DEVELOPMENT OF ENERGY RECUPERATION SYSTEM FOR THE DC THIRD RAIL SYSYTEM

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DEVELOPMENT OF ENERGY RECUPERATION SYSTEM FOR THE DC THIRD RAIL SYSTEM

By

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ABSTRACT

In line with the initiative in achieving zero carbon emission in 2050, railway industries are developing a railway system with electric train rolling stock. These electric trains are equipped with the capability of regenerative braking which reduce the usage of mechanical braking on-board. Various methods and techniques are introduced on the recuperative regenerative train braking such as resistor units, inverters and energy storage systems. In this research, we will observe the characteristic of non-regenerative and regenerative electric train with the effects on current, voltage, power and energy to the traction system. In addition, we will evaluate the amount of energy produced from regenerative braking to determine a better solution of energy recuperative system either battery energy storage system or an inverter system to enhanced the current resistive unit system implemented previously. With the increase of electricity tariff year by years, the asset owner and operators are suffering with the high amount of energy billing to operate the railway system. Hence, traction system that equipped with resistor units may consider to upgrade the system in incorporating an inverter system or an energy storage system which will reduce the peak demand power consumption and obtain the benefits of re-used the recovered energy.

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APPROVAL SHEET

This project entitled "**DEVELOPMENT OF ENERGY RECUPERATION SYSTEM FOR THE DC THIRD RAIL SYSTEM**" was prepared by SITI FARHANA BINTI FARIDUDIN and submitted as partial fulfillment of the requirements for the degree of Master of Engineering (Electrical) at Universiti Tunku Abdul Rahman.

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Date: 8 April 2022

SUBMISSION OF PROJECT

It is hereby certified that **SITI FARHANA BINTI FARIDUDIN** (ID No: ***20UEM00242***) has completed this project entitled "DEVELOPMENT OF ENERGY RECUPERATION SYSTEM FOR THE DC THIRD RAIL SYSTEM" under the supervision of Dr. Chua Kein Huat (Supervisor) from the Department of Electrical and Electronic Engineering, Lee Kong Chian Faculty of Engineering and Science, Lee Kong Chian Faculty of Engineering and Science.

I understand that University will upload softcopy of my project in PDF format into UTAR Institutional Repository, which may be made accessible to UTAR community and the public.

Yours truly,

(Siti Farhana binti Faridudin)

DECLARATION

I (SITI FARHANA BINTI FARIDUDIN) hereby declare that the project is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

(SITI FARHANA)

Date: 8 April 2022

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LIST OF ABBREVIATIONS

AARU	Automatic assured receptivity unit
AC	Alternate current
BESS	Battery energy storage system
DC	Direct current
ESS	Energy storage system
ETAP	Electrical transient analyzer program
GHG	Greenhouse gas
HESOP	Harmonic and energy saving optimizer
Li-ion	Lithium-ion
LRT	Light rail transit
LTO	Lithium titanate oxide
MRT	Mass rapid transit
PWM	Pulse width modulation
SOC	State of charge

CHAPTER 1

INTRODUCTION

MRT Kajang Line has been operating for more than 5 years since its first opening to public. The system is similar to Light Rail Transit (LRT) Sri Petaling Line which using 3rd rail system with AARU and resistor bank unit to stabilize the traction power system voltage. The AARU is responsible to absorb the excessive regenerative braking and transform the energy to heat at resistors unit. A good power supply system design will have a high efficiency power consumption. This can be achieved by optimizing the usage of regenerative energy to supply back to railway system hence reducing the power consumption and peak demand from the energy provider, Tenaga Nasional Berhad (TNB). Therefore, this research is to investigate the characteristic of regenerative electric train and the potential total of energy can be recovered in order to oversee the feasibility of replacing the current system with energy recuperative system in future.

1.1 Research objectives

The objectives of this research work are as follow:

1. To investigate the amount of energy generated from the regenerative braking
2. To design an energy recuperation system to recover the energy from the regenerative braking
3. To evaluate the performance of the system developed
4. To evaluate the feasibility of replacing the AARU system to recuperation system.

1.2 Scope of research

DC railway simulations are limited in Malaysia currently due to most of the simulation studies were conducted by international organization either using their in-house software or by using a combination of two different software for AC system and DC track system.

This research will focus on simulating the DC railway system by using ETAP 1901 software to investigate the effect of non-regenerative and regenerative train braking to the power supply systems. By referring to the amount of regenerative braking, we shall determine the suitable recuperative system available in the market to ensure some of the regenerative braking will be feedback to the system.

In order to create a similar DC railway system, I will refer to some of the MRT Kajang Line design documents for references. However, the parameters used in this simulation will also be based on the assumption basis to protect the private and confidential information of the project.

Design of the recuperative system will not be discussed in depth in this research as the development of simulation will be more focus on studying the amount of regenerative braking produced in the DC railway system. For your information, MRT Kajang Line is not adopting recuperative energy system which have the advantage of saving the electricity consumptions. Not to mentioned, the railway system is design with an AARU (Automatic Assured Receptivity Unit) and resistor bank to control the safety level of 3rd rail voltages feeding to the electric train.

1.3 Project organization

The structure of the project is organized as follows:

Chapter 2 will be the literature review related to the regenerative recuperation system available in the market. In this chapter, the principle and differences between recuperative energy are discuss in this chapter for better understanding.

Chapter 3 is the concise information on the methodology application in obtaining the desired result and discussion.

Chapter 4 will be discussing on the result in depth, understanding the graph from the simulation.

Chapter 5 is the conclusion based on the findings and objectives from this research. In this chapter, limitation and future works will also be stated in this chapter for future continuation.

CHAPTER 2

LITRETURE REVIEW

Railway technologies evolving towards a better environment in achieving zero greenhouse gas (GHG) or in another word zero carbon foot print. Therefore, most of the trains are designed with electrical train equipped with regenerative braking. Regenerative braking was introduced to reduce the total power consumption consume by the train operation. During train braking or deceleration, the traction motor will act as a generator by converting mechanical energy to electrical energy. The regenerative braking will be used to provide power to the train auxiliary supply and feedback the energy to the third rail system or overhead line.

Regenerative energy will be reused by the nearby accelerating train within the same power supply section. In the absent of electric train to consume the regenerative braking, the third rail voltage will increase and the excess energy must be discarded from the system. One of the earliest solutions was the energy will be dissipated as heat through an on-board resistor or wayside resistor unit to avoid damage on the electric train equipment. Therefore, the overall system must be designed within certain limit to ensure safe electric train operation. For example, Mass Rapid Transit (MRT) was designed with triggering voltage of 830V in the third rail system equipped with wayside resistor unit.

There are various methods introduced as the method to manage energy braking such as chopper resistor and energy storage system as shown in Figure 2. 1. In addition, the optimization of regenerative braking can be achieved by several methods such as electric train timetable optimization, adopting energy storage system or designing a reversible substation.

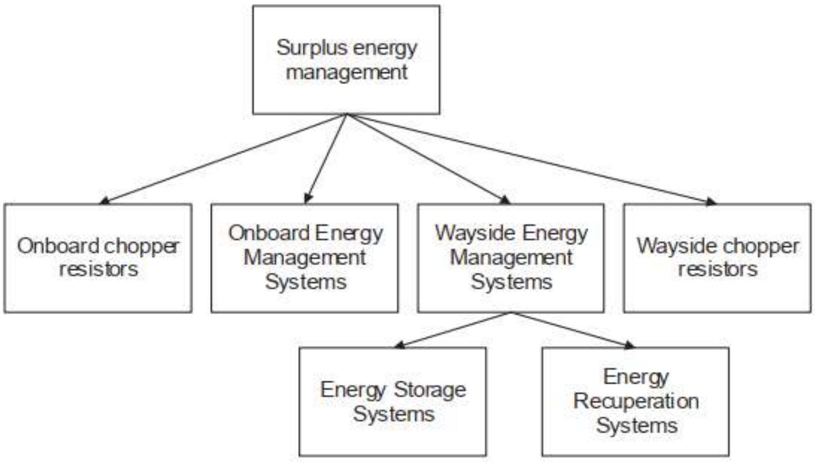

Figure 2. 1 Method of energy braking management (Mousavi G *et al.*, 2017)

2.1 Train Time Table Optimization

Train time table optimization can be achieved by studying the coordination of train departing and train stopping in one electric supply section. Train in braking mode will be decelerate when approaching the train platform and produce the regenerative energy. The energy is then absorbed by nearby accelerating train, hence reducing the third rail voltage to the optimum value of operating design voltage.

However, in some of the condition, the regenerative braking may classify as regeneration failure when the regenerative braking power is not taken by any load in which means regenerative power is not created. In other word, the regenerative failure will be occurred if accelerating train connected in the same wire section (Lee, Lee and Kwak, 2008)

As describe in (Lee, Lee and Kwak, 2008), we may avoid regenerative failure by controlling the train operation timetable. By optimizing the operation timetable, the peak power consumption will be reduced and regenerative braking utilization can be increased. Paper by (Yuksel, 2018) provide a summarize on the train timetable optimization with the concept of overlapping the train acceleration with another train deceleration to obtain maximum regenerative energy utilization thus lower the energy usage for another train in the same zone section. For example, when there are trains that accelerate or decelerate at the same time at one zone section, the voltage will increase and peak power consumption will occur as shown in Figure 2. 2 Power Dissipation in Traction Phase (Yuksel, 2018).Figure 2. 2 Therefore, it is very crucial in determine the optimal train timetable in order to increase the utilization of regenerative braking. As shown in Figure 2. 2 and Figure 2. 3, the peak train will use regenerative braking power to accelerate. There are a lot of studies conducted on the train timetable optimization in regenerative braking as described in (Demirci and Celikoglu, 2018) for the Istanbul Metro line case study.

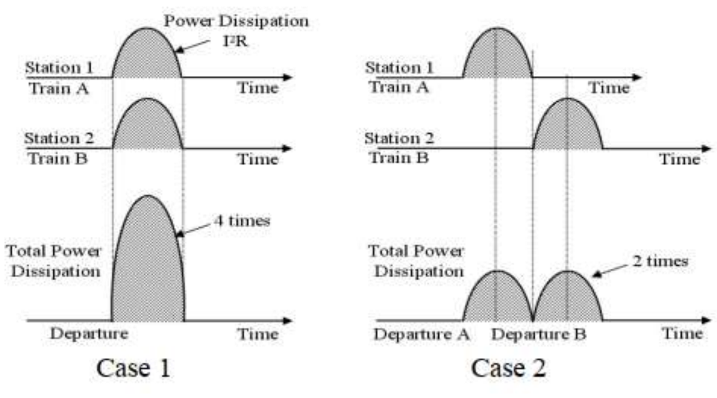

Figure 2. 2 Power Dissipation in Traction Phase (Yuksel, 2018).

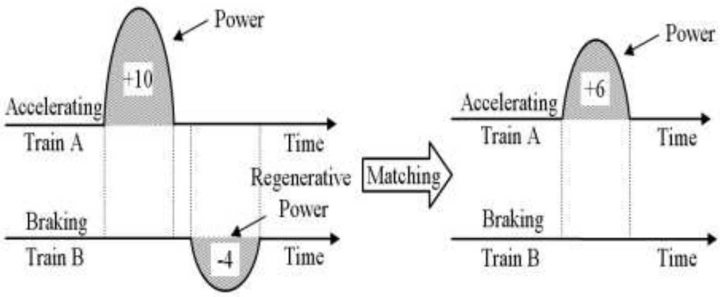

Figure 2. 3 Power Dissipation in Traction Phase when Using Regenerative Energy (Yuksel, 2018)

In railway industries, it is a norm for a train operation design to be based on headway. Headway is the travel duration between each train. Research by (Adilah, Tan and Toh, 2019) discussed on the changes of headway will have direct impact to the power consumption Table 2. 1. Given the formula to determine headway as:

$$Headway\ Time = \frac{Journey\ Time}{No.of\ Train\ Per\ Time\ Slot}$$

The total train energy consumption per day is calculated as

$$E_c = \sum_{t=1}^{Time\ Slot} n \times P \times T_t$$

Table 2. 1 Energy consumption percentage savings based on headway changes between 5% and 20% (Adilah, Tan and Toh, 2019)

Scenarios	Headway (Increases)				Headway (Decreases)			
	+5%	+10%	+15%	+20%	-5%	-10%	-15%	-20%
Scenario 2	-4.8%	-9.4%	-13.1%	-16.1%	5.1%	11.0%	17.7%	26.0%
Scenario 3	-1.1%	-5.9%	-9.4%	-12.9%	9.9%	15.5%	22.5%	31.6%
Scenario 4	-4.0%	-8.3%	-12.1%	-15.8%	6.4%	11.8%	19.0%	27.9%
Scenario 5	-9.7%	-14.2%	-17.2%	-20.4%	0.3%	5.4%	12.1%	20.4%
Scenario 6	-15.5%	-19.0%	-22.5%	-25.5%	-5.9%	-1.1%	5.1%	12.6%

Referring to the Light Rail Transit (LRT) headways, in (Adilah, Tan and Toh, 2019) research, by reducing 5% of the existing headway may increase 5.9% of the energy efficiency while with reduction of 10% headway, the energy efficiency increases by 1.1%. In the research, the headway was observed with the difference between +/- 5% and +/- 20% from the existing headway. This research observes the effective of overlapping activity between departing train and accelerating train have an influence towards energy efficiency. However, the railway system for this LRT is not equipped with energy storage system. Instead, it using the wayside Automatic Assured Receptivity Unit with a resistor unit.

Another approach is an integration of timetable optimization and energy storage system as studied in (Kampeerawat and Koseki, 2017) paper on Bangkok Rapid Transit system. Timetable optimization affected by the train traffic condition. Therefore, by integrating the right size of ESS at the right location will compensate on the low receptivity of regenerative braking during moderate to low traffic condition. During high traffic condition, the overall network receptivity is increase up to 76.4% and energy saving is increase to 17.76% by optimizing the time table. On the other hand, the energy saving is improved for another 2% for integrated approach. Not to mentioned, during moderate and low traffic, the energy saving is improving by 3.6%.

2.1 Energy Storage Solution

The energy storage system has to be designed properly to ensure its efficiency. The storage system must absorb and store the regenerative braking energy and discharge it when required. This method will reduce the amount of energy required from grid substations as well as reduce the peak power demand.

Energy storage system can either be installed on-board at the roof of electric train or wayside substation. If the ESS are installed on-board, there are several concerns need to be addressed such as the train weight will be increased as well as increasing of heat in the tunnel. Both solutions shall be able to store the regenerative braking in case there is a surplus at the traction supply system. There are three (3) common energy storage technologies adapt in railway industry such as batteries, flywheel and supercapacitors.

Batteries are comprising of multiple electrochemical cells connected in parallel and series to form a unit. The common batteries used in rail transit Lead-acid, Lithium-ion (Li-ion), Nickel metal hydride (Ni-MH) and Sodium sulfur (Na-s).

Lithium-ion (Li-ion) batteries are known to be in high energy density, high efficiency, long-lift time, light-weight and fast in charge and discharge ability which widely used in automotive industry. One example of using the Li-ion in DC electrified system is Mass Rapid Transit Sukhumvit Line, Bangkok Thailand which applying the concept of wayside battery storage system at one of the selected traction substations. The product is using DC-DC converter B-Chop Hitachi product that will be charged to store the regenerative braking from electric train and discharged at the DC busbar to be used during adjacent train acceleration. The basic concept of the application is shown in Figure 2. 4.

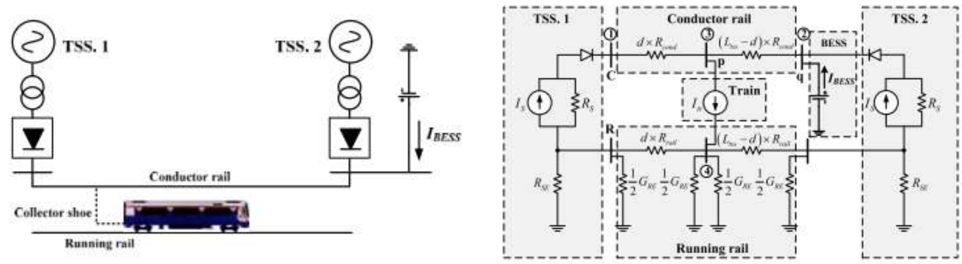

Figure 2. 4 Battery energy storage system circuit representation (Ratniyomchai and Kulworawanichpong, 2017)

Flywheel on the other hand, is an electrochemical ESS that stores and delivers kinetic energy when needed. The rotor will be spinning at high speed as the amount of energy stored depends on the inertia and speed of rotating mass. During the charging process, an electric machine acts as a motor and speed of rotor increasing the kinetic energy of the flywheel system. While during discharging process, the rotational speed of rotor decreases and releasing its stored energy through electric machine which acts as generator. The electric machine is coupled to a variable frequency power converter. In order to reduce friction losses, flywheel uses magnetic bearing and the rotor is contained in vacuum chamber to reduce air friction loss. Flywheel is having a high energy efficiency of 95%, high power density (5000W/kg) high energy density >50Wh/kg. It is also having less maintenance and low environmental concern. Based on simulation presented in 1, the ESS flywheel will achieve 31% energy saving in light rail train system.

Supercapacitor is an electrochemical capacitors consisting two porous electrodes immersed in an electrolyte solution. By applying voltage across two electrodes, the electrolyte solution is polarized. Consequently, two thin layers of capacitive storage are crated near the electrode. There is no chemical reaction, energy is stored electrostatically. The electrical characteristic of supercapacitor highly depends on selection of electrolyte and electrode materials Supercapacitors are having advantages of high energy efficiency, large charge and discharge current capacity, long lifecycle, high power density and low heating losses. While the disadvantages are maximum operating voltage is very low and it suffers from high leakage current thus, it cannot hold energy for a longer time. Recently, Li-ion capacitor have been developed with less leakage current and higher energy and power densities compared to batteries and standard super capacitor. Table 2. 2 below summarise the advantages and disadvantages of batteries technologies.

Table 2. 2 Batteries technologies comparison (Khodaparastan, Mohamed and Brandauer, 2019)

Type	Advantages	Disadvantages	Comment
Pbso4	• Low cost per Wh • Long history • Wide deployment • High reliability • High power density	• Low number of cycle • Low charging current • Limited service life • Environmental concern • Poor performance in low temperature	-Recently, extensive research has been carried out on replacing lead with other materials, such as carbon, to increase its power and energy density
Ni-MH	• Long service life • High energy • High charge/discharge current • High cycle durability • Low Environmental concern	• High cost per Wh • High maintenance • High self-discharge rate.	-The main disadvantage is high self-discharge rate, might be overcome using novel separators
Li-ion	• High energy density • Being small and light • Low maintenance • High number of cycle	• High cost per Wh • Require cell balance and control to avoid overcharge • Required special packing and protection circuit	- Currently, researchers investigate a combination of electrochemical and nanostructures that can improve the performance of Li-ion batteries
Na-s	• High energy density • High power density • Highly Energy efficiency	• High cost • Environmental concern • Need cooling unit	-Researchers are investigating new ways to reduce their high operating temperature.

(Liu, Xu and Tang, 2017) on the other hand had conducted research on installing the on-board super capacitor to the electric train. In the simulation study, 18.23% energy saving were recorded for a straight-line track without curve and gradient (Khodaparastan, Mohamed and Brandauer, 2019). However, the super capacitor size is depending on the amount of regenerative braking energy absorbed. In order to reduce the control circuit compartment usage and weight on the train, it is more practical to have a wayside super capacitor storage.

Super capacitor storage system varies from on-board commercialize design such as Sitras MES by Siemens, MITRAC by Bombardier and wayside super capacitor such as Capapost developed by Meiden which marketed by Envitech Energy. These systems were reviewed in (Khodaparastan *et al.*, 2019) journal.

2.2 Reversible Substation

Reversible substation is known as bi-directional or inverter substation that provide a path through an inverter for regenerative braking energy to feed back to the upstream AC. This energy is to be consumed by the domestic AC supply as well as the traction equipment. It can also be feed back to the main grid but an acceptable power quality level must be maintained to minimizing harmonic level. There are two (2) common ways to provide reverse path:

- DC/AC converter in combination of diode rectifier
- Reversible thyristor-controlled rectifier (RTRC)

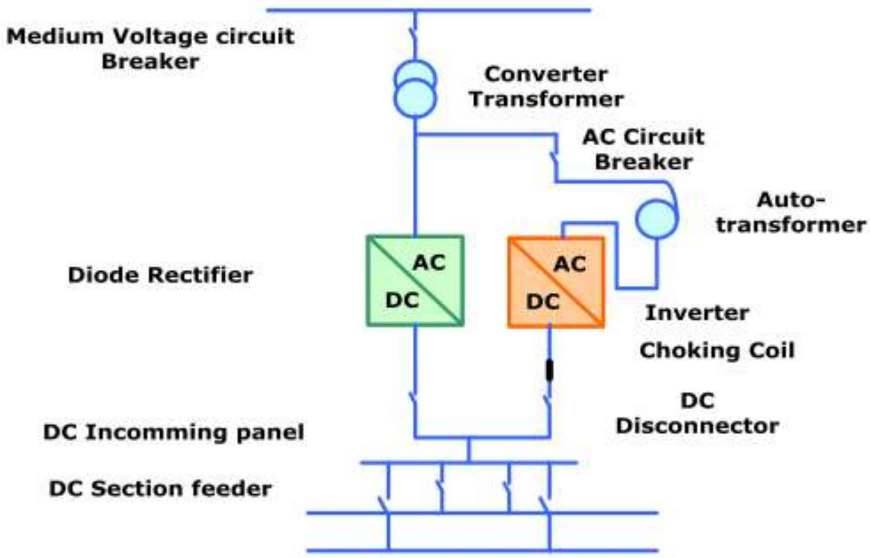

Figure 2. 5 HESOP reversible substation block diagram (Khodaparastan, Mohamed and Brandauer, 2019)

Figure 2. 1 describes that the DC/AC converter can either be PWM converter or thyristor line commutated inverter TCI. TCI is an anti-parallel thyristor-controlled rectifier (TCR) connected backward to provide a path for transferring energy from the DC side to the AC one. The technology been used in Alstom HESOP (harmonic and energy saving optimizer) The rated current in TCI is half of that forward TCR which reduced it cost. In order to use this technology (TCI) in existing circuit, an auto transformer and DC reactor should be used to increase AC voltage and limit circulating current between TCI and diode rectifier. To minimize AC harmonics, 12 pulse system has been proposed. Step up DC/DC converter need to be added between PWM converter and DC bus as in Figure 2. 6. DC filter to be added at the output of converter – to reduce harmonics level and avoid current circulation. Similar technology developed by INGEBER – an inverter and DC chopper (DC/DC converter) connected in series and connected with existing substations.

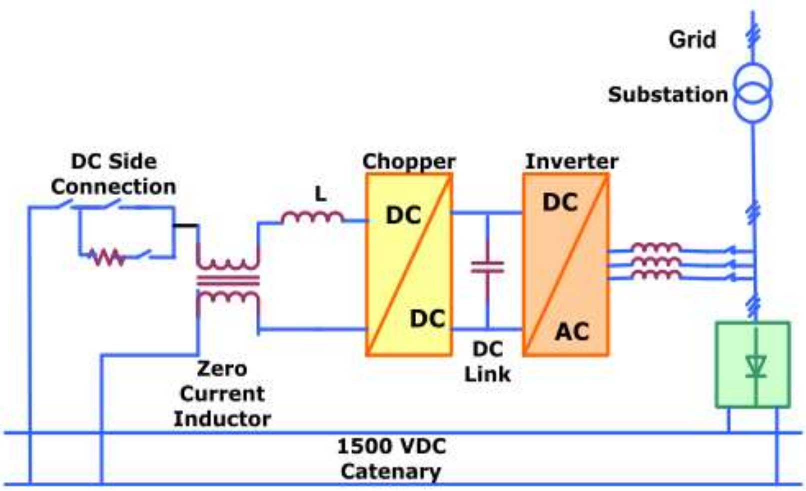

Figure 2. 6 Diode rectifier / PWM converter reversible substation block diagram (Khodaparastan, Mohamed and Brandauer, 2019)

The converter is consisting of two (2) TCR connected in parallel, providing a path for the energy in forward and reverse direction. One TCRs can be fired at a time, thus no current circulation between them and no DC inductor needed. The inverter act as active filter when RTCR working in the forward direction (AC/DC) while the rectifier only works in the traction mode. To switch between rectifier and inverter modes, a single controller provides pulses for both of them without any dead time. This method is the same concept as provided by ABB; Enviline TCR and Enviline ERS.

Enviline TCR is Traction Control Rectifier that uses four (4) quadrant converters to provide a reverse path for energy flow in the substation. This technology can be connected in parallel with an existing diode rectifier in a substation. Enviline ERS is a wayside energy recuperation system consisting of an IGBT based inverter that connected in parallel with existing substation rectifier to return surplus energy to the main grid. It can also be configured to work as a rectifier to boost rectification and provide reactive power support (Khodaparastan, Mohamed and Brandauer, 2019). Table 2. 3 summarise the differences of inverter technologies available in the market and a proven track record installed at various railway projects.

Table 2. 3 Inverter technologies comparison (Khodaparastan, Mohamed and Brandauer, 2019)

Company	Location	Voltage Level	Technology	Energy Saving	Comment
Alstom-HESOP	Paris Tramway Utrecht–Zwolle London	750	Thyristor rectifier bridge associated with an IGBT converter	7% of traction consumed energy	- Recuperated more than 99% of recoverable braking energy. - Reduced train heat dissipation, which led to reducing energy consumption used for ventilation. - No need for onboard braking resistors; therefore, train mass was reduced leading to less energy consumption during acceleration.
	Milan Metro	1500			
Simense-Sitras TCI	Oslo, Singapore	750	Inverter, B6 thyristor bridge, autotransformer in parallel with a diode rectifier	-	-Remote control is possible through a communication interface. - Reduced the number of braking resistors on the train. - In the 750V version, an autotransformer is integrated with the inverter, but in the 1500V version or high power 750V, an autotransformer is installed separately.
	Zugspitze, Germany	1500			
Ingeber-Ingteam	Bilbao -Spain	1500	Inverter in parallel with existing rectifier and transformer	13% of the substation annual energy consumption	- The current injected to the AC grid is in high quality (THD < 3%). - A DC/DC converter and an inverter are connected in series, and their combination is connected to an existing grid. - Reduced carbon emissions by 40%.
	Malaga -Spain	3000			
	Bielefeld-Germany	750			
	Metro Brussels.	750			

In the (Cascetta *et al.*, 2021) paper, Line 10B Metro de Madrid has introduced a 2MVA anti-parallel DC/AC converter to one of the existing 3MVA rectifier substation to create a bi-directional energy flow. The concept will minimize the modification needed on the existing traction power substation as shown in Figure 2. 7.

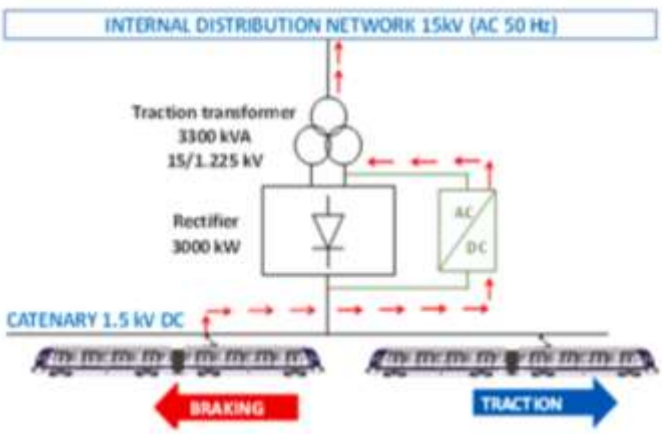

Figure 2. 7 RSS working principle (Cascetta *et al.*, 2021)

The electric train are design with on-board resistor unit. With the new reversible substation design, the control of surplus regenerative braking will prioritize to feedback to traction for nearby train usage before the excess energy is feedback to the internal AC grid. However, if the voltage is still having high value, on-board resistor unit will operate to reduce the traction voltage. The study was conducted in conventional substation mode, RSS OFF and reversible substation mode, RSS ON.

Table 2. 4 Dissipated Energy Analysis (Cascetta *et al.*, 2021)

Traffic Conditions	All	Train n. $\geq$ 9	Train n. $\leq$ 3
Average E_D [kWh] Conventional	202	183	427
Average E_D [kWh] Reversible	159	145	296
Relative Increment [%]	21.4	20.9	30.7

Based on the measurement result obtained in **Error! Reference source not found.**, RSS improves energy saving by allowing a reduction of 21.4% of energy dissipate through the resistor unit. In a long run, the RSS installation does align with the Europe Energy Policy aim to reduce 50% emission from the railway transport by 2030.

Another study in (Krim *et al.*, no date) done on Massena substation line C Paris suburban rail, the inverter is installed parallel to the 12 phase diode rectifier as in Figure 2. 8. The inverter will operate the most during low traffic condition whereby it will feedback maximum regenerative energy to the AC grid. In this case, the inverter will help in maintaining the DC supply voltage to the acceptable limit that electric train may withstand.

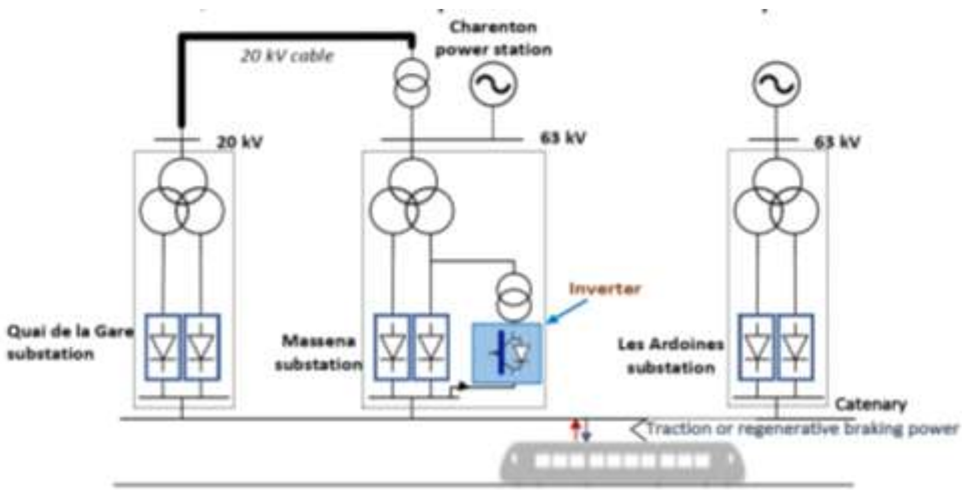

Figure 2. 8 Power supply substation schematic diagram (Krim *et al.*, no date)

The study is done to compare on the inverter control method in increasing energy efficiency of the system by maximizing recovered regenerative braking. There are two methods introduced which are DC voltage control loop and droop control method. The Result shown in Figure 2. 9 shown 32.89% optimized recovery rate by using droop control method while with DC voltage control loop shown significant recovery rate of 54.45% (Krim *et al.*, no date).

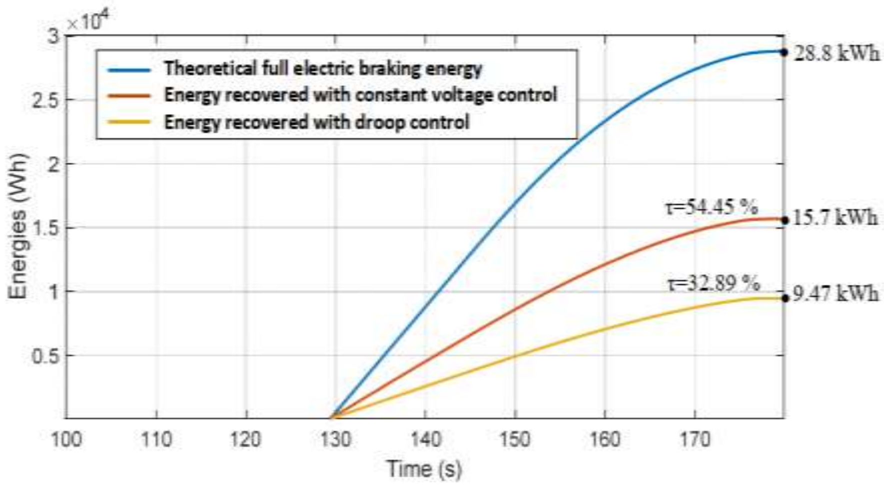

Figure 2. 9 Two-inverter control strategies recovery rate (Krim *et al.*, no date)

Table 2.5 below summarize the three (3) energy recuperative method that can be adopted in the railway industry to achieve higher energy efficiency. By applying the recuperation energy method, the system is able to reduce power consumption demand with the same number of operations. However, it depends on the system design and value engineering concept to determine the most suitable method based on train operation behavior.

Since MRT Kajang Line is not equipped with recuperative system, the entire traction power system can be considered to apply either inverter system or battery energy storage system as adopted in Mass Rapid Transit Sukhumvit Line, Bangkok (Ratniyomchai and Kulworawanichpong, 2017)

Table 2.5 Comparison between different recuperative techniques (Khodaparastan, Mohamed and Brandauer, 2019)

Application	Advantages	Disadvantages
Onboard ESS	-Provides possibility for catenary-free operation. -Reduces voltage drop. -Reduces third rail losses and increases efficiency.	-High cost due to placement of ESS on the vehicle. -High safety constraints due to onboard passengers. -Standstill vehicles for maintenance and repair.
Wayside ESS	-Mitigates voltage sag. -Can be used by all vehicles running on the line (within the same section). -Maintenance and repair do not impact train operation.	-Increases overhead line losses due to the absorption and release of energy over the traction line. -Analysis is needed to choose the right sizing and location.
Reversible Substation	-Provides possibility for selling electricity to the main grid. -Can be used by all vehicles running on the line. -Maintenance and repair do not impact train operation. -Lower safety constraints.	-No voltage stabilization. -Analysis is needed for choosing the right location.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In conjunction with Ministry of Transport commitment to achieve zero carbon emission by the year 2050, railway projects nowadays are using the electric train rolling stock instead of diesel-powered rolling stock. This initiative contributes to a better environment hence reduced the toxic fumes emission to the environment.

Although the initiative is better for environment, the railway operators are suffering with high electricity bills commitment with roughly 40% of the total operation expenditure. Railway system energy consumption is usually design with 80% energy consume by the electric train while another 20% is the domestic usage. In order to reduce the electricity billing, the operator must reduce the energy consumption in railway operation by one of the methods nowadays is to look into the energy recovery system.

Inverter system and batteries storage system are among the popular energy recovery system successfully adopted in most of the railway system in overseas. However, in Malaysia the technology is consider a new initiative implement at MRT Putrajaya Line and LRT 3 projects with both are adapting energy recovery inverter system.

Ampang Line LRT, Kelana Jaya Line LRT and MRT Kajang Line are using the AARU and resistor bank system to maintain the 3rd rail system voltage by transform the excess energy into heat energy to be released into the air. Compared to the traction system that adopting energy recuperative system, the excess energy will be feedback to the system and can be used for domestic supply as well as the traction. Thus, this will lower the energy consumption from the power supply provider such as Tenaga Nasional Berhad (TNB).

Since most of the power equipment will be undergone a retrofit process after approximately of 15 years in operation, it is a good opportunity to explore on the enhancement of traction power substation. Some of the traction power substation may be upgraded with either inverter system or energy storage system to recover the regenerative braking from electric train as has been done at Bangkok metro (Ratniyomchai and Kulworawanichpong, 2017).

3.2 Circuit Modelling

The circuit modelling will be constructed using an ETAP 1901 software based on the single line diagram from MRT Kajang Line project. The reference is not limited to the AC and DC simulation study project document as well as manufacturer catalogue on the parameters. The circuit and parameters used during the simulation will not be exactly the same as MRT Kajang Line but only a representation of DC railway power supply circuit to study the regenerative braking in electric train and the amount of energy recovered from the regenerative braking.

The basic principle of MRT Kajang Line railway power supply circuit is represented in Figure 3. 1 for better understanding.

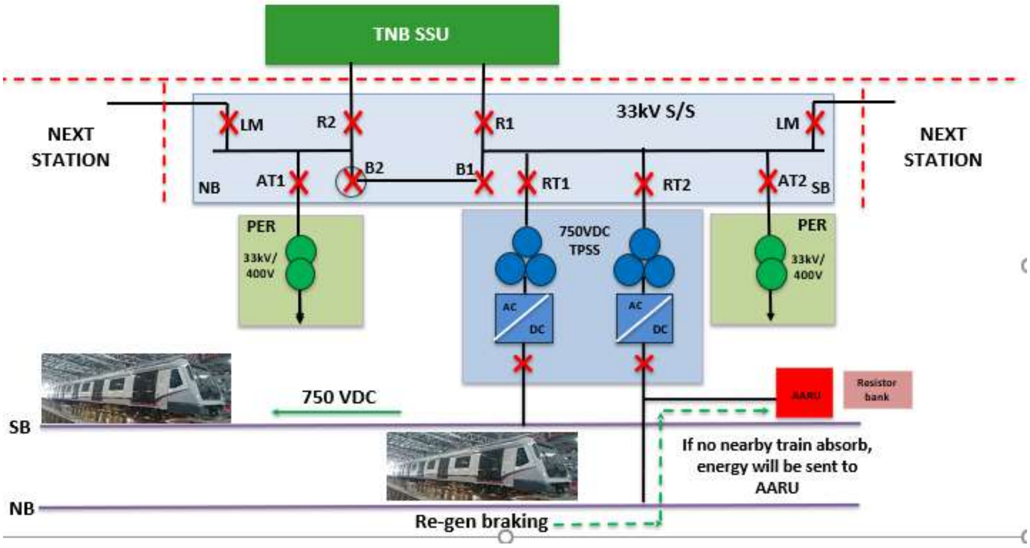

Figure 3. 1 Basic representation of DC railway power supply system

3.2.1 High Voltage Supply

The circuit will be having two separate incoming supply from power supply provider TNB SSU at 33kV voltage level. The supply will not be a parallel system as we required two separate supplies from the TNB. However, at consumer level there will be a bus section as a redundancy during the outage of one incoming supply from the SSU.

A single 33kV busbar switchgear with a bus section will be adapted similar to the MRT Kajang Line single line diagram in figure 11. Each busbar will be having two (2) auxiliary feeder, two (2) rectifier transformer feeder and two (2) loop main feeder to extend the 33kV power supply to the adjacent stations.

Auxiliary feeders will be connected to individually to each auxiliary transformers will the capability to cater all the domestic or station loads in case loss of single supply; n-1 redundancy. Therefore, each transformer is design to be loaded at maximum 50% of total capacity.

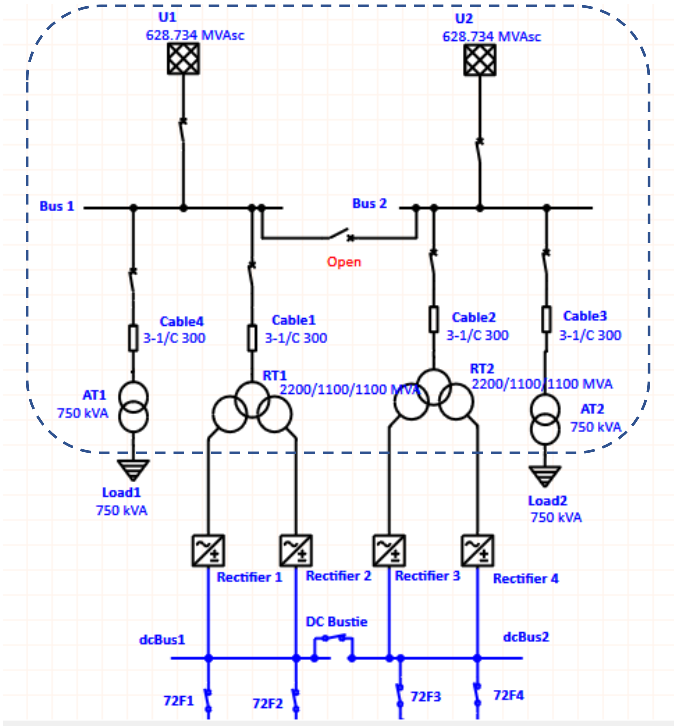

Figure 3. 2 Single line diagram AC power supply system

In the simulation software under OVL worksheet, Figure 3. 2 will be constructed with the following parameters of AC power system as tabulated in Table 3. 1. The parameters shall be checked thoroughly prior running the simulation and any errors shall be addressed accordingly.

Table 3. 1 AC power system equipment parameters

No.	Equipment	Parameter
1	Power Grid	Rated voltage: 33kV X/R: 10 Short circuit current: 11kA
2	33kV AC Switchgear	33kV
3	AC Bus Voltage	33kV
4	33kV AC Cable	3 x single core copper

		50Hz XLPE insulation Armour cable
5	Auxiliary Transformer	Step down transformer Dry-type transformer 750kVA; Dyn11 33kV/415V Dry AN
6	Rectifier Transformer	3-windings transformer 2200 / 1100 /1100 MVA 33kV/585V/585V Vent-Dry ONAN/ONAF
7	Static Load	350kW

3.2.2 DC Power Supply

The DC power supply feeding to the electric train will be at 750V DC which rectified from 33kV AC supply through the three windings rectifier transformer and a rectifier. There will be two (2) sets of rectifier and rectifier transformer connecting to the same busbar to create 24 pulses firing angle as shown in the Figure 3. 3 single line diagram. The parameters for DC equipment are tabulated in Table 3. 2.

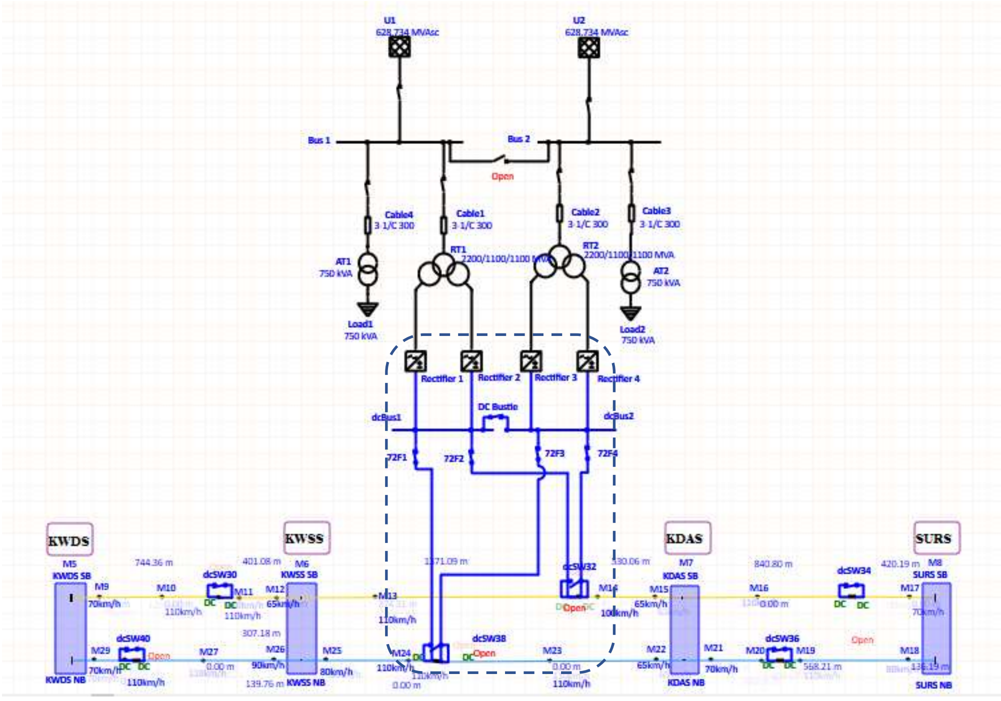

Figure 3. 3 Single line diagram DC power supply system

Table 3. 2 DC equipment parameters

No.	Equipment	Parameter
1	Rectifier	Rated voltage: 33kV X/R: 10 Short circuit current: 11kA
2	DC Switchgear	750V DC
3	DC Bus Voltage	750V DC

3.2.3 Track

Track construction is based on four numbers of stations which supplying from one 33kV TNB SSU power supply. Power rail sectioning is segregate by using isolators to separate the DC supply from different DC isolator feeders.

Total length of the track is approximately 4300m each track bound with bend radius and elevation are omitted in this simulation to reduce the complexity. However, there are numbers of civil speed limit placed along the track to represent the location of bend radius on the track area as indicate in the Appendix A.

The distance between stations is more less similar to MRT Kajang Line distance which tabulated in the Table 3. 3 and Table 3. 4 respectively.

Table 3. 3 Northbound track station distance information

From Station	To Station	Distance (m)
KWDS SB	KWSS SB	1150.44
KWSS SB	KDAS SB	1906.15
KDAS SB	SURS SB	1265.99

Table 3. 4 Northbound track station distance information

From Station	To Station	Distance (m)
SURS NB	KDAS NB	1256.44
KDAS NB	KWSS NB	1915.71
KWSS NB	KWDS NB	1141.77

3.2.4 Rolling Stock

In this simulation, we will be using a DC rolling stock since the track is design with a 3rd rail DC system. In the ETAP software, the specifications of the required DC rolling stock including the tractive effort and regenerative braking characteristic need to be filled in the library data for our simulation purposes. In this case, the DC rolling stock parameters used for this simulation are listed in Table 3. 5, Table 3. 6 and Table 3. 7 respectively.

Table 3. 5 Rolling stock parameters

Auxiliary	
Voltage	750V
Power	218kVA
Bogie	
Number of axles	8
Brakes	
Regenerative type	Yes
General	
Line voltage	0.75kV
Weight	230.6T
Length, Width, Height	89m, 3.1m, 3.7m
Continuous Rating	
Power	3500kW
Tractive Effort	235kN
Speed	110 km/h

Maximum Tractive Effort	235kN
Maximum speed	110 km/h
Efficiency	90
Resistance Coefficient	
A	0.0129322497
B	0.0001475495872
C	2.094242196E-07
Wheel Diameter	
New, Half, Full	0.85m, 0.81m,0.77m
Inverter	
Efficiency	90

Tractive effort and regenerative braking effort are based on assumption as table below:

Table 3. 6 Tractive effort information

Tractive Effort (kN)	Speed (km/h)	Tractive Effort (kN)	Speed (km/h)
248	0	124	56
248	1	121.82	57
248	2	119.72	58
248	3	117.69	59
248	4	115.73	60
248	5	113.84	61
248	6	112	62
248	7	110.22	63

248	8	108.5	64
248	9	106.83	65
248	10	105.21	66
248	11	103.64	67
248	12	102.12	68
248	13	100.64	69
248	14	99.2	70
248	15	97.8	71
248	16	96.44	72
248	17	95.12	73
248	18	93.84	74
248	19	92.59	75
248	20	91.37	76
248	21	90.18	77
248	22	89.03	78
248	23	87.9	79
248	24	86.8	80
248	25	84.67	81
248	26	82.62	82
248	27	80.64	83
248	28	78.73	84
239.45	29	76.89	85
231.47	30	75.11	86
224	31	73.39	87

217	32	71.74	88
210.42	33	70.13	89
204.24	34	68.58	90
198.4	35	67.08	91
192.89	36	65.63	92
187.78	37	64.23	93
182.74	38	62.87	94
178.05	39	61.55	95
173.6	40	60.28	96
169.37	41	59.04	97
165.33	42	57.84	98
161.49	43	56.68	99
157.82	44	55.55	100
154.31	45	54.46	101
150.96	46	53.39	102
147.74	47	52.36	103
144.67	48	51.36	104
141.71	49	50.39	105
138.88	50	49.44	106
136.16	51	48.52	107
133.54	52	47.63	108
131.02	53	46.76	109
128.59	54	45.91	110
126.25	55		

Figure 3. 4 is a graph of tractive effort data key-in with respect to the speed in Table 3. 6.

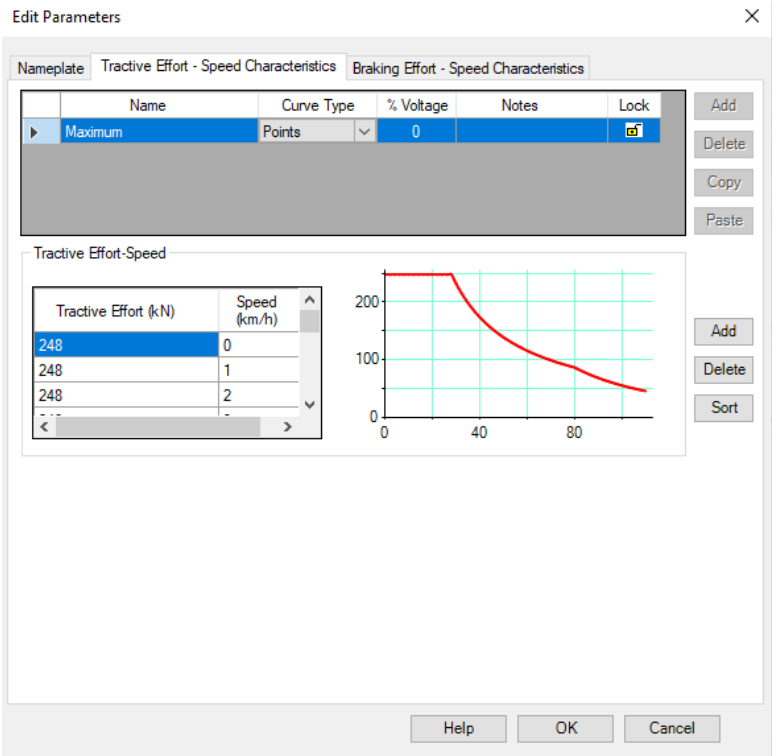

Figure 3. 4 Tractive effort characteristic

Table 3. 7 Regenerative braking effort information

Regenerative Braking Effort (kN)	Speed (km/h)	Regenerative Braking Effort (kN)	Speed (km/h)
60.75	4	182.24	58
121.49	5	182.24	59
182.24	6	182.24	60
182.24	7	176.31	61
182.24	8	170.67	62
182.24	9	165.3	63
182.24	10	160.17	64
182.24	11	155.28	65

182.24	12	150.61	66
182.24	13	146.15	67
182.24	14	141.88	68
182.24	15	137.8	69
182.24	16	133.89	70
182.24	17	130.15	71
182.24	18	126.56	72
182.24	19	123.11	73
182.24	20	119.81	74
182.24	21	116.63	75
182.24	22	113.58	76
182.24	23	110.65	77
182.24	24	107.83	78
182.24	25	105.12	79
182.24	26	102.51	80
182.24	27	99.99	81
182.24	28	97.57	82
182.24	29	95.23	83
182.24	30	92.98	84
182.24	31	90.8	85
182.24	32	88.71	86
182.24	33	86.68	87
182.24	34	84.72	88
182.24	35	82.83	89

182.24	36	81	90
182.24	37	79.23	91
182.24	38	77.51	92
182.24	39	75.85	93
182.24	40	74.25	94
182.24	41	72.69	95
182.24	42	71.19	96
182.24	43	69.73	97
182.24	44	68.31	98
182.24	45	66.94	99
182.24	46	65.61	100
182.24	47	64.31	101
182.24	48	63.06	102
182.24	49	61.84	103
182.24	50	60.66	104
182.24	51	59.51	105
182.24	52	58.39	106
182.24	53	57.3	107
182.24	54	56.25	108
182.24	55	55.22	109
182.24	56	54.22	110
182.24	57		

Figure 3. 5 is the graph of regenerative braking effort with respect to the speed data as in Table 3. 7.

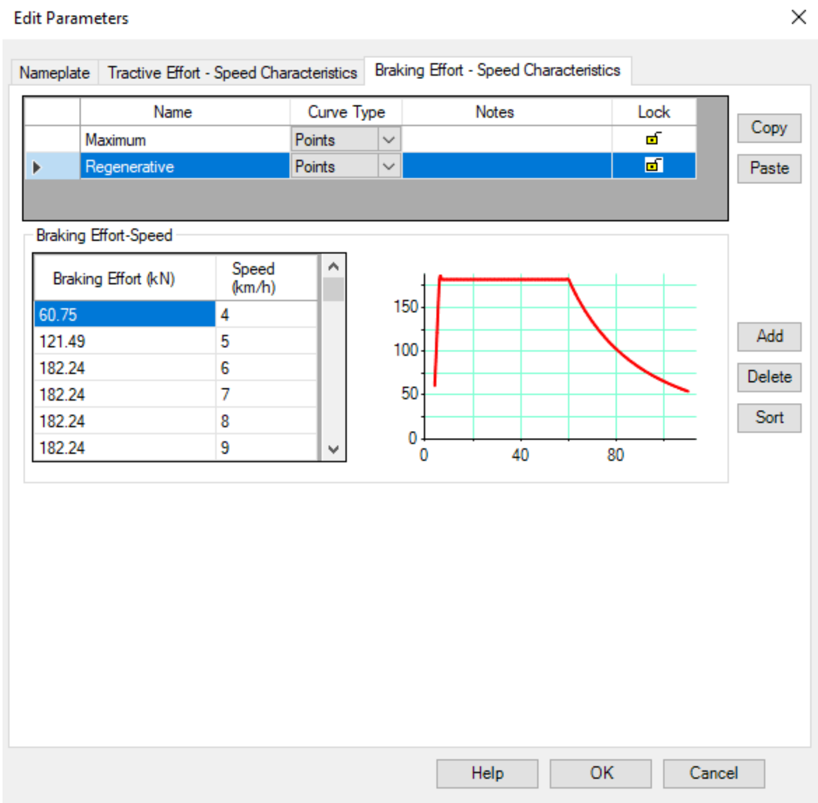

Figure 3. 5 Regenerative braking characteristic

CHAPTER 4

RESULT AND DISCUSSION

4.1 Non-Regenerative Braking Train

The first simulation was done by disabling the regenerative braking capability from the rolling stock in order to observe the result based on non-regenerative electric train. Non-regenerative braking means that the train is using mechanical braking system without relying on electrical braking. This phenomenon will affect the passenger comfort as well as increasing the wear and tear to the wheel. Nevertheless, we will study the non-regenerative braking train characteristic for more understanding.

4.1.1 Simulation Result

Figure 4.1 to Figure 4.6 represents the results of train voltage, current, speed, tractive effort, power and energy produced based on non-regenerative braking train. Based on Figure 4.2, the train consumes 2800A during train motoring and maintain around 220A during train stopping at station platform. The pattern of current is the same as train power consumption in Figure 4.5. Train consumes around 2300kW during motoring operation and constant 230kW during train stopping at platform for the auxiliary supplies.

Figure 4. 1 Non-regenerative train voltage

Figure 4. 2 Non-regenerative train current

Figure 4. 3 Non-regenerative train speed

Figure 4. 4 Non-regenerative train tractive effort

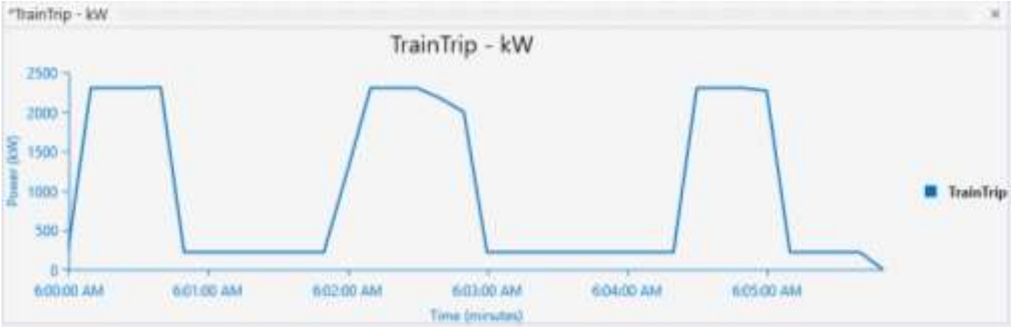

Figure 4. 5 Non-regenerative train power (kW)

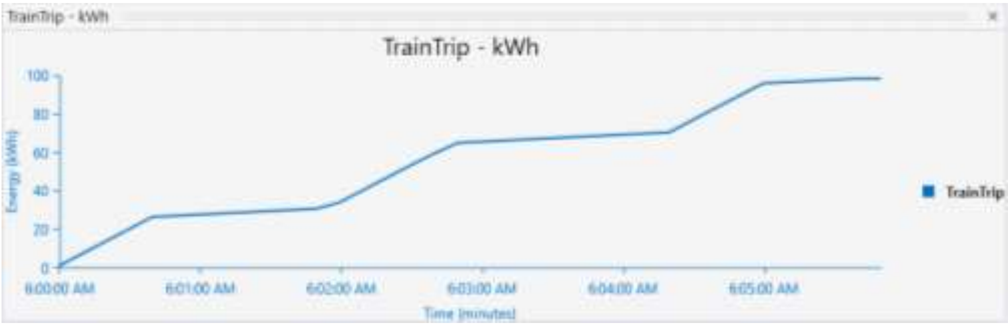

Figure 4. 6 Non-regenerative train energy (kWh)

4.1.2 Tractive Effort and Speed

Based on the tractive effort characteristic and braking characteristic specified for this electric train, the graph in Figure 4. 7 represent the train motoring or acceleration mode, cruising mode, coasting mode and braking mode. When train speed constantly increased, the tractive effort shown constant power before its responding to the decreasing in speed during braking. During train stopping at platform with 0km/h, the tractive effort is at a constant force.

Figure 4. 7 Non-regenerative train tractive effort vs speed

4.1.3 Voltage, Current and Speed

Based on Figure 4. 10, train will consume high amount of current during train acceleration and maintain during train cruising before it drops during deceleration. From the graph, the maximum operating current is approximately 2800A and the minimum current is around 200A. There is no negative current hence this is a non-regenerative braking train. As shown in Figure 4.8, the current and voltage is inversely proportionate during train operation. In this simulation, the operating voltage is between 830V to 900V as in Figure 4. 9.

Figure 4. 8 Non-regenerative train voltage vs current

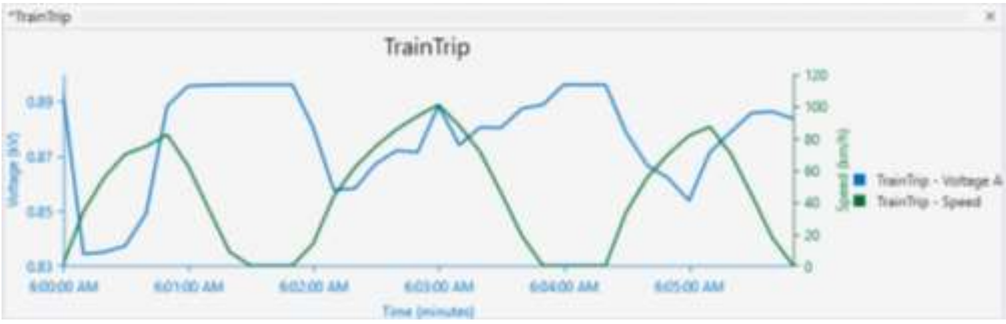

Figure 4. 9 Non-regenerative train voltage vs speed

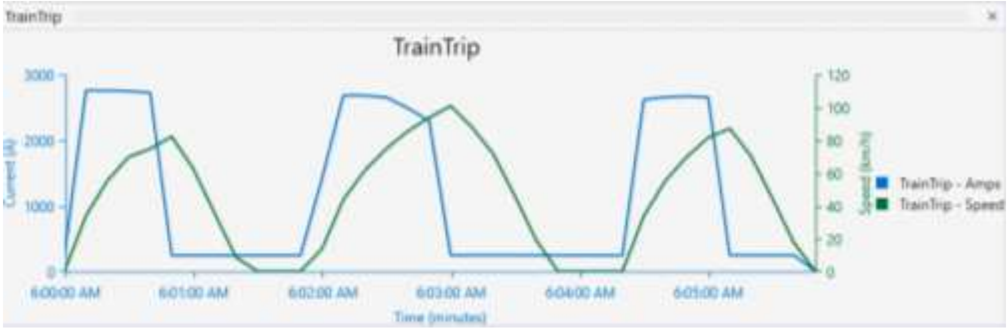

Figure 4. 10 Non-regenerative train current vs speed

4.1.4 Power, Energy and Speed

Based in Figure 4. 11, the movement from one station to another station showing an increase in train power up to 2300kW and 30kWh of energy in a single journey. After the train reaches and stopping at the next station platform, the train is using a constant 218kW and the energy is almost constant as well. The energy graph in Figure 4. 12 is well representing the train without any regenerative braking system since the energy is constant during train decreasing in speed before stopping at the next platform.

Figure 4. 11 Non-regenerative train power vs energy

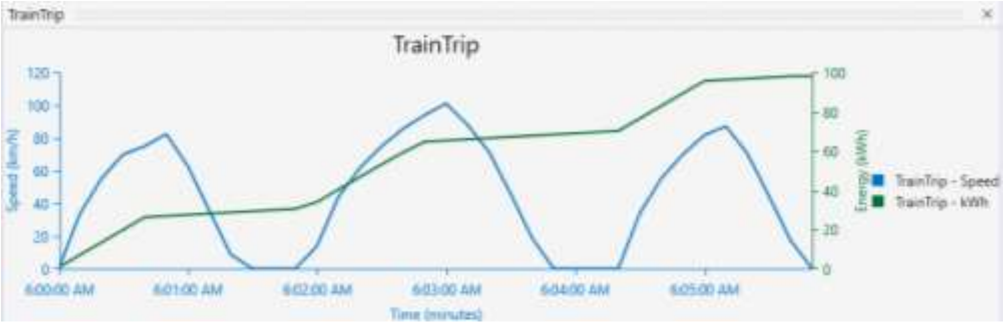

Figure 4. 12 Non-regenerative train energy vs speed

4.2 Regenerative Braking Train

The second simulation was done by enabling the regenerative braking capability of the rolling stock in order to observe the result based on regenerative braking from electric train. Regenerative braking means that the train will be utilising the electrical braking before fully stopped with mechanical braking. In this case, it minimises the mechanical braking effort hence reducing the wear and tear of the wheel. In addition, the braking management in regenerative train will ensure 3rd rail voltages are within the allowable tolerance and providing comfortable ride to the passengers.

4.2.1 Simulation Result

Figure 4.13 to Figure 4.18 represents the results of train voltage, current, speed, tractive effort, power and energy produced based on non-regenerative braking train. Based on Figure 4.14, the train consumes 2800A during train motoring and produced around 2000A to 2500A regenerative braking before maintaining around 220A during train complete stop at station platform. The pattern of current is the same as train power consumption in Figure 4.17. Train consumes around 2300kW during motoring operation and produced 2000kW to 2200kW instantaneous power before constant 230kW during train stopping at platform for the train auxiliary power consumption.

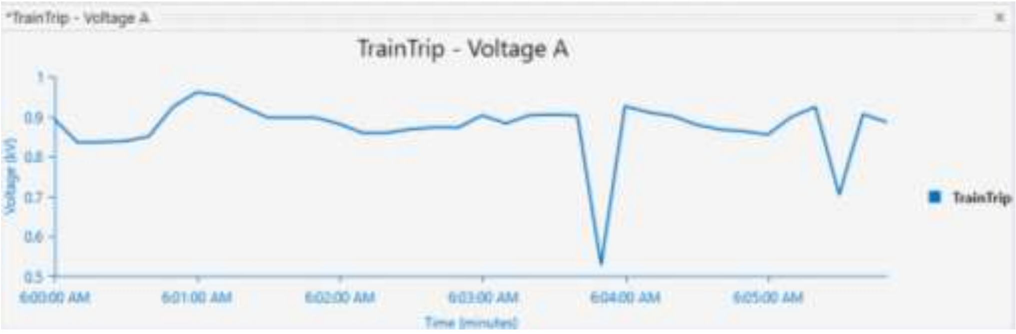

Figure 4. 13 Regenerative train voltage

Figure 4. 14 Regenerative train current

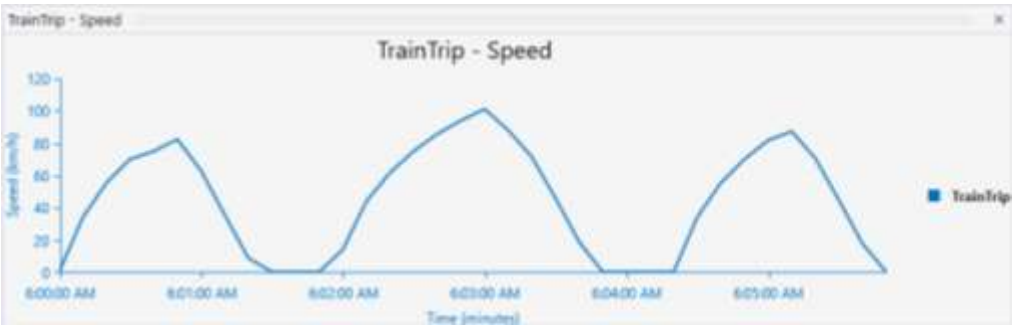

Figure 4. 15 Regenerative train speed

Figure 4. 16 Regenerative train tractive effort

Figure 4. 17 Regenerative train power

Figure 4. 18 Regenerative train energy

4.2.2 Tractive Effort and Speed

Either regenerative braking or non-regenerative braking, the behaviour of tractive effort and speed during train operation are the same. The tractive effort shown in Figure 4. 19 is responding to the electric train speed operation.

Figure 4. 19 Regenerative train tractive effort vs speed

4.2.3 Voltage, Current and Speed

Compared to non-regenerative train simulation result, Figure 4. 20 comprises of voltage and current recorded different behaviour due to regenerative braking effect. In this section, we can see the current is in a negative region which proves that there is a regenerative braking applied by the electric train. Based on the result, the regenerative braking current is approximately 2000A to 2500A.

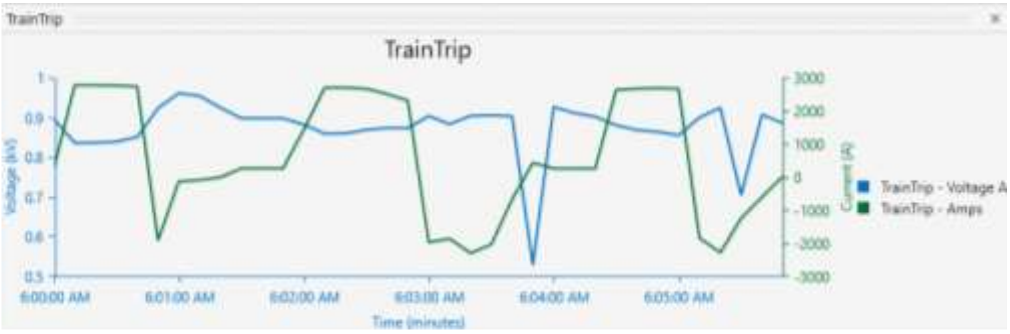

Figure 4. 20 Regenerative train voltage vs current

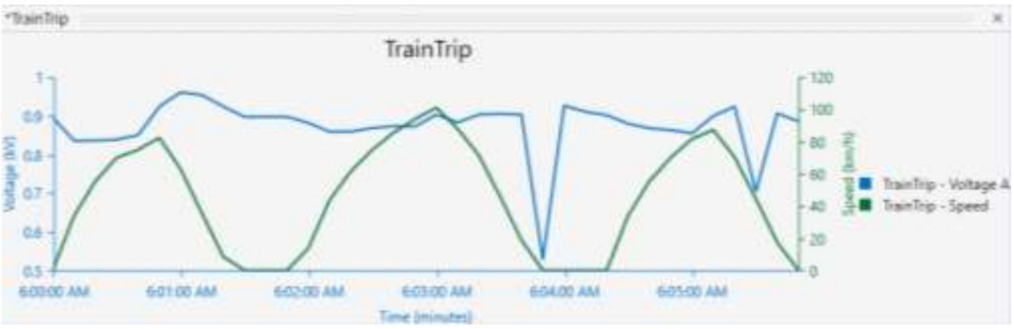

Figure 4. 21 Regenerative train voltage vs speed

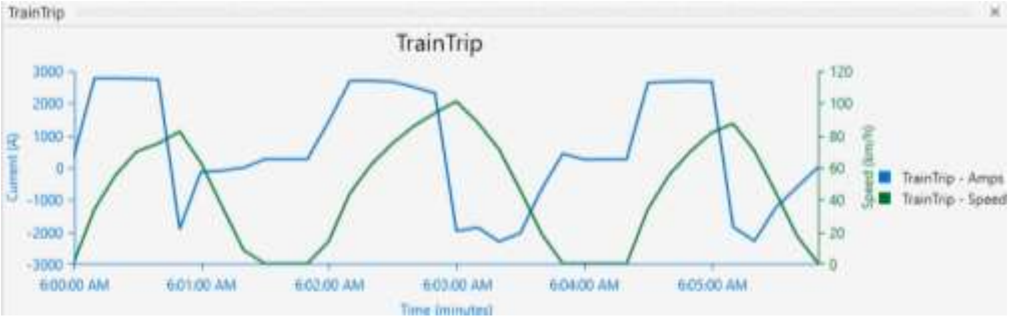

Figure 4. 22 Regenerative train current vs speed

4.2.4 Power, Energy and Speed

In this section, there is a significant difference in power and energy compared to non-regenerative braking simulation. As shown in Figure 4. 23, when the train is starting to braking, the regenerative braking energy is dropping from 60kWh to 35kWh resulting a total of 25kWh regenerative braking energy from the electric train. In addition, if we look at the instantaneous regenerative power in Figure 4. 24, the total instantaneous power during regenerative braking is around 2000kW which is quite huge and can be considered to be utilised for train acceleration instead of waste the surplus power to heat form.

With the amount of energy produced, these regenerative braking may be used back into the power supply system by using an inverter to convert from DC to AC supply or stored in a battery energy storage system at DC voltage supply level.

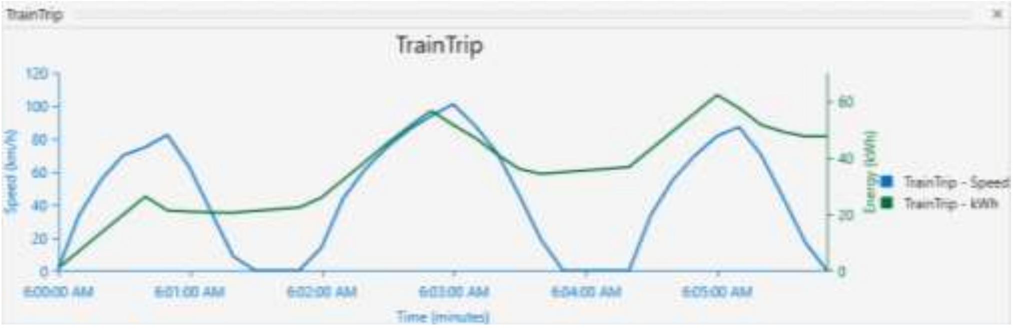

Figure 4. 23 Regenerative train energy vs speed

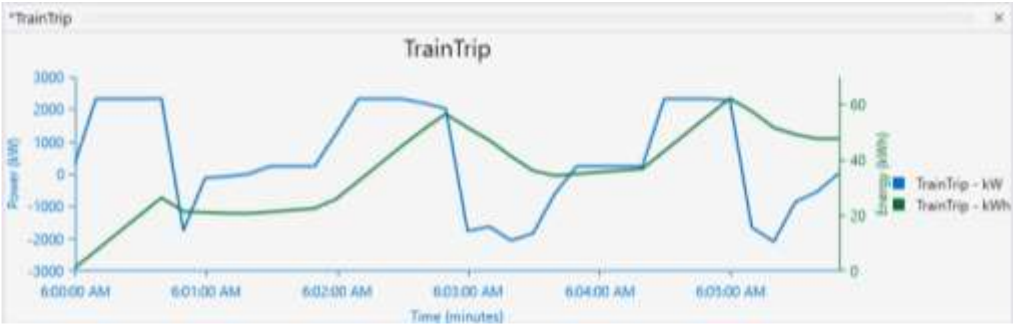

Figure 4. 24 Regenerative train power vs energy

4.3 Battery Energy Storage Design Requirement

An inverter system will need additional 33kV switchgear, converter system and a transformer. This configuration is needed to ensure DC regenerative energy will be absorb and feedback to 33 kV AC voltage level to be used by the entire AC system (Liu and Li, 2020). On the other hand, battery energy storage system will only require a DC-DC converter, controller and batteries pack. The energy will be re-used at a DC busbar level for adjacent train acceleration.

As discussed in (Li, Zhang and Liu, 2021) due to high in demand expected in year 2025 for the Li-ion batteries, therefore, the industries are expecting a great price reduction of battery energy storage system. At the moment, the total cost of whole one set of battery energy storage system is considered higher than an inverter system. For example, ELDC complete set is at RM 8 million per unit.

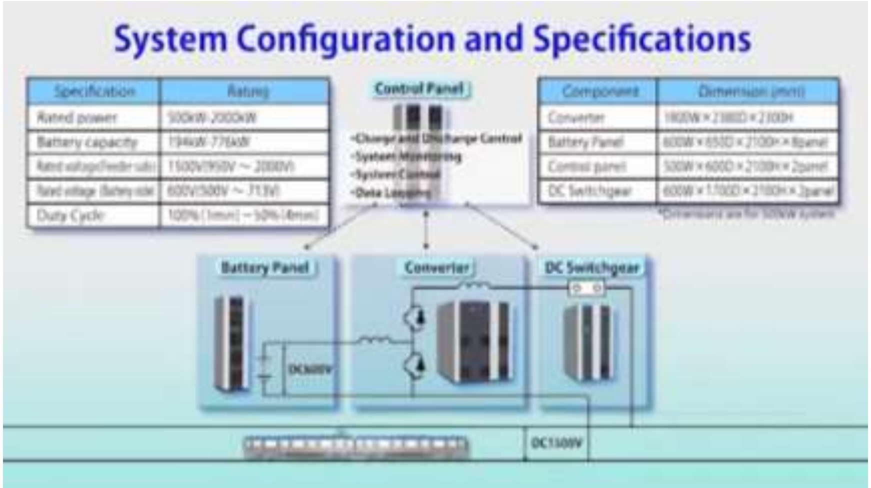

Figure 4. 25 DC traction energy storage system

Taking into consideration of the existing system and the available room size at traction substation to replace the resistive unit, battery energy storage system is a more suitable to adopt compared to an inverter system. This is because it does not require big space and will not disturb the AC supply system which potentially exposed to having harmonic issues. In addition, to have a better value engineering, the Return of Investment (ROI) of each selection need to be studied in details and calculated.

$$Battery\ Capacity = \frac{Train\ Regenerative\ Energy\ (kWh)}{Depth\ of\ Discharge} \quad (1)$$

Let say, depth of discharge (DOD) is at 80%; hence,

$$Battery\ Capacity = \frac{25\ kWh}{0.8} \quad (2)$$

$$Battery\ Capacity = 31.25\ kWh \quad (3)$$

Let say if we are using 12V Li-ion battery pack, the Ah will be

$$Battery\ capacity\ in\ Ah = \frac{31250}{12} = 2604.17\ Ah \quad (4)$$

Lithium ion batteries product by Toshiba SCiB is using lithium titanate oxide (LTO) as the anode material which has the advantage in collecting regenerative energy efficiently due to lower internal resistance (Nobuhiko, 2021). In addition, based on case study done by Toshiba in using the SCiB, it was also capable of correcting the voltage drop along the line issue as well as using the energy storage system during emergency power outage. Thus, we may consider to look into this product which described as having fast charging and longer life span at least for 10 years.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

Nowadays, most the recent electric trains are equipped with regenerative braking capabilities and various braking energy management techniques to ensure the following can be achieved:

- Reduce the railway operational cost due to lesser wheel wear and tear, as well as reduce the peak demand charges to the operator.
- Control the power rail voltages
- Provide comfort to the passengers by using less mechanical braking

With various recuperative energy system available in the market from resistive unit, inverter and battery energy storage system, it will provide wide selection to the project developer or asset management to look into the products that best suit their railway system operations. Not to mentioned, there will be a difference in a way the operator operates the railway system from what has been designed. Therefore, it is crucial for the asset management to look into the system energy efficiency to consider for future traction substation enhancement.

For example, MRT Kajang Line is currently adopting the resistive unit as the recuperative energy management which obviously wasting the surplus energy into heat instead of re-used the energy back to the power supply system. Therefore, by referring to this simulation and the available space at the traction substation, it is more practical to opt for battery energy storage system compared to an inverter system.

Based on Chapter 4 result and discussion, we can roughly estimate the capacity of the battery packs to be adopted in the system for future upgrading.

These are the conclusion based on the objectives defined in Chapter 1:

1. Based on the result in Chapter 4, the amount of approximate 2000A to 2500A instantaneous current and 25kWh of energy from the regenerative braking is considerable to adopt a better recuperative energy storage system to be re-used in the traction power supply system. Hence, reducing the amount of energy consumption from the TNB power supply provider.
2. Not to mentioned an inverter system is much cheaper than the battery energy storage system. However, due to there is a possibility of harmonics effects to the AC supply system and current traction substation space constraint, we may study on adopting battery energy storage system which can be used at DC power supply level for train acceleration and during an emergency blackout supply event.

5.2 Limitations and future works

In order to determine the right capacity sizing required for energy recuperative system, information of the electric train and track shall be available and the software should be able to run the simulation successfully. Nowadays, most of the consultant need to use two (2) different software to run AC and DC simulation study to achieve desired result.

Nonetheless, since the information based on MRT Kajang Line are limited thus the simulation is run only to the four (4) stations power supply ring with the track information is limited to the civil speed limit information only. Although the radius and elevation information were both exempted from the simulation construction, the civil speed limit will play a role to represent other track information since the electric trains are operating based on the speed limit sets at the signalling system.

Based on this research, the simulation can be enhanced by obtaining all the required information related to the electric train used at this MRT Kajang Line track as well as the full information of the track system in order to determine the actual regenerative braking from the current train operation.

Besides using a software simulation method, the researcher may also install oscilloscope recorder such as HIOKI at traction substation to get the real-time reading of the voltage and current during train regenerative braking. This method will be more accurate in determine the right regenerative braking management method suitable to the train operation as well as the sizing of the recuperative system.

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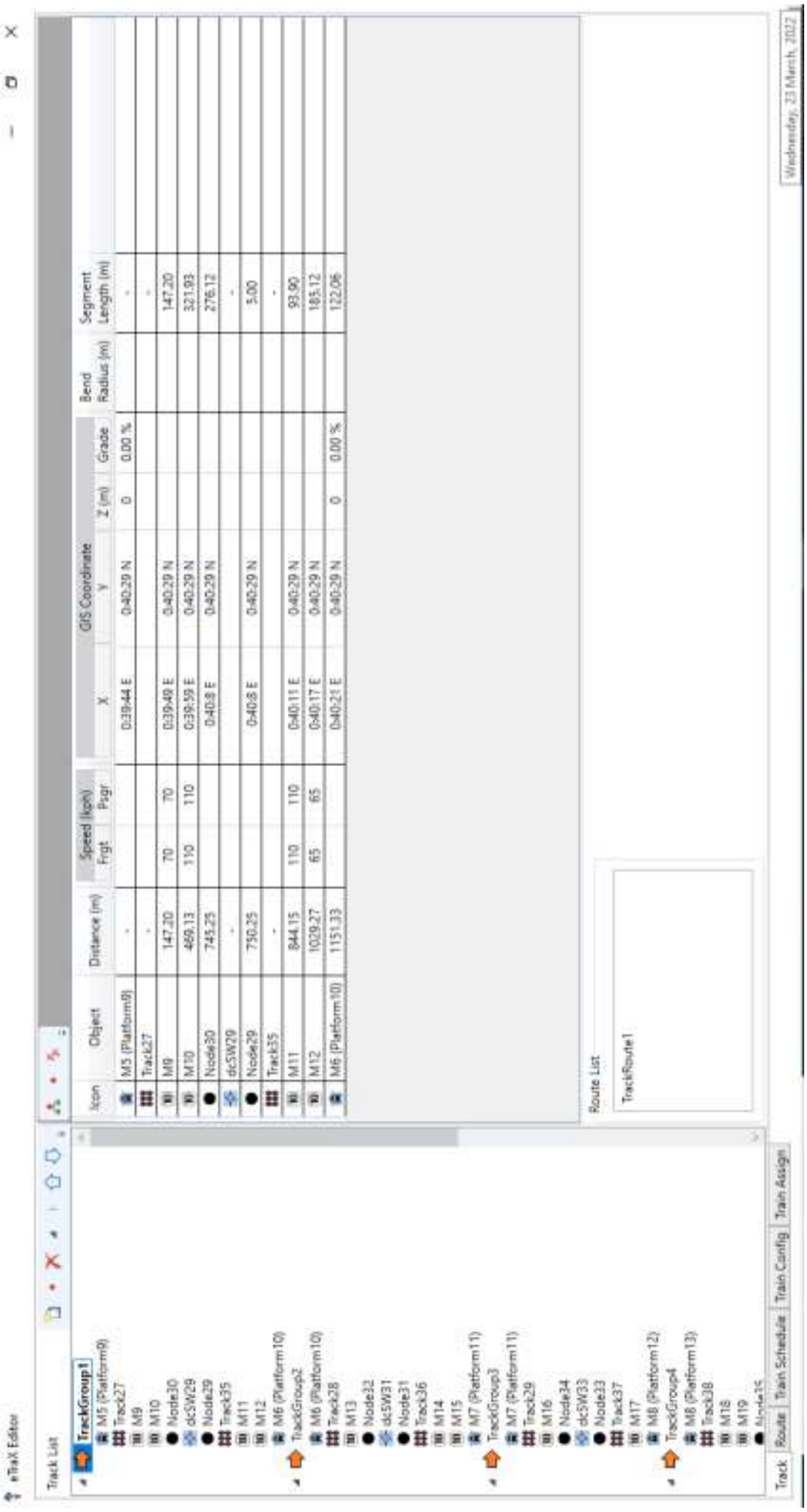
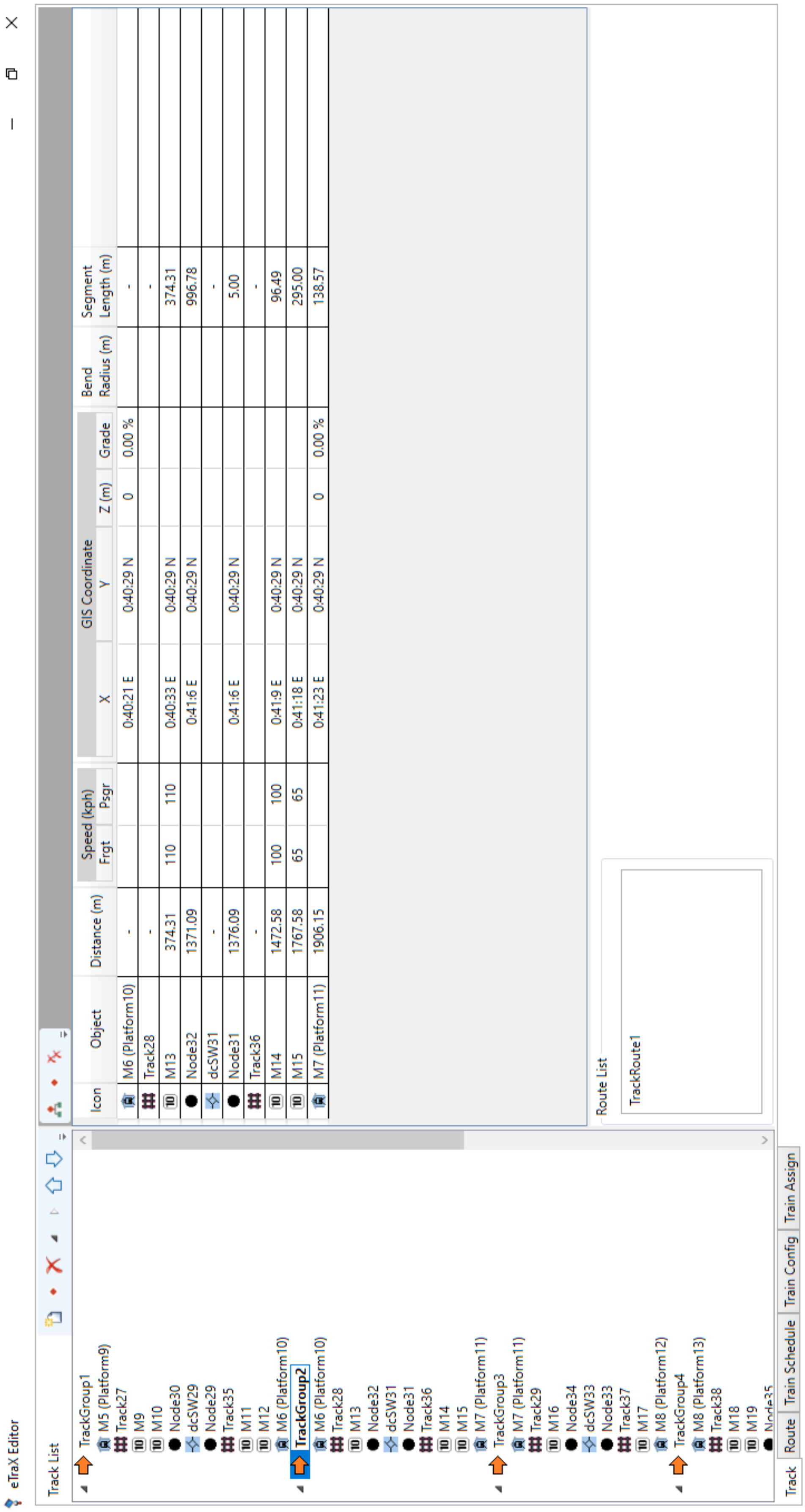
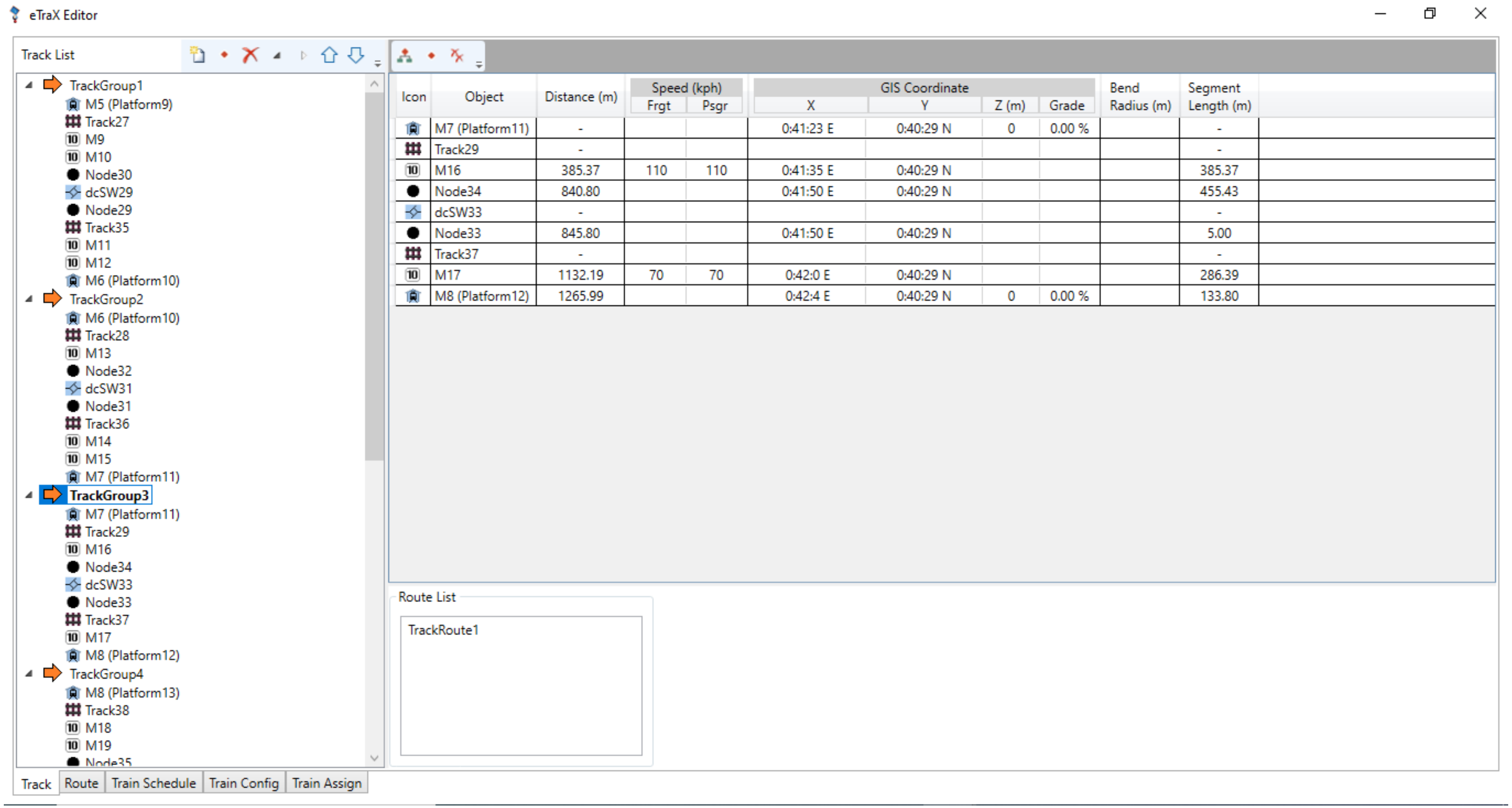
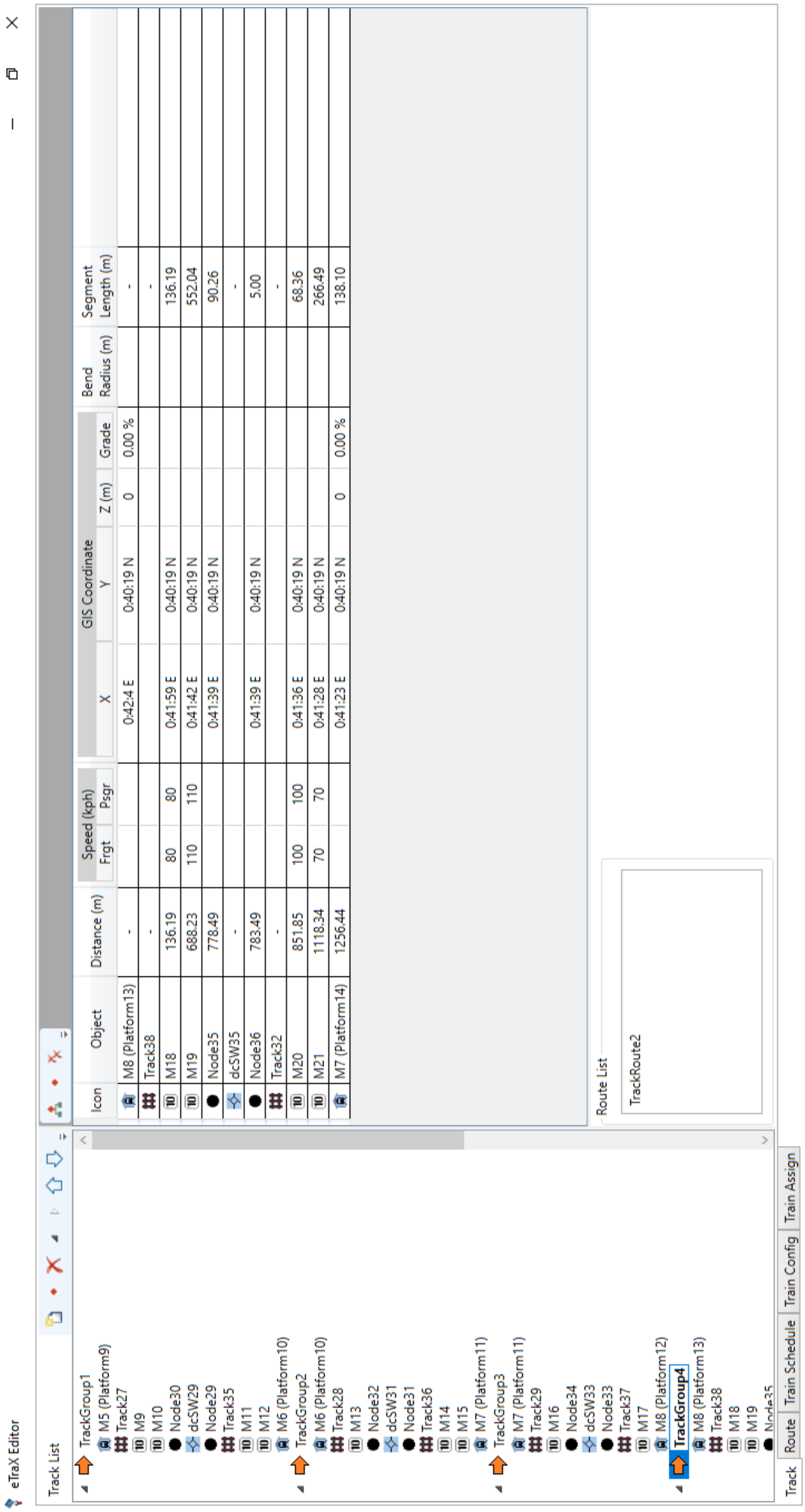
APPENDIX A

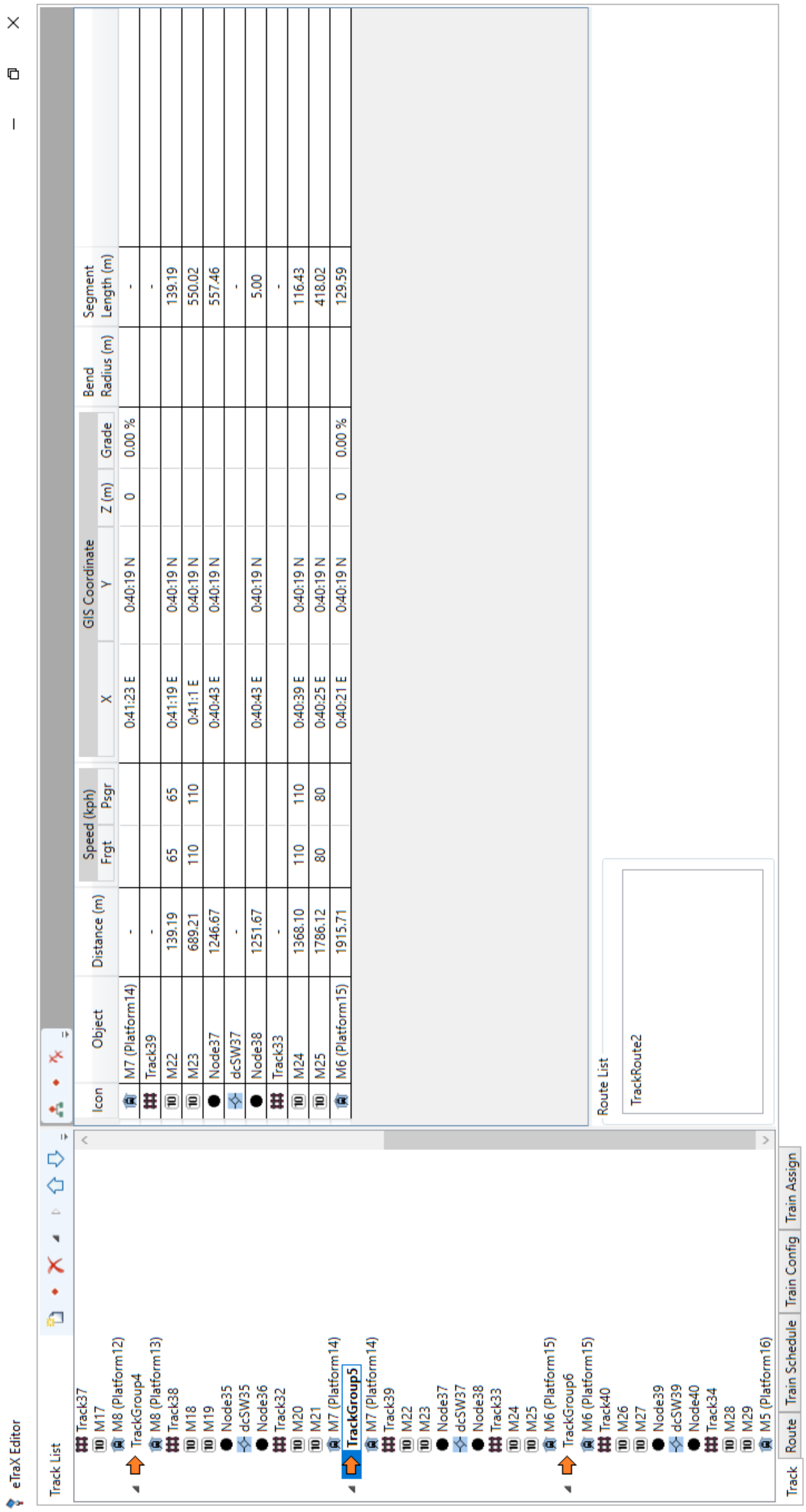
In this Appendix A, all the civil track details for six (6) track groups construction are listed in this section.

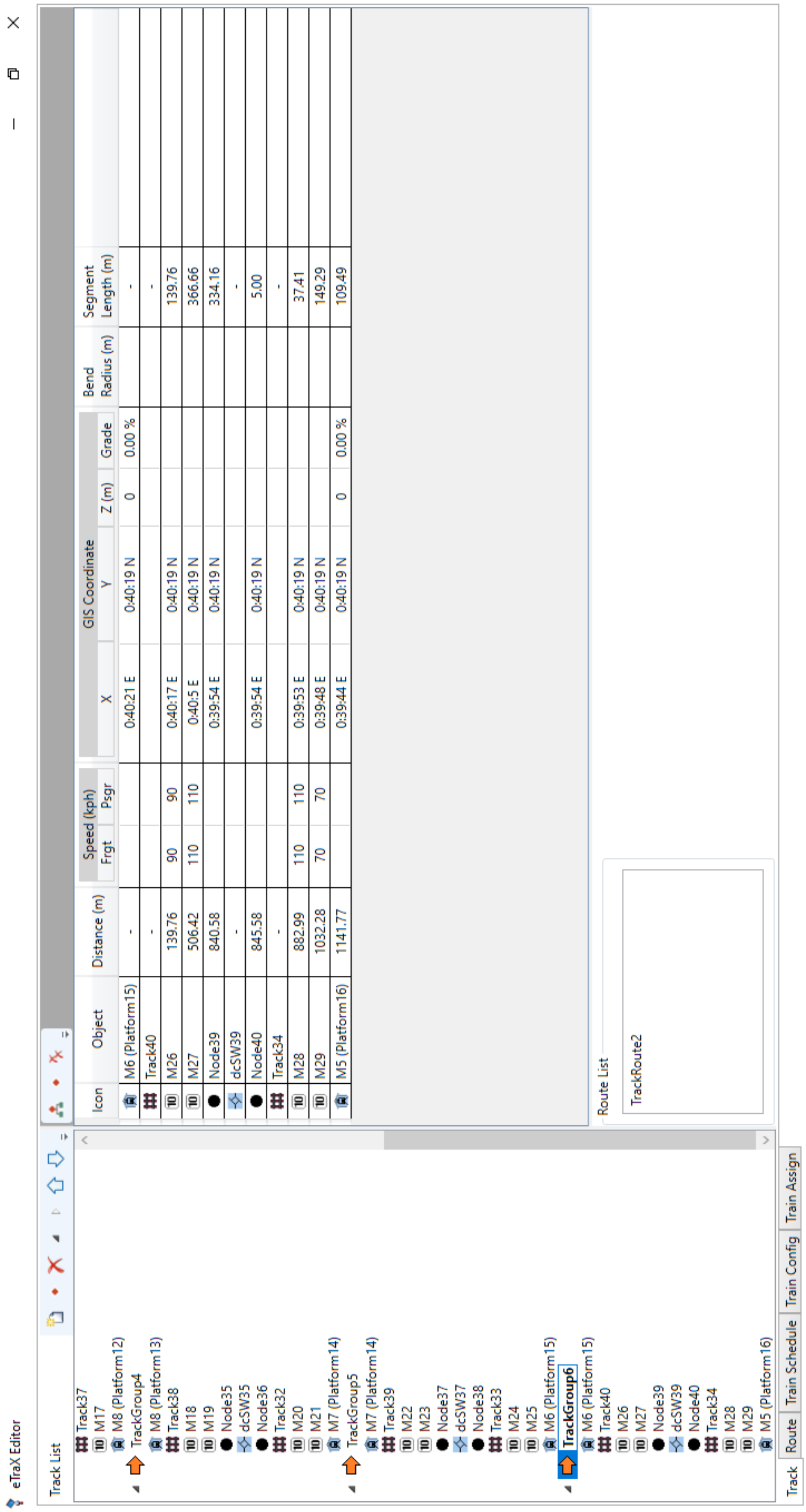



eTraX Editor
Track List
TrackGroup1
M5 (Platform9)
Track27
M9
M10
Node30
dcSW29
Node29
Track35
M11
M12
M6 (Platform10)
TrackGroup2
M6 (Platform10)
Track28
M13
Node32
dcSW31
Node31
Track36
M14
M15
M7 (Platform11)
TrackGroup3
M7 (Platform11)
Track29
M16
Node34
dcSW33
Node33
Track37
M17
M8 (Platform12)
TrackGroup4
M8 (Platform13)
Track38
M18
M19
Node35
Icon | Object | Distance (m) | Speed (kph) Frgt | Psgr | GIS Coordinate X | Y | Z (m) | Grade | Bend Radius (m) | Segment Length (m)
M6 (Platform10) | - | | | 0:40:21 E | 0:40:29 N | 0 | 0.00 % | | -
Track28 | - | | | | | | | | -
M13 | 374.31 | 110 | 110 | 0:40:33 E | 0:40:29 N | | | | 374.31
Node32 | 1371.09 | | | 0:41:6 E | 0:40:29 N | | | | 996.78
dcSW31 | - | | | | | | | | -
Node31 | 1376.09 | | | 0:41:6 E | 0:40:29 N | | | | 5.00
Track36 | - | | | | | | | | -
M14 | 1472.58 | 100 | 100 | 0:41:9 E | 0:40:29 N | | | | 96.49
M15 | 1767.58 | 65 | 65 | 0:41:18 E | 0:40:29 N | | | | 295.00
M7 (Platform11) | 1906.15 | | | 0:41:23 E | 0:40:29 N | 0 | 0.00 % | | 138.57
Route List
TrackRoute1
Track
Route
Train Schedule
Train Config
Train Assign


eTraX Editor
Track List
TrackGroup1
M5 (Platform9)
Track27
M9
M10
Node30
dcSW29
Node29
Track35
M11
M12
M6 (Platform10)
TrackGroup2
M6 (Platform10)
Track28
M13
Node32
dcSW31
Node31
Track36
M14
M15
M7 (Platform11)
TrackGroup3
M7 (Platform11)
Track29
M16
Node34
dcSW33
Node33
Track37
M17
M8 (Platform12)
TrackGroup4
M8 (Platform13)
Track38
M18
M19
Node35
Track
Route
Train Schedule
Train Config
Train Assign
Icon
Object
Distance (m)
Speed (kph)
Frgt
Psgr
GIS Coordinate
X
Y
Z (m)
Grade
Bend Radius (m)
Segment Length (m)
M7 (Platform11) - 0:41:23 E 0:40:29 N 0 0.00 % -
Track29 - -
M16 385.37 110 110 0:41:35 E 0:40:29 N 385.37
Node34 840.80 0:41:50 E 0:40:29 N 455.43
dcSW33 - -
Node33 845.80 0:41:50 E 0:40:29 N 5.00
Track37 - -
M17 1132.19 70 70 0:42:0 E 0:40:29 N 286.39
M8 (Platform12) 1265.99 0:42:4 E 0:40:29 N 0 0.00 % 133.80
Route List
TrackRoute1


eTraX Editor
Track List
TrackGroup1
M5 (Platform9)
Track27
M9
M10
Node30
dcSW29
Node29
Track35
M11
M12
M6 (Platform10)
TrackGroup2
M6 (Platform10)
Track28
M13
Node32
dcSW31
Node31
Track36
M14
M15
M7 (Platform11)
TrackGroup3
M7 (Platform11)
Track29
M16
Node34
dcSW33
Node33
Track37
M17
M8 (Platform12)
TrackGroup4
M8 (Platform13)
Track38
M18
M19
Node35
Track
Route
Train Schedule
Train Config
Train Assign
Icon
Object
Distance (m)
Speed (kph)
Frgt
Psgr
GIS Coordinate
X
Y
Z (m)
Grade
Bend Radius (m)
Segment Length (m)
M8 (Platform13) - 0:42:4 E 0:40:19 N 0 0.00 % -
Track38 - -
M18 136.19 80 80 0:41:59 E 0:40:19 N 136.19
M19 688.23 110 110 0:41:42 E 0:40:19 N 552.04
Node35 778.49 0:41:39 E 0:40:19 N 90.26
dcSW35 - -
Node36 783.49 0:41:39 E 0:40:19 N 5.00
Track32 - -
M20 851.85 100 100 0:41:36 E 0:40:19 N 68.36
M21 1118.34 70 70 0:41:28 E 0:40:19 N 266.49
M7 (Platform14) 1256.44 0:41:23 E 0:40:19 N 0 0.00 % 138.10
Route List
TrackRoute2


eTraX Editor
Track List
Track37
M17
M8 (Platform12)
TrackGroup4
M8 (Platform13)
Track38
M18
M19
Node35
dcSW35
Node36
Track32
M20
M21
M7 (Platform14)
TrackGroup5
M7 (Platform14)
Track39
M22
M23
Node37
dcSW37
Node38
Track33
M24
M25
M6 (Platform15)
TrackGroup6
M6 (Platform15)
Track40
M26
M27
Node39
dcSW39
Node40
Track34
M28
M29
M5 (Platform16)
Track
Route
Train Schedule
Train Config
Train Assign
Icon
Object
Distance (m)
Speed (kph)
Frgt
Psgr
GIS Coordinate
X
Y
Z (m)
Grade
Bend Radius (m)
Segment Length (m)
M7 (Platform14) - 0:41:23 E 0:40:19 N 0 0.00 % -
Track39 - -
M22 139.19 65 65 0:41:19 E 0:40:19 N 139.19
M23 689.21 110 110 0:41:1 E 0:40:19 N 550.02
Node37 1246.67 0:40:43 E 0:40:19 N 557.46
dcSW37 - -
Node38 1251.67 0:40:43 E 0:40:19 N 5.00
Track33 - -
M24 1368.10 110 110 0:40:39 E 0:40:19 N 116.43
M25 1786.12 80 80 0:40:25 E 0:40:19 N 418.02
M6 (Platform15) 1915.71 0:40:21 E 0:40:19 N 0 0.00 % 129.59
Route List
TrackRoute2


eTraX Editor
Track List
Track37
M17
M8 (Platform12)
TrackGroup4
M8 (Platform13)
Track38
M18
M19
Node35
dcSW35
Node36
Track32
M20
M21
M7 (Platform14)
TrackGroup5
M7 (Platform14)
Track39
M22
M23
Node37
dcSW37
Node38
Track33
M24
M25
M6 (Platform15)
TrackGroup6
M6 (Platform15)
Track40
M26
M27
Node39
dcSW39
Node40
Track34
M28
M29
M5 (Platform16)
Icon
Object
Distance (m)
Speed (kph)
Frgt
Psgr
GIS Coordinate
X
Y
Z (m)
Grade
Bend Radius (m)
Segment Length (m)
M6 (Platform15) - 0:40:21 E 0:40:19 N 0 0.00 % -
Track40 - -
M26 139.76 90 90 0:40:17 E 0:40:19 N 139.76
M27 506.42 110 110 0:40:5 E 0:40:19 N 366.66
Node39 840.58 0:39:54 E 0:40:19 N 334.16
dcSW39 - -
Node40 845.58 0:39:54 E 0:40:19 N 5.00
Track34 - -
M28 882.99 110 110 0:39:53 E 0:40:19 N 37.41
M29 1032.28 70 70 0:39:48 E 0:40:19 N 149.29
M5 (Platform16) 1141.77 0:39:44 E 0:40:19 N 0 0.00 % 109.49
Route List
TrackRoute2
Track
Route
Train Schedule
Train Config
Train Assign

APPENDIX B

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