3: Consumed and regenerated energy

Energy Consumed and Regenerated (kWh)	
Energy consumed	10933 MWh
Energy Regenerated	2835 MWh

Based on the data from TCMS software the locomotive 19002 consumed 10933 MWh and regenerated 2835 MWh refer to Table 4.3. The regenerated energy is 25.9 % of the total power consumption. Figure 4.4 shows energy consumption and regenerated energy of six locomotives in the consist.

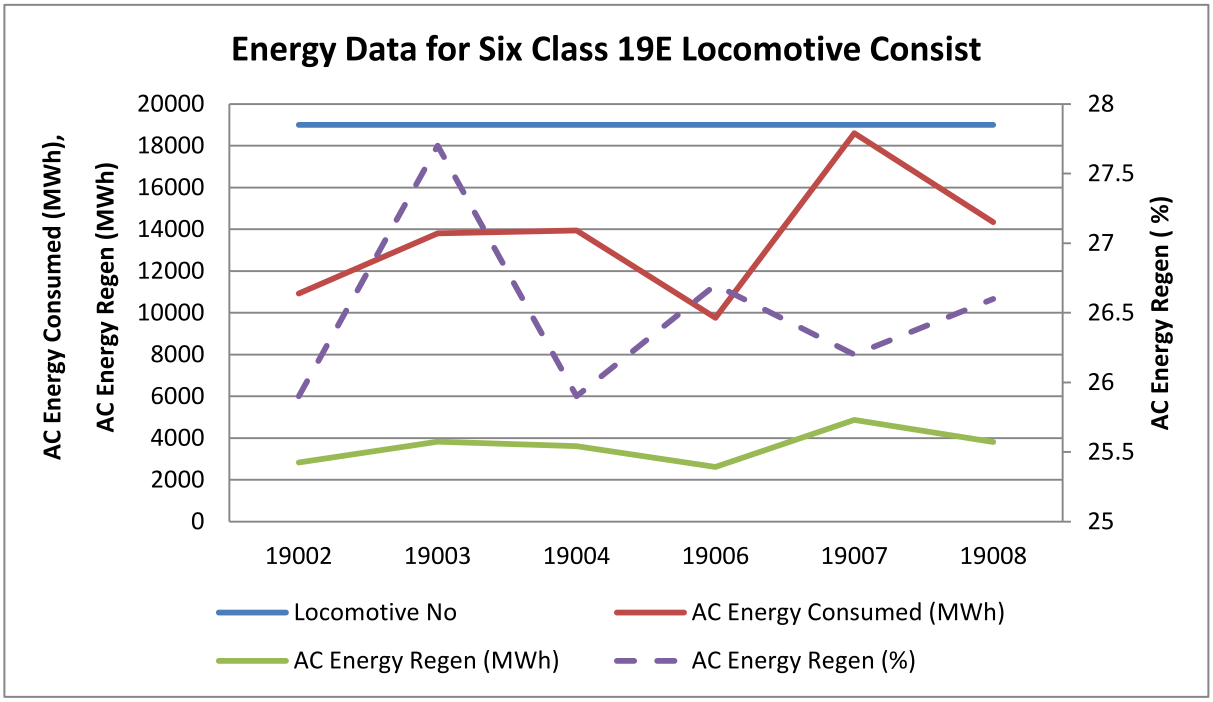


Figure 4.4: TCMS Software Data for Class 19E Locomotives

Table 4.4: TCMS Software Energy Data for Class 19E Locomotives

Locomotive No	AC Energy Consumed (MWh)	AC Energy Regen (MWh)	AC Energy Regen (%)
19002	10933	2835	25.9
19003	13804	3824	27.7
19004	13948	3616	25.9
19006	9768	2613	26.7
19007	18610	4874	26.2
19008	14338	3811	26.6

4.3 Case study

The scenario used for this study is the line between Ermelo to Richard bay in South African as shown in Figure 4.5.

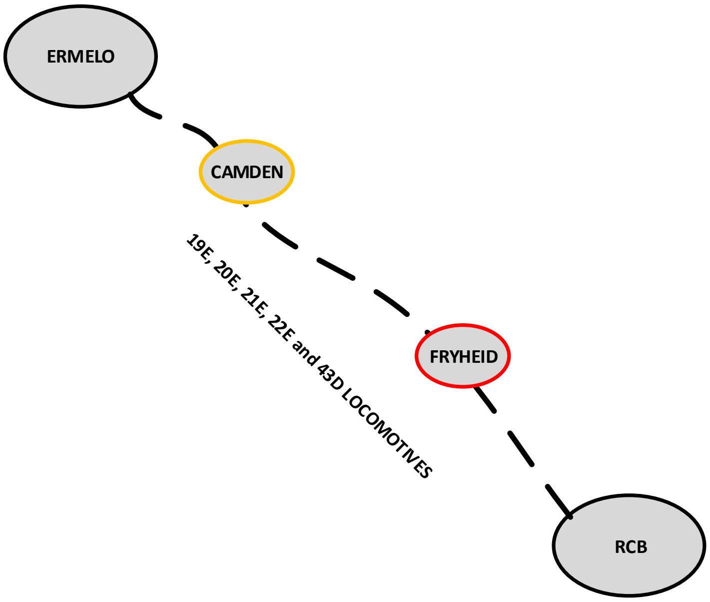


Figure 4.5: Map Ermelo to Richard bay Coal Network (25 kV Line)

Parameters of the line are:

- Line length = 450 km with a 30 km distance between the traction substations.
- The line Impedance of a single-track lines [Ohms/km] = 0.1+ j0.27 Ω.
- The line voltage is 25 kV at 0 phase angle.

4.3.1 Generation of Regenerative Energy

Heavy-haul trains generate regenerative braking when they run on long downhill tracks. If this capacity can be used by uphill trains with the same power supply part a decrease in the cost of coal transport and an increase in the quality of power will result. A single unit locomotive model was used to predict the energy consumption and regenerative braking energy of a heavy-haul on a long slope. According to the train longitudinal section simplification theory, the energy consumption and the regenerative braking model of a single locomotive are based on train characteristics, line conditions and running speed. As the locomotive travels down the slope more energy will be regenerated by the train and as a result, more energy could be stored by the flywheel to supplement the train power as it moves uphill. To demonstrate, it is assumed that:

- The class 19E locomotive is descending at a distance of 1000 m above sea level for 5 km as shown in Figure 4.6.
- The locomotive is equipped with a FESS to capture the regenerative braking energy.

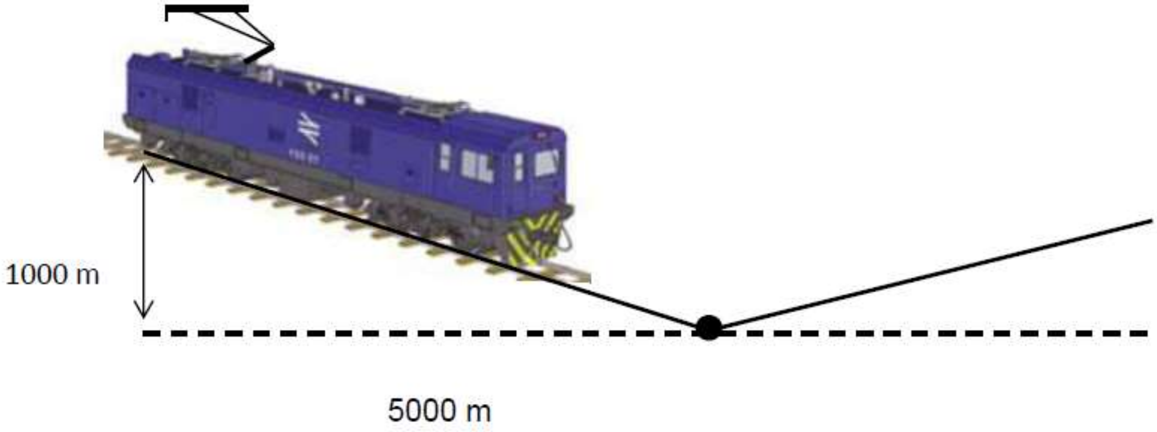


Figure 4.6: Showing the gradient from Ermelo to Richards Coal Terminal

In evaluating the braking effort with the highest regenerated energy closer to the class 19E locomotive braking effort, ten scenarios were created. Figure 4.7 shows the energy regenerated at a velocity of 23 m/s at various distances from 1 to 10 km. It is observed that at a distance of 5 km and speed of 23 m/s, the train is capable of achieving energy of 3.469 MW that is closer to the class 19E locomotive braking effort that may generate a braking force to stop the locomotive, and energy can be safely regenerated back to the overhead line.

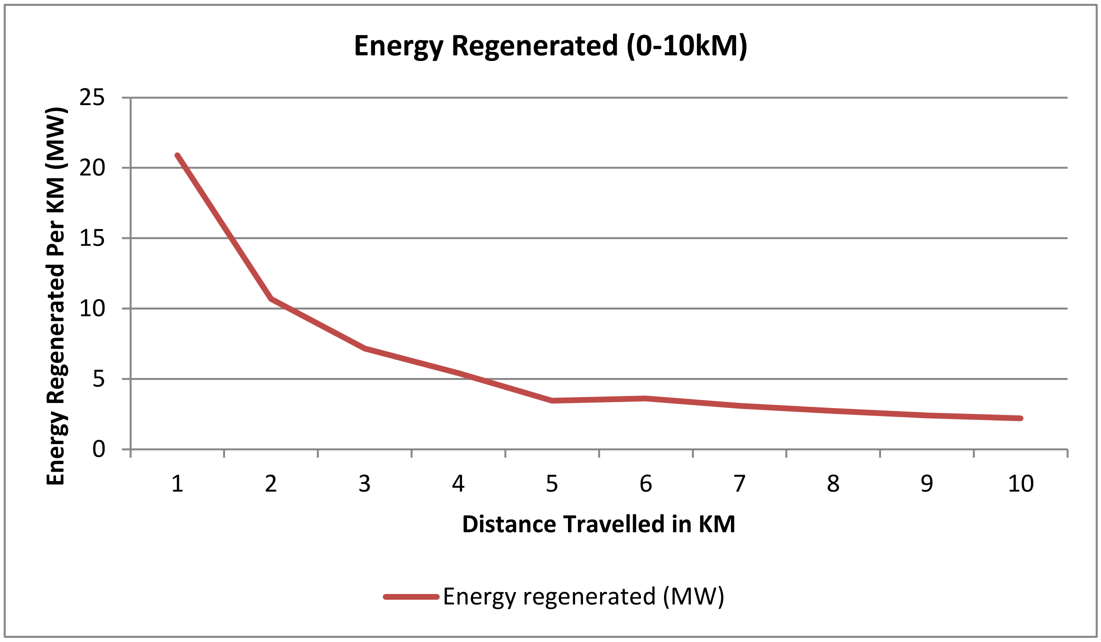


Figure 4.7: Energy regenerated [0 – 10 KM]

If the regenerated energy is stored, it can then be supplied during the uphill. During the regenerative braking operation, the line voltage should not exceed 30kV [69] [81] [82]. In order to meet the requirements, there are several technical solutions. One of the solutions is to restrict the line voltage to 30 kV at the new rolling stock. Another solution is to regulate the cos θ. Figure 4.8 and 4.9 presents the regulation of power factor during regenerative braking. In motoring, a locomotive utilizes cos θ to control and deliver a unit power factor and voltage level is dependent on power factor when braking. During braking of the train, cos θ maintains the curve, in Figure 4.9 shows ideal supply voltages, U below 25 KV. In order to regulate the power factor for voltages above 25 KV, the locomotive begins to consume reactive power.

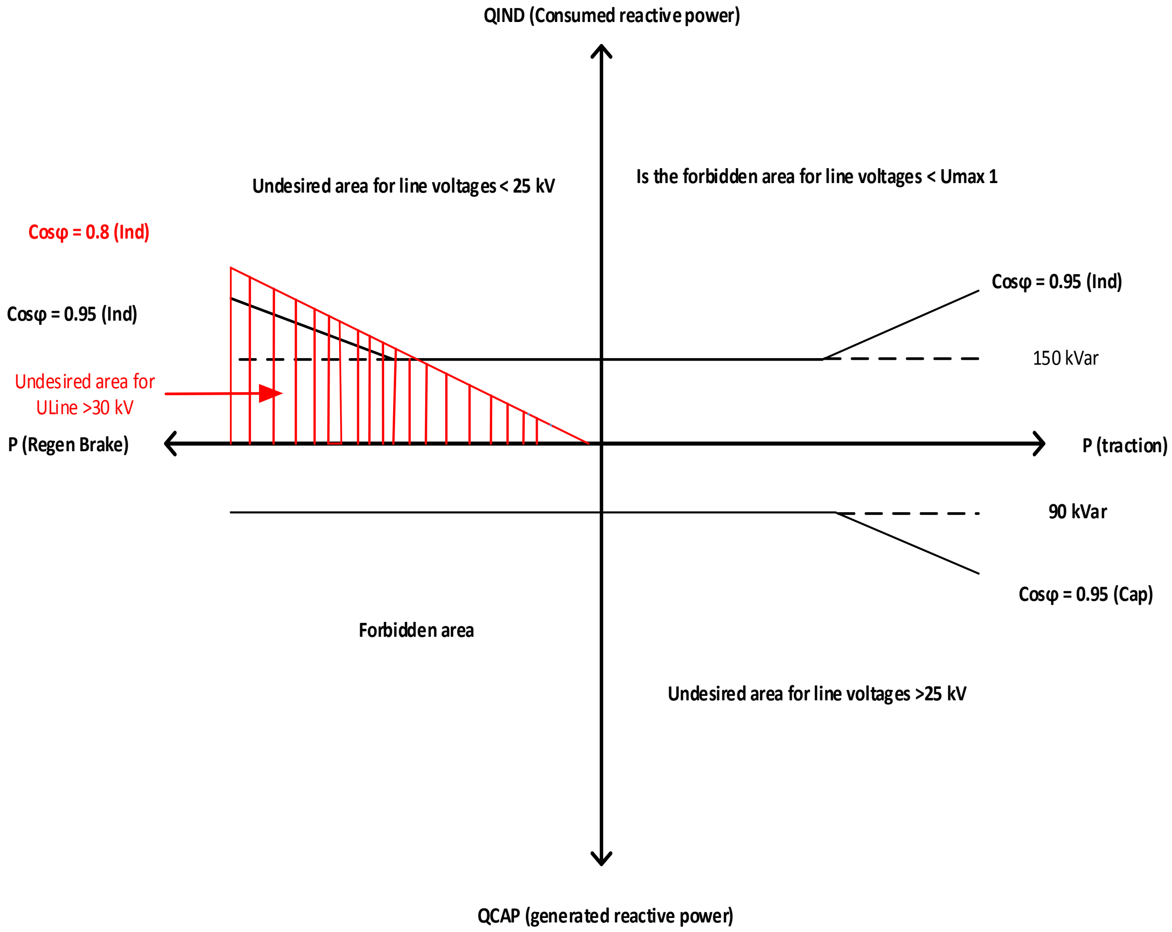


Figure 4.8 Cos(φ) control in regenerative braking [69]**and** [81], [82]

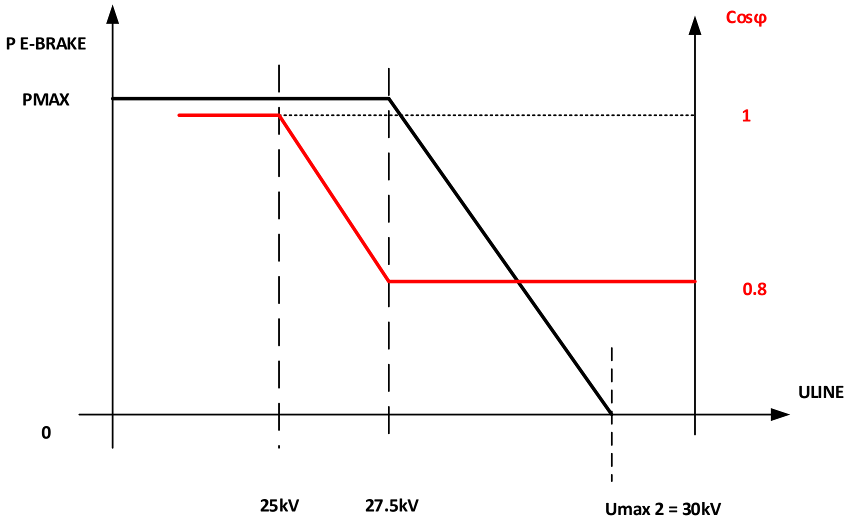


Figure 4.9 Power limitation and power factor control in regenerative braking [69] **and** [81]**,** [82]

It can be seen in Figure 4.8 and 4.9 that regenerated reactive power is restricted to a particular set of parameters, which limits the possibility of regulating the power factor. Capacitive power, if any, is limited to 150 kVar within the range of voltages from Umin1 to Umax1 shown in Table 3.5 during regenerative mode as indicated in [69] [81] [82]. In the regeneration mode, the train must therefore not operate as a capacitor greater than 150 kVar at any regenerative power. During regenerative braking, the capacitive power factor is forbidden. Except for 150 kVar capacitive reactive power, filters can be installed on the high voltage side of the locomotive. The filters must therefore not be more than 150 kVar capacitive. An inductive reactive power is unacceptable for certain reasons. Thus, the regenerated reactive power is set to 0 MVAr and 3.469 MW is the regenerated energy.

4.3.2 Catenary line without FESS

In this study, traction stations are considered a constant supply of 25 kV at 0 phase angle. At points far from a substation, the dual voltage systems suffer from voltage drops along the length of the catenary and locomotives may see severely reduced voltages up to 5 kV or more [83]. Figure 4.6 shows a drop in catenary line voltage down to 18587.52 kV at a distance of 13 km away from a substation. According to [81], the voltage decreases when the train distance rises with respect to the traction substation. As the distance increases the traction network impedance rises, which in turn increase the voltage drop. In addition, the number of trains running at the same time increases the current flowing though the catenary network resulting in higher voltage drops [81].

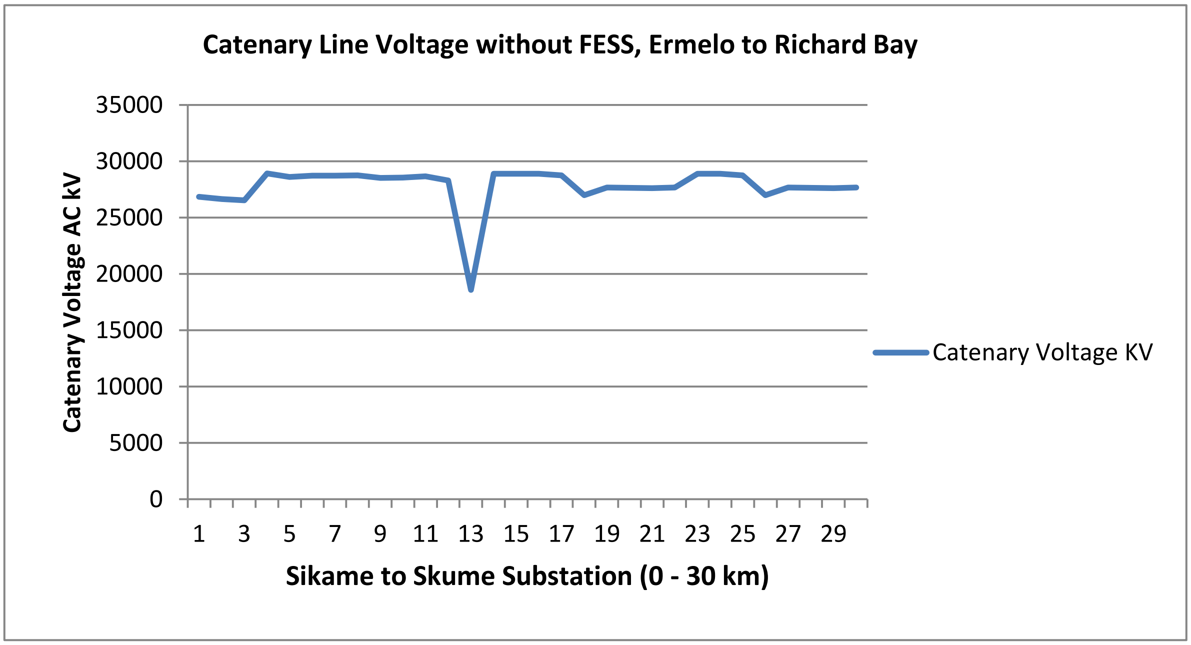


Figure 4.10: Catenary Voltage drop at 13 km away from Sikame

4.3.3 Catenary line Voltage Enhancement with a FESS

The FESS on-board the locomotive will operate as both PQ and PV bus. It will absorb regenerated energy for temporary storage during electric braking (PQ Bus) and supply power (PV Bus) to the catenary lines whenever the energy is needed by the locomotive. To enhance the catenary voltage profile, the energy delivered by FESS can be calculated as in Section 3.7. The energy is delivered for up to 10 minutes at a distance of approximately 13 km from the traction station. Figure 4.9 shows the FESS supplying power to boost the catenary line during the volt drop.

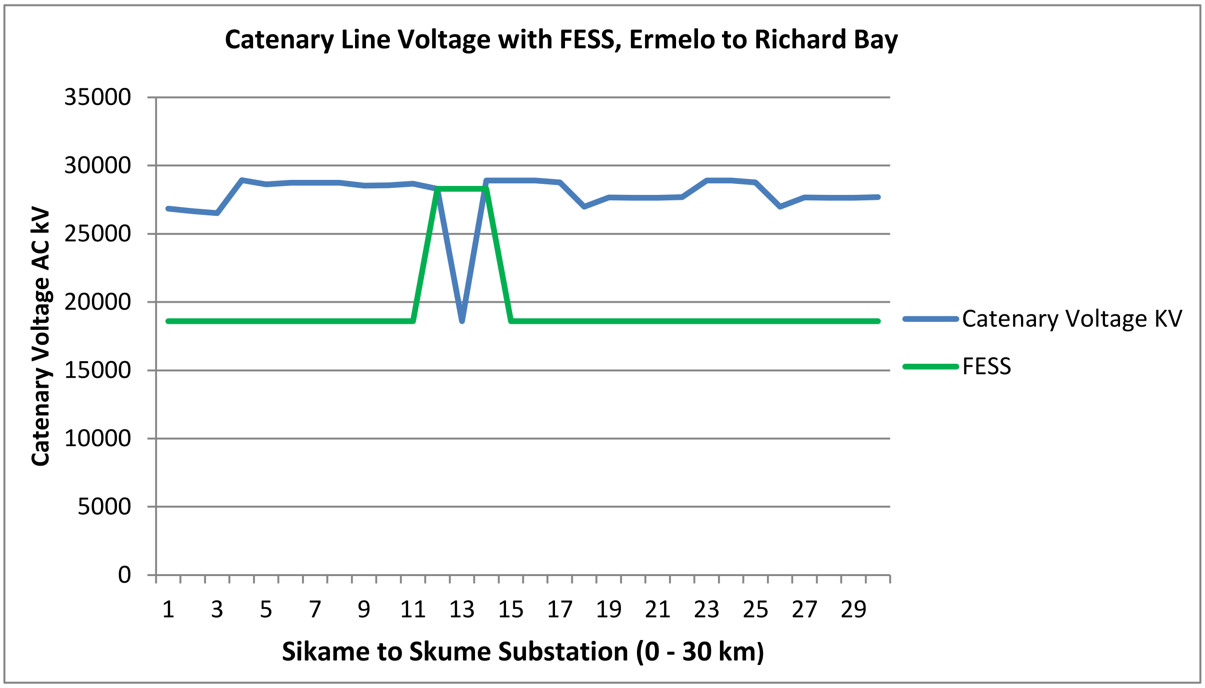


Figure 4.11: Catenary Voltage Supplemented by FESS

4.4 Summary

The project profile for this study is the regenerative braking energy analysis of class 19E heavy-duty locomotive on the route from Ermelo to Richard bay coal terminal. In this chapter, it can be seen that the FESS is capable of being charged from regenerative braking of the trains and discharged when the train demands energy, delivering it closer to the loads and away from any traction station. A 2.5 MW equivalent to 416.667 MWh of power with a discharge time of up to 10 minutes enables the full recovery of braking energy within the overhead voltage regulation. The flywheel has a limit of 3.6 percent of the total energy loss of storage capacity. In a model with a FESS, the catenary line voltage is raised by 6.25 kV. While the output is entirely dependent on geographic terrain, a value of 2.5 MW guarantees 416.667 MWh energy recovery for the steep slope. In this study, the usefulness of FESS mounted on-board the locomotive is shown to absorb regenerative braking energy when electric braking is applied by the train and to use that energy when the train is accelerating to increase the catenary voltage. Results show that 25.9 % percent of the overall power is regenerated by the locomotive, thus improving the network efficiency and reducing energy usage by about 25.9 %.

Chapter 5 : Summary, Conclusion and Suggestion for Future work

5.0 Summary, Conclusion and Suggestions for future works

This chapter presents the summary of the work done, a conclusion based on the results obtained and some suggestions for the future are made. In Chapter 2, the literature on aspects of the energy storage system (ESS) in electrical and railway vehicles is presented. Various types of ESS based on their energy formations, compositional material, and technique of power delivery over their ability and overall life expectancy efficiencies are presented. The literature further provides power and energy costs for each energy storage technology, including energy and power densities. Chapter 3 presents railway power network modelling. In South Africa, RPNs are electrified using three methods 3 kV DC, 25 kV AC and 50 kV AC. The 25 kV AC electrification system is used by the Coal Link and the long distances between the cities. The line between Ermelo to Richards bay uses 25 kV AC 50 Hz. This RPN has a total length of 450 km and a distance of approximately 20 – 30 km between traction stations. The continuous ratings of the various types of traction stations are single units 3.0 MW, 4.5 MW, 5.0 MW and double units 6.0 MW, 9.0 MW and 10.0 MW. Chapter 4 present a train model equipped with an event recorder. It records data on the operation of train control and output in response to the controls and other train control systems. The event recorders are integrated with the Train Control and Monitoring System (TMCS) software. A trip from Ermelo to Richards Bay using class 19E locomotives has been used as a case study. Analysis of data from the TCMS enables theoretical validation. A journey from Ermelo to Richards Bay Coal Terminal, it normally takes approximately 10 hours to rich the ports. At points far from a substation, the dual voltage systems suffer from voltage drops along the length of the catenary line and the locomotives may see severely reduced voltages up to 5 kV or more. A locomotive suffers voltage drops at a distance of 13 km away from the substation.

5.1 Conclusion

Thus, this work concludes that, the utilisation of locomotive for mid-term energy storage system using a flywheel energy storage system to recover energy from regenerative braking for electrified railways. There seems to be an interest in using flywheel on-board the locomotive to store energy to stabilize the line voltage drops. The study requires the analysis of the data collected from the TCMS system, after a real journey, conducted a realistic assessment. In a case study, the suggested solution was the use of real data from Ermelo to Richards Bay Coal terminal. Based on a single train model and railway overhead line theory, a train energy consumption and regenerative braking energy were determined. Train characteristics, overhead line status, and running speed were taken as the key variables of the model. In this study, the size and integration of the flywheel energy storage system for locomotive on-board application have been calculated and a 2.5 MW which is equivalents to 416.667 kWh at 10 minutes discharge time is used. The optimal size of the flywheel energy storage system device was determined based on locomotive regenerated energy data. The results of this study, as a conceptual investment analysis report, can assist the rail operators and also better outline the feasibility of the study. The findings from this research analysis indicate that there is a strong agreement between TCMS train values and calculated parameters. Theoretical, simulations have shown that 25.9 % efficiency could be achieved on energy savings. In general, on the basis of a favourable return on investment, it can be argued that energy recuperation from regenerative braking is a viable investment and can be strongly recommended when dealing with the need to improve efficiency levels.

In heavy haul locomotives, on-board FESS can make a major contribution to energy savings. A FESS of 2.5 MW power is capable of enhancing the catenary voltage and save up to 25.9 % of energy to be used by the locomotives. In order to optimize the savings and increase catenary voltage levels, the energy supplied by the FESS has to be close to the train demand. Not only FESS has energy savings, but it also improves efficiency when train loads are higher than 3.68 MW for a single train moving 13 km away from the traction station. The incentive to explore the FESS investment is that the cost of power and energy for this innovation will decline in the near future while at the same time; the cost of electricity will rise, making energy savings quite valuable. In addition, in order to maximize the capacity of locomotives, if FESS is incorporated into the power grid, power lines would not be a limiting factor. Lastly, FESS may help to stabilize the voltage by limiting the catenary voltage drops in the supply network system, which may lead to an enhanced traffic density without further alterations in the current supply infrastructure. In reality, with an on-board energy storage unit, the vehicle would need ample space to accommodate the FESS, and the vehicle would have almost 2 percent more weight, which could contribute to the increase in traction power consumption.

5.2 Suggestions for Future

In this section, the manner in which the study can be further developed and checked will be addressed on the basis of knowledge and information gained after this dissertation has been completed. The author’s suggestion is to use the design software’s to run simulations for more accurate results. Simulate trains running between two traction stations for a period of a month, where more than two trains running simultaneously between two traction stations. This would result in imperative monitoring of overhead line voltage values and line losses, so it may be more desirable to implement the FESS, yet at the same, time the results will be closer to life. Basic calculations of the proposed method for charging and discharging the FESS may be included to minimize the energy lost by the flywheel. A mixture of multiple technology solutions, using a high power density of the flywheel and high energy density of the batteries collective known as the hybrid system, could be worthwhile for a powerful energy storage system. Further study is required to reduce the weight of the energy storage systems, yet to maximise power and energy density. Electricity demand and prices will rise in the near future and renewable alternatives will be subsidized and funded by the Government. It is proposed that train operators should engage with train manufactures in advance in order to build space for potential energy storage system installations. However, future research should be undertaken to also identify the costs of power electronics to be incurred in order to interface and manage the energy recovery process.

References

[1] S. Vazquez, S. Lukic, E. Galvan, L. G. Franquelo, J. M. Carrasco, and J. I. Leon, “Recent advances on energy storage systems,” in *IECON 2011-37th Annual Conference of the IEEE Industrial Electronics Society*, 2011, pp. 4636–4640.

[2] L. Latto, “Regenerative Braking Systems in Rail application,” *Bishop & Associates Inc*, p. 3, 2014.

[3] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, “Progress in electrical energy storage system: A critical review,” *Prog. Nat. Sci.*, vol. 19, no. 3, pp. 291–312, 2009, doi: 10.1016/j.pnsc.2008.07.014.

[4] M. Khodaparastan, A. A. Mohamed, and W. Brandauer, “Recuperation of regenerative braking energy in electric rail transit systems,” *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 8, pp. 2831–2847, 2019, doi: 10.1109/TITS.2018.2886809.

[5] P. V Solar, “Kinetic Energy Storage (Flywheels).”

[6] A. Pyper, “SA freight rail operations can benefit from regenerative braking system,” *11th International Heavy Haul Association (IHHA) Conference in Cape Town*, 2017. .

[7] W. Jeong, S.-B. Kwon, D. Park, and W. S. Jung, “Efficient energy management for onboard battery-driven light railway vehicle,” in *9th World Congress on Railway Research–WCRR*, 2011.

[8] J. Kang and W. Kim, “Proceedings of the Institution of Mechanical Engineers: Journal of automobile engineering,” *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.*, 2009, doi: 10.1243/09544070JAUTO1405.

[9] A. Rufer, D. Hotellier, and P. Barrade, “A supercapacitor-based energy storage substation for voltage compensation in weak transportation networks,” *IEEE Trans. power Deliv.*, vol. 19, no. 2, pp. 629–636, 2004.

[10] N. Ghaviha, J. Campillo, M. Bohlin, and E. Dahlquist, “Review of application of energy storage devices in railway transportation,” *Energy Procedia*, vol. 105, pp. 4561–4568, 2017.

[11] M. Steiner and J. Scholten, “Energy storage on board of DC fed railway vehicles

PESC 2004 conference in Aachen, Germany," in *2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No. 04CH37551)*, 2004, vol. 1, pp. 666–671.

[12] M. Steiner and J. Scholten, "Energy storage on board of railway vehicles," in *2005 European Conference on Power Electronics and Applications*, 2005, pp. 10-pp.

[13] S. Sigle, S. Kaimer, H. Dittus, A. Barai, A. McGordon, and W. D. Widanage, "Evaluation of cyclic battery ageing for railway vehicle application," 2017.

[14] M. A. Hannan, M. M. Hoque, A. Mohamed, and A. Ayob, "Review of energy storage systems for electric vehicle applications: Issues and challenges," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 771–789, 2017.

[15] T. Ratniyomchai, S. Hillmansen, and P. Tricoli, "Recent developments and applications of energy storage devices in electrified railways," *IET Electr. Syst. Transp.*, vol. 4, no. 1, pp. 9–20, 2013.

[16] F. Nadeem, S. M. S. Hussain, P. K. Tiwari, A. K. Goswami, and T. S. Ustun, "Comparative review of energy storage systems, their roles, and impacts on future power systems," *IEEE Access*, vol. 7, pp. 4555–4585, 2018.

[17] S. Vazquez, S. M. Lukic, E. Galvan, L. G. Franquelo, and J. M. Carrasco, "Energy storage systems for transport and grid applications," *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp. 3881–3895, 2010.

[18] M. G. Molina, "Energy Storage and Power Electronics Technologies: A Strong Combination to Empower the Transformation to the Smart Grid," *Proc. IEEE*, vol. 105, no. 11, pp. 2191–2219, 2017, doi: 10.1109/JPROC.2017.2702627.

[19] W. Choi *et al.*, "Reviews on grid-connected inverter, utility-scaled battery energy storage system, and vehicle-to-grid application - Challenges and opportunities," in *2017 IEEE Transportation and Electrification Conference and Expo, ITEC 2017*, 2017, doi: 10.1109/ITEC.2017.7993272.

[20] S. Mayrink, J. G. Oliveira, B. H. Dias, L. W. Oliveira, J. S. Ochoa, and G. S. Rosseti, "Regenerative Braking for Energy Recovering in Diesel-Electric Freight Trains: A Technical and Economic Evaluation," *Energies*, vol. 13, no. 4, p. 963, 2020.

[21] T. Fujihara, H. Imano, and K. Oshima, "Development of pump turbine for

seawater pumped-storage power plant," *Hitachi Rev.*, vol. 47, no. 5, pp. 199–202, 1998.

[22] S. Lemofouet and A. Rufer, "Hybrid energy storage system based on compressed air and super-capacitors with maximum efficiency point tracking (MEPT)," *IEEJ Trans. Ind. Appl.*, vol. 126, no. 7, pp. 911–920, 2006.

[23] V. Singh, "Efficient Utilization of Regenerative Braking in Railway Operations," *Int. Res. J. Eng. Technol*, vol. 4, pp. 1421–1428, 2017.

[24] S. M. Schoenung, "Characteristics and technologies for long-vs. short-term energy storage: a study by the DOE energy storage systems program," Sandia National Labs., Albuquerque, NM (US); Sandia National Labs …, 2001.

[25] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Appl. Energy*, vol. 137, pp. 511–536, 2015.

[26] W. Gunselmann, "Technologies for increased energy efficiency in railway systems," in *2005 European Conference on Power Electronics and Applications*, 2005, pp. 10-pp.

[27] H. Liu and J. Jiang, "Flywheel energy storage—An upswing technology for energy sustainability," *Energy Build.*, vol. 39, no. 5, pp. 599–604, 2007.

[28] B. Bolund, H. Bernhoff, and M. Leijon, "Flywheel energy and power storage systems," *Renewable and Sustainable Energy Reviews*. 2007, doi: 10.1016/j.rser.2005.01.004.

[29] K. van Berkel, S. Rullens, T. Hofman, B. Vroemen, and M. Steinbuch, "Topology and flywheel size optimization for mechanical hybrid powertrains," *IEEE Trans. Veh. Technol.*, vol. 63, no. 9, pp. 4192–4205, 2014.

[30] Y. Xu *et al.*, "Design of a multipulse high-magnetic-field system based on flywheel energy storage," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, pp. 1–5, 2016.

[31] K. Xu, D. Wu, Y. L. Jiao, and M. H. Zheng, "A fully superconducting bearing system for flywheel applications," *Supercond. Sci. Technol.*, vol. 29, no. 6, p. 64001, 2016.

[32] M. Ogata *et al.*, "Test equipment for a flywheel energy storage system using a magnetic bearing composed of superconducting coils and superconducting

bulks," *Superconductor Science and Technology*. 2016, doi: 10.1088/0953-2048/29/5/054002.

[33] Y. Yuan, Y. Sun, and Y. Huang, "Design and analysis of bearingless flywheel motor specially for flywheel energy storage," *Electron. Lett.*, vol. 52, no. 1, pp. 66–68, 2015.

[34] M. I. Daoud, A. M. Massoud, A. S. Abdel-Khalik, A. Elserougi, and S. Ahmed, "A flywheel energy storage system for fault ride through support of grid-connected VSC HVDC-based offshore wind farms," *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 1671–1680, 2015.

[35] F. J. M. Thoolen, *Development of an advanced high speed flywheel energy storage system*. Eindhoven University of Technology, 1993.

[36] M. I. Daoud, A. S. Abdel-Khalik, A. Massoud, S. Ahmed, and N. H. Abbasy, "On the development of flywheel storage systems for power system applications: A survey," in *Proceedings - 2012 20th International Conference on Electrical Machines, ICEM 2012*, 2012, doi: 10.1109/ICElMach.2012.6350175.

[37] P. Ralon, M. Taylor, A. Ilas, H. Diaz-Bone, and K. Kairies, "Electricity storage and renewables: Costs and markets to 2030," *Int. Renew. Energy Agency Abu Dhabi, United Arab Emirates*, 2017.

[38] N. Hiroshima *et al.*, "Spin test of three-dimensional composite rotor for flywheel energy storage system," *Compos. Struct.*, vol. 136, pp. 626–634, 2016.

[39] T. B. Reddy, *Linden's handbook of batteries*, vol. 4. Mcgraw-hill New York, 2011.

[40] H. Ibrahim, A. Ilinca, and J. Perron, "Energy storage systems—Characteristics and comparisons," *Renew. Sustain. energy Rev.*, vol. 12, no. 5, pp. 1221–1250, 2008.

[41] K. C. Divya and J. Østergaard, "Battery energy storage technology for power systems-An overview," *Electric Power Systems Research*. 2009, doi: 10.1016/j.epsr.2008.09.017.

[42] J. Cho, S. Jeong, and Y. Kim, "Commercial and research battery technologies for electrical energy storage applications," *Progress in Energy and Combustion Science*. 2015, doi: 10.1016/j.pecs.2015.01.002.

[43] S. Piriienko, A. Balakhontsev, A. Beshta, A. Albu, and S. Khudoliy, "Optimization

of hybrid energy storage system for electric vehicles," *Power Electron. drives*, vol. 1, no. 2, pp. 97–111, 2016.

[44] S. F. Tie and C. W. Tan, "A review of energy sources and energy management system in electric vehicles," *Renew. Sustain. energy Rev.*, vol. 20, pp. 82–102, 2013.

[45] L. Brandeis, D. Sprake, Y. Vagapov, and H. Tun, "Analysis of electrical energy storage technologies for future electric grids," in *2016 IEEE NW Russia Young Researchers in Electrical and Electronic Engineering Conference (EIConRusNW)*, 2016, pp. 513–518.

[46] L. Yao, B. Yang, H. Cui, J. Zhuang, J. Ye, and J. Xue, "Challenges and progresses of energy storage technology and its application in power systems," *J. Mod. Power Syst. Clean Energy*, vol. 4, no. 4, pp. 519–528, 2016.

[47] S. Alahakoon, M. Leksell, and S. Östlund, "Emerging Energy Storage Solutions for Transportation Electrification–A Review," *Int. J. Eng. Technol. Innov.*, vol. 9, no. 2, p. 75, 2019.

[48] M. Spiryagin, Q. Wu, P. Wolfs, Y. Sun, and C. Cole, "Comparison of locomotive energy storage systems for heavy-haul operation," *Int. J. Rail Transp.*, vol. 6, no. 1, pp. 1–15, 2018.

[49] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: A critical review," *Progress in Natural Science*. 2009, doi: 10.1016/j.pnsc.2008.07.014.

[50] I. Hadjipaschalis, A. Poullikkas, and V. Efthimiou, "Overview of current and future energy storage technologies for electric power applications," *Renew. Sustain. energy Rev.*, vol. 13, no. 6–7, pp. 1513–1522, 2009.

[51] A. González-Gil, R. Palacin, and P. Batty, "Sustainable urban rail systems: Strategies and technologies for optimal management of regenerative braking energy," *Energy Convers. Manag.*, vol. 75, pp. 374–388, 2013.

[52] Y. Wang, Z. Yang, F. Lin, X. An, H. Zhou, and X. Fang, "A Hybrid Energy Management Strategy based on Line Prediction and Condition Analysis for the Hybrid Energy Storage System of Tram," *IEEE Trans. Ind. Appl.*, vol. 56, no. 2, pp. 1793–1803, 2020.

[53] B. Battke, T. S. Schmidt, D. Grosspietsch, and V. H. Hoffmann, “A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications,” *Renew. Sustain. Energy Rev.*, vol. 25, pp. 240–250, 2013.

[54] V. Arangarajan, A. M. T. Oo, J. Chandran, G. Shafiullah, and A. Stojcevski, “Role of energy storage in the power system network,” *Renew. energy Sustain. Dev.*, pp. 201–225, 2015.

[55] A. Chatzivasileiadi, E. Ampatzi, and I. Knight, “Characteristics of electrical energy storage technologies and their applications in buildings,” *Renew. Sustain. Energy Rev.*, vol. 25, pp. 814–830, 2013.

[56] S. M. Schoenung, “Characteristics and technologies for long-vs. short-term energy storage,” *United States Dep. Energy*, 2001.

[57] K. Mongird *et al.*, “Energy storage technology and cost characterization report,” Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2019.

[58] J. Ehnberg, Y. Liu, and M. Grahn, “Grid and Storage,” *Div. Electr. Power Eng. Div. Phys. Resour. Theory, Göteborg*, 2014.

[59] B. Bhargava, “Benefits of a low frequency, low voltage railway electrification system,” in *Proceedings of the 1996 ASME/IEEE Joint Railroad Conference*, 1996, pp. 177–184.

[60] J. J. Burke, A. P. Engel, S. R. Gilligan, and N. A. Mincer, “Increasing the power system capacity of the 50 kV Black Mesa and Lake Powell Railroad through harmonic filtering and series compensation,” *IEEE Trans. Power Appar. Syst.*, no. 4, pp. 1268–1274, 1979.

[61] J. I. C. A. (JICA), “Data Collection Survey on Railway Sector in the Republic of South Africa,” 2013.

[62] Toshiba, “19E Electric Locomotive Maintenance Manual.” 2009.

[63] M. Mondi, “Challenges and developments facing SA Coal Logistics”,” in *IHS Energy SA Coal Conference*, 2019, pp. 1–35.

[64] Z. Tian, N. Zhao, S. Hillmansen, S. Su, and C. Wen, “Traction Power Substation Load Analysis with Various Train Operating Styles and Substation Fault Modes,” *Energies*, vol. 13, no. 11, p. 2788, 2020.

[65] S. L. Grassie and J. A. Elkins, “Tractive effort, curving and surface damage of

rails: Part 1. Forces exerted on the rails," *Wear*, vol. 258, no. 7–8, pp. 1235–1244, 2005.

[66] S. S. Y Kobayashi, "19E Locomotives perfomance Curves (Traction and Electric Braking)." pp. 1–9, 2006.

[67] J. D. Glover, M. S. Sarma, and T. Overbye, *Power system analysis & design, SI version*, 5th Ed. Cengage Learning, 2012.

[68] J. J. Grainger, W. D. Stevenson, and W. D. Stevenson, *Power system analysis*. North Carolina, 2003.

[69] B. S. EN, "50163: 2004:'Railway applications,'" *Supply voltages Tract. Syst*.

[70] Y. Seferi, P. Clarkson, S. M. Blair, A. Mariscotti, and B. G. Stewart, "Power quality event analysis in 25 kV 50 Hz AC railway system networks," in *2019 IEEE 10th International Workshop on Applied Measurements for Power Systems (AMPS)*, 2019, pp. 1–6.

[71] B. Std, "Railway applications—power supply and rolling stock—technical crite-ria for the coordination between power supply (substation) and rolling stock to achieve interoperability," *BSI Std*, no. 2012, p. 54, 2012.

[72] M. Plakhova, B. Mohamed, and P. Arboleya, "Static model of a 2× 25kV AC traction system," in *2015 6th International Conference on Power Electronics Systems and Applications (PESA)*, 2015, pp. 1–5.

[73] R. C. Sharma, M. Dhingra, and R. K. Pathak, "Braking systems in railway vehicles," *Int. J. Eng. Res. Technol.*, vol. 4, no. 1, pp. 206–211, 2015.

[74] M. E. Amiryar and K. R. Pullen, "A review of flywheel energy storage system technologies and their applications," *Appl. Sci.*, vol. 7, no. 3, p. 286, 2017.

[75] Z. Long and Q. Zhiping, "Review of flywheel energy storage system," in *Proceedings of ISES World Congress 2007 (Vol. I–Vol. V)*, 2008, pp. 2815–2819.

[76] R. Pena-Alzola, R. Sebastián, J. Quesada, and A. Colmenar, "Review of flywheel based energy storage systems," in *2011 International Conference on Power Engineering, Energy and Electrical Drives*, 2011, pp. 1–6.

[77] B. Kaftanoğlu, "FLYWHEELS AND SUPER-FLYWHEELS," *Energy Storage Syst. I*, p. 301, 2009.

[78] T. Suzuki, "DC power-supply system with inverting substations for traction

systems using regenerative brakes," in *IEE Proceedings B (Electric Power Applications)*, 1982, vol. 129, no. 1, pp. 18–26.

[79] Q. Lu *et al.*, "Establishment and analysis of energy consumption model of heavy-haul train on large long slope," *Energies*, vol. 11, no. 4, p. 965, 2018.

[80] M. Di Manno, P. Varilone, P. Verde, M. De Santis, C. Di Perna, and M. Salemme, "User friendly smart distributed measurement system for monitoring and assessing the electrical power quality," in *2015 AEIT International Annual Conference (AEIT)*, 2015, pp. 1–5.

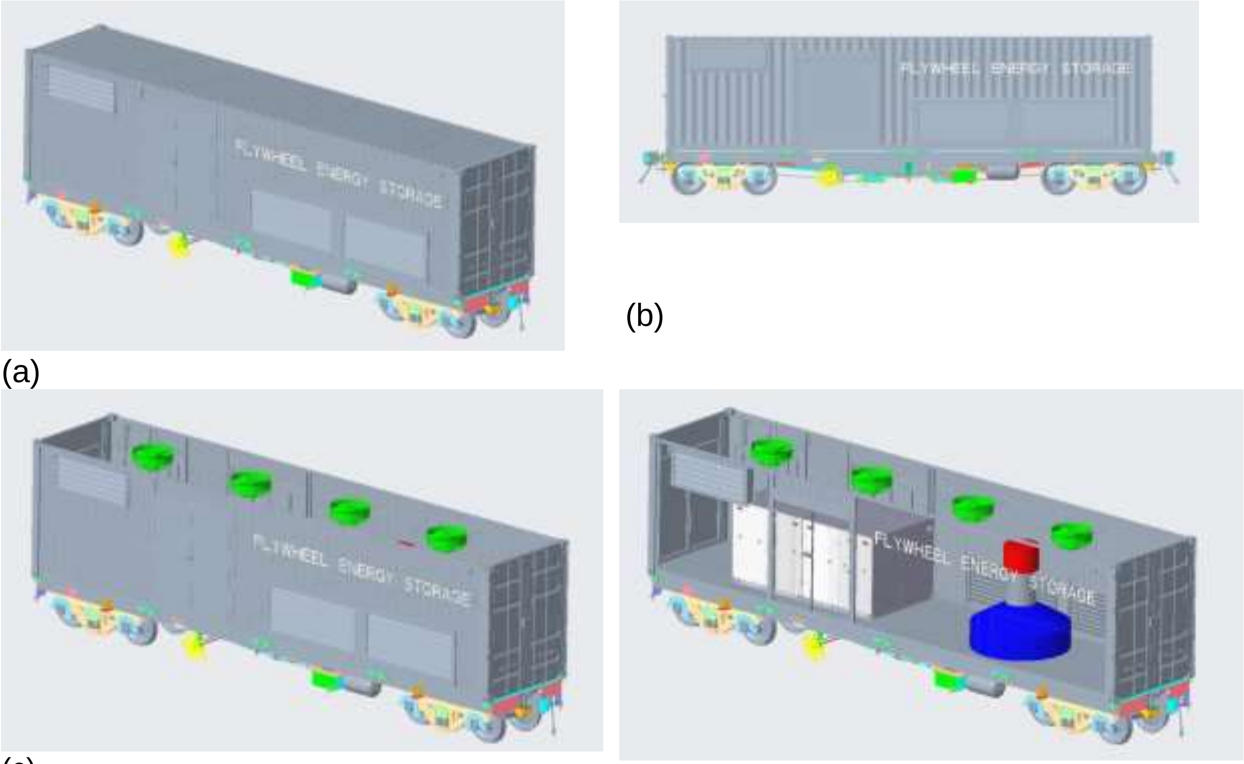
[81] G. B. Worku and A. B. Kebede, "Modeling and simulation of traction of power supply system case study: Modjo-Hawassa Railway Line in Ethiopia," *Zede J.*, vol. 36, pp. 54–66, 2018.

[82] M. K. Jain, "Train, Grade, Curve and Acceleration Resistance." 2013.

[83] I. I. Railways, "https://www.irfca.org/faq/faq-elec2.html," *The Indian Railway Fan Club*. 2010.

Appendix A

The FESS application is considered on-board the vehicle which is the advantage to supply power at a shorter distance. Although, the FESS is on-board the vehicle, the limitations on its size and weight are more stringent. A wagon concept design was used for FESS as mid-term energy storage for locomotives due to locomotive on-board space limitation. Figure A.1 shows the on-board energy storage system with a power range of 2.5 MW, 416.667 kWh at 10 minutes discharge time.



(a)

(b)

(c)

(d)

Figure A.1: Flywheel Energy Storage System on-board the locomotive