Modeling and Simulation of Traction Power Supply System
In the case of “Sebeta Substation”

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This is to certify that the thesis prepared by Molalegn Sisay, entitled: Modeling and Simulation of Traction Power Supply System, In the case of "Sebeta Substation" and submitted in partial fulfillment of the requirements for the degree of Master of Sciences (Electrical and Computer Engineering) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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DECLARATION

I, the undersigned, declare that this thesis is my original work, and has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged in their respective points.

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This thesis has been submitted with my approval as a university advisor.

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Abstract

Traction power supply system is an electrical power network used to receive power from three phase power transmission system and supply power for the train driving on the single-phase AC power supply system. It is composed of the traction substation, traction network, partition substation, switch substation and other components.

In a railway traction power supply system, voltage variations, dynamic load characteristics and other types of supply changes, can influence the performance and movements of trains, the load in the electrical circuit are the trains/locomotives which are moving and demanding different levels of power according to their dynamic characteristics, operational mode and their speeds. Due to load variations, the voltage drop in the feeding circuit differs substantially depending up on the train position, train current, number of train in the same power feeding section, track impendence etc. Power transfer problems have occurred frequently within large variations of loads. These issues are important in traction power supply system to ensure normal operation of the electric locomotives.

Therefore, this thesis models and analyses the various force acting on the train using Davis equation for the train resistance regression coefficient for both freight and passenger locomotives. To minimize long calculation of the gradient force determination, this thesis considers a technique called equivalent gradient approximation.

Sebeta to Indode traction power supply system and its general parameter such as catenary or the feeding line model, substation model, transmission line model and the load model of the system is modeled in this thesis,

- ✓ Overall specific energy consumption, total running time and power consumption of passenger and freight train from Sebeta to Indode substation is determined.
- ✓ The power flow of the modeled system investigated.
- ✓ Substation voltage drop, catenary voltage drop, power consumption and power loss in the Sebeta substation and also their fault location is investigated. Generally, it is limited to modeling and simulation of Sebeta to Indode traction Substation.

The modeling and simulation of AC traction power supply system, power flow and short circuit fault analysis from Sebeta to Indode substation is done using DIgSILENT/*PowerFactory* software. This thesis also verify the installed transformer capacity of 16 MVA at Sebeta substation is capable with the calculated capacity of 7.098MVA.

Two cases are considered in this thesis work (for power flow solution) case one considers only two passenger trains occupied in the section with calculated power consumption of 3.22 MW at load side, from the load flow result the voltage drop is within the standard. In case two, one passenger train and one freight train are considered, load flow result shows that the voltage drop is between the standard at normal condition (at no fault condition). When fault occurred at Sebeta substation the train get power from Lebu section post through interrupter switch/load breaker. In this case the length becomes increased to supply power to the load, then the voltage drop becomes high, to minimize this voltage drop a compensator (shunt capacitor) at load voltage side with a 3.41MVAr is designed. The voltage drop for buses 8, 9 and 10 is improved from 2.63, 2.61 and 2.69kV to 2.1, 2.07 and 2.15kV respectively. After compensation the voltage at buses 6, 8, 9, 10 and 11 are improved from 0.917, 0.904, 0.905, 0.902 and 0.969 p.u to 0.936, 0.924, 0.925, 0.922 and 0.989 p.u, respectively. Also the total power loss for the modeled system is decreased from 0.6MW to 0.56 MW. Therefore, based on the result of this thesis work, it is recommended that the Ethiopian Railway Corporation has to consider compensator at Sebeta substation to enhance overall system power transfer capability, improving the network voltage and reduce voltage drop across the line in the system.

Furthermore, a single line to ground and short circuit fault analysis for the modeled system is investigated. From the transient simulation result at bus 5, the maximum peak short circuit current for single line to ground fault is 2.747kA and for two phase short circuit fault current is 6.973kA. Therefore, this thesis deduce that the worst type of fault is the short circuit fault in the overhead contact system of the trains.

Keywords: AC Electrified railway, Modeling, Traction power supply system, Power flow, Dynamic characteristics, Short circuit fault, DIgSILENT/*PowerFactory* software.

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Finally, I would like to use this chance to thank my family and my friends, specially my friend Samson Shewa for his unbounded love and support. Last but not certainly least I thank him from the bottom of my heart for all his deeds.

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List of Abbreviations and Symbols

a	Acceleration in meter-per-second-square
a	Substation’s transformer ratio
A	Cross sectional area of the conductor
AC	Alternating current
AT	Auto transformer
B_e	Braking effort
BT	Boost transformer
C	Overhead Catenary Contact Wire
CREC	China railway engineering corporation
DC	Direct current
D	Distance
E_t	Voltage source of the train model
ERC	Ethiopian Railway Corporation
E	Total energy consumption
f	Operating frequency, normally 50 Hz
F	Feeder wire
FS	Feeder Substation
$F_{Rolling}$	Rolling resistance
Far	Aerodynamic resistance
FR	Running Resistance
Fc	Curve Resistance
Fg	Gradient Resistance
F_t	Tractive Effort
g	Acceleration due to gravity (9.81 m/s^2)
HV	High voltage
Hz	Hertz
Hard seat	Types of seats in passenger coaches these types of seats are cheapest and smallest
I_C, V_C	Current and voltage of the overhead catenary contact wire

IF, VF	Current and voltage of the feeder wire
IR, VR	Current and voltage of the rails
I	Current (A)
J	Joule
Km/hr	Kilometer per hour
Kg	Kilo gram
kV	Kilo Volt
Km	Kilo meter
L_t	Locomotive length
L	Inductor (H)
l	Length (mm)
LV	Low voltage
MVA	Mega Volt Ampere
Mps	Meter per second
MW	Mega Watt
Mfrgt	Freight load
Mpsg	Passenger mass
MVA	Mega Volt-Ampere
p.u.	Per-unit
pf	Power Factor
R	Radius of curvature
R	Resistance (ohm)
R	Rail (Return conductor)
R'	Resistance per unit length ($^{\Omega}/_{Km}$)
S_K	Power system primary side
S_T	Traction transformer capacity
T	Time
T	Track (rail)
TE	Tractive Effort (N)

TL	Transmission line
TSS	Traction substation
Train	locomotive with its wagons or coaches
Train sets	a set of railway wagons often with a locomotive coupled together
U_k	Short circuit voltage
V	Speed
V	Voltage (V)
Vgrid	Nominal voltage of the utility supply grid
VS	Thevenin voltage of the substation
VSS	Substation terminal voltage
χ	Inductance (reactance) (ohm/m)
Z	Impedance
Z_O	Characteristic impedance (Ohm/m)
Z_{grid}	Short-circuit impedance of the utility supply grid
α	Vertical gradient angle
η	Mechanical Efficiency
ρ	Mass correction factor
ρ	Specific resistivity of the conductor in Ωm
Ω	Ohm
Z_t, Y_t	Impedance/admittance of the train model
Z_{Thevi}	Thevenin equivalent impedance

Chapter One

Introduction

1. Introduction

1.1 Background

Electrified railway systems (RES) are used widely around the world as a significant means of fright and public transportation. They are expanding at great speed throughout the world. Like many other nations, Ethiopia also working hard to have the worldwide High Speed/High Capacity (HS/HC) railway lines that use the AC power supply system. A traction power supply or traction power network is an electricity grid for the supply of electrified railway networks. Rail transit power supply system converts electrical energy in to mechanical energy to drive electric trains, electric multiple units and urban trains. The evolution in electrical traction systems has produced a variety of electrification systems inspired to very different principles [1, 2].

Ethiopia recently becomes a crucial economic player in East Africa, and as one of the continent’s most populous countries [3]. Ethiopia already has a 781-km diesel railway that stretches from Addis Ababa to Djibouti and served almost 100 years. Nevertheless, as time passed its capacity deteriorated and currently it is out of service. No doubt, the current railway construction plan of the government is of paramount significance. The government plans railway transport as an important alternative in the country’s transportation system. Railway has more advantages compared to road transport. Railways are better suited for serving bulk freight on long distance over 250-300-km and above, rail mode of transport is cheaper at critical traffic figure of up to one million tons per year carried for over 1000km and can be economically behind without government funding. In recent studies, it is showed that railways cover their operating cost and achieve normal return on capital under competitive cost. In conditions of energy, railway takes 80T/km per liter compared to 24T/km by trucks and electrification of railways advances its advantage making it six times cheaper than diesel train [4]. Traction power supply system is in easiest form, a vast electrical circuit. The power supply may be in single or multiple sources and the feeding arrangements vary in different system. In Ethiopian electric train which is first its type in East Africa will run at a speed of 120km/h and will be both easier and low-priced to maintain, as it will be computerized and rely on locally-produced hydropower to run. In October 2011, China railway engineering corporation (CREC) struck a deal with Ethiopia railway corporation (ERC) which is Engineering

Project Contracting (EPC) turnkey contract agreement for Addis Ababa- Djibouti railway project Sebeta-Adama-Mieso section [3]. Traction power supply system is an electrical power network used to receive power from three phase power transmission system and supply power for the train driving on the single-phase AC power system electric railway, for the most part collected of the traction substation, traction network, separation substation, switch substation and other parts. Traction power supply system can apply several feeding modes; direct power mode (TR), direct power with return wire mode (DR), boost transformer power supply (BT), auto transformer power mode (AT), direct power with enhanced conductor supply mode and so on. In Ethiopia’s Sebeta~Adama~Mieso traction network feeding system use direct feeding system with return wire is adopted. The traction network of direct feeding system with return wire is simple and reliable in structure, overhead return wires are connected in parallel on the rail, which can reduce the rail potential in an effective manner and also well restrain interference to communication lines, substation facilities are simply and can operate reliably with low operation and maintenance fees and project investment and construction cost are low. The traction substation has different transformers’ connection scheme; these are single-phase connection, single-phase (3-phase) Vv connection, 3-phase YNd11 (3-phase and 2-phase with different capacity) connection, Scott connection and impedance-matching balance connection. Thus, this thesis focus on sebeta substation with single phase connection transformer type [5].

1.2 Statement of the Problem

In railway traction power supply system the transmission lines should not be overloaded, the catenary voltage should be within specified voltage level, the train power requirements should met, and the system should operate effectively and efficiently. In electrified railway traction power supply system the load in the electrical circuit are the trains/locomotives which are moving and demanding different levels of power according to their dynamic characteristics, operational mode and their speeds. So that, due to load variations, voltage drops in the feeding circuit differs substantially depending up on the train position, train current, number of train in the same power feeding section, track impendence etc. On the other hand, power consumption problems have occurred frequently within large variation of loads. These issues are important in traction power supply system to ensure normal operation of the electric locomotives. Thus, to address the above requirements this thesis present modeling and simulation of the traction power supply system “case study on SEBETA SUBSTATION”. Therefore, this thesis analyze the modeling of a traction power supply system, the power flow of the system model, and short circuit fault analysis investigated.

Finally, the analysis and modeling of Sebeta to Indode substation is simulated using DIgSILENT/*PowerFactory* software.

1.3. Objectives

1.3.1. General objective

The main objectives of this thesis work is to model and simulate a traction power supply system, case study on “SEBETA SUBSTATION” railway electrification power line. The analysis and also the simulation result conducted using DIgSILENT/*PowerFactory* software.

1.3.2. Specific objectives

The specific objective of this thesis are:

- To model train dynamics and analyze the train data
- To model electric traction power supply system
    - Traction network modeling
    - Locomotive /train load modeling
    - Traction substation and utility grid modeling at load side
- To analyze the power flow of the load model.
- To investigate the fault location and analyze the short circuit fault.
- To improve the feeding section of the power factor.

Finally, simulation result conducted using DIgSILENT/*PowerFactory* simulator software.

1.4 Methodology

In order to achieve the main aim of the study there are various procedural tasks followed by the researcher. The first method towards processing the work is started with reviewing different journals, literatures, books and on the world wide web (internet) where all the theoretical information regarding modeling and simulation of traction power supply system in electrified railway and related work on power flow, and short circuit fault analysis is gathered and a comparison of previous related research is studied. Along with literature reviewing, the collection and verification of data for the analysis is performed. This is followed by studying the characteristic and modeling of the traction power supply system components/loads. In addition to this where there is insufficient information available, reasonable assumptions have been quantitatively done for the calculations. Some simplifications are made to the calculations where needed, Once the model is developed, then using DIgSILENT/*PowerFactory* simulator software the simulation and analysis of the system is performed. The general block diagram of the methodology is given below:

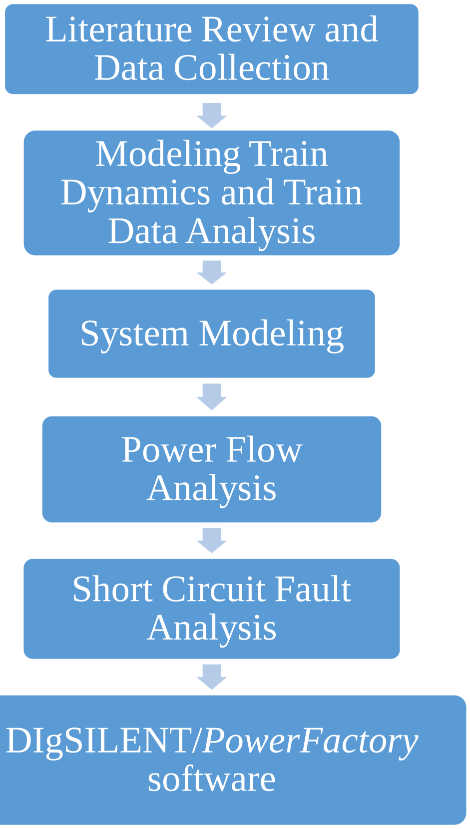


Figure 1.1 Block Summery of Methodology

1.5 Literature Review

In this research this thesis focus on modeling and simulation of traction power supply system in electrified railway, There are a lot of research has been done regarding on short circuit fault analysis, power flow analysis, modeling and simulation traction power supply system in order to plan and operational safety and also efficient operation of a system but due to the dynamic load variation of the train effective modeling is very difficult. So, now, this thesis try to model efficient load modeling and simulation using DIgSILENT/*PowerFactory* software,

Much investigation has been done considering electrified railway traction power supply system modeling, power flow analysis and short circuit fault analysis issues. In this work some of the related works will be discussed.

Han Zhengqing, Zhang Yuge, Liu Shuping, Gao Shibin [6], define a term traction power supply system and about various feeding modes such as track return feeding, boosting transformer feeding and autotransformer feeding. Traction power supply system consists of traction substation, autotransformer substation, sectioning post and traction electric network. From all these feeding techniques AT feeding technique is used widely for high speed traction system in china. Cross-paralleling AT feeding mode is selected in Beijing-Tianjin inter-city and Beijing-Shanghai line in china. Also using MATLAB Simulink model of traction power supply has established and variety of fault condition has analyzed. The simulation result give good result both compensation mode.

U. J. Shenoy, K. G. Sheshadri, K. Parthasarathy, H. P.Kincha and D. Thukaram [7], this thesis described the modeling of 25kV, 50Hz AC traction system along with necessary simulation using Simulink software of MATLAB. The Simulink model includes three phase system included with substations, track section contains rectifier fed DC locomotives and load summary in detail. This paper explains about in detail about relay quadrilateral characteristic used in traction system and also descriptive summary on hardware setup. Texas Instruments TMS320C50 digital signal processor (DSP) is used for identification of relay characteristic. For effective study of different types of fault on 25 kV traction system this paper is very useful.

Zhengqing Han, Zhihui Dong, Shibin Gao, ZhiqianBo [8], This thesis Introduce an out-of-phase short circuit fault which is new type of fault occur in AC railway traction system. If Pantograph of en-energized train may run through neutral section then two feeding lines will be short circuited through the arc and ultimately will damage the pantograph and rest of the AC traction system. The paper deeply explains about overlap neutral section in traction line. Comparison is made between overlap neutral section and insulator-structured neutral section. A brief discussion is also available about the reason why conventional distance protection fails to operate under out of phase short circuit occur. Finally, a new protection scheme for out of phase short circuit fault is introduced and a Simulink Model built up in MATLAB to introduced the protection scheme.

Thanatchai Kulworawanichpong [10], In this thesis, AC railway power flows are optimized in real time and the results are used to achieve some particular system objective via control of the PWM equipment as mobile reactive power compensators. The system voltage profile and the total power losses was improved while the overall power factor at the feeder substation is also made nearer to unity.

Tao Wen [11], he investigate on the impact of single-phase 25kV AC traction power supply system and, there are some outstanding power quality problems including three-phase voltage unbalance and large reactive power. Moreover, the neutral section insulators at exits of substations affect the safety and efficiency of the electric trains, especially in high speed railway and heavy haul railway. Therefore, in this thesis, a new traction power supply system adopting single-phase traction transformer and active power flow controller (PFC) is proposed. In the new system, the power quality problems caused by single-phase traction load are solved in grid side and the continuous power can be provided to electric trains without neutral sections in traction side. The mathematical model of the new system is built and the compensation currents of PFC are calculated. Moreover, the optimized topology and control method of PFC are studied. Based on MATLAB software platform, the simulation results verify the validity of the proposed system.

1.6 Organization of the Thesis

This thesis paper is organized into seven chapters. These are Introduction, ac traction power supply system, Train Data Analysis and Modeling of Train Movement, Modeling Traction Power Supply System in Electrified Railway, Power Flow and Short-Circuit Analysis, Simulation and Result and finally Conclusion and Recommendation. The first chapter discusses the introduction part in which the background, objective, literature review, and methodology are discussed in detail. The second chapter discusses about ac traction power supply system, external power grid for traction power supply system and power supply mode for traction system is discussed in detail. The third chapter high lights the Train data analysis and models of train movement, speed time curve of the train, Mathematical analysis (models) of train in motion, such as calculation of resistance force using Davis equation, calculation of curve resistance force, determination of gradient force using equivalent gradient approximation method, furthermore energy consumption by gradient force, verification of traction power and finally overall specific energy consumption of passenger and freight train is discussed in detail. In Chapter 4, Models of the traction power supply system components are presented using typical data. These components are: transmission line model, traction power feeding(catenary)system network modeling, overhead contact system traction impedance modeling ,traction substation modeling and train /locomotive modeling using constant power system modeling approach is presented and also train average current ,feeder effective current and traction transformer capacity calculation is discussed in detail. In the fifth chapter power flow and short circuit analysis is discussed, In Sixth chapter of this thesis simulation result using DIgSILENT/*PowerFactory* software is shown. Lastly, the conclusions, recommendations and further research are discussed in the seventh Chapter. The conclusions drawn from the research work, recommended solutions and areas of study suggested for further research are included in this chapter.

CHAPTER 2

AC TRACTION POWER SUPPLY SYSTEM

2.1 Introduction of AC traction power supply system.

Railway traction power supply system is a system which delivers an electrical traction and vehicles operating on the railway corridors. Generally power supply system for the railway has the following scheme shown in the figure 2.1 [12, 13].

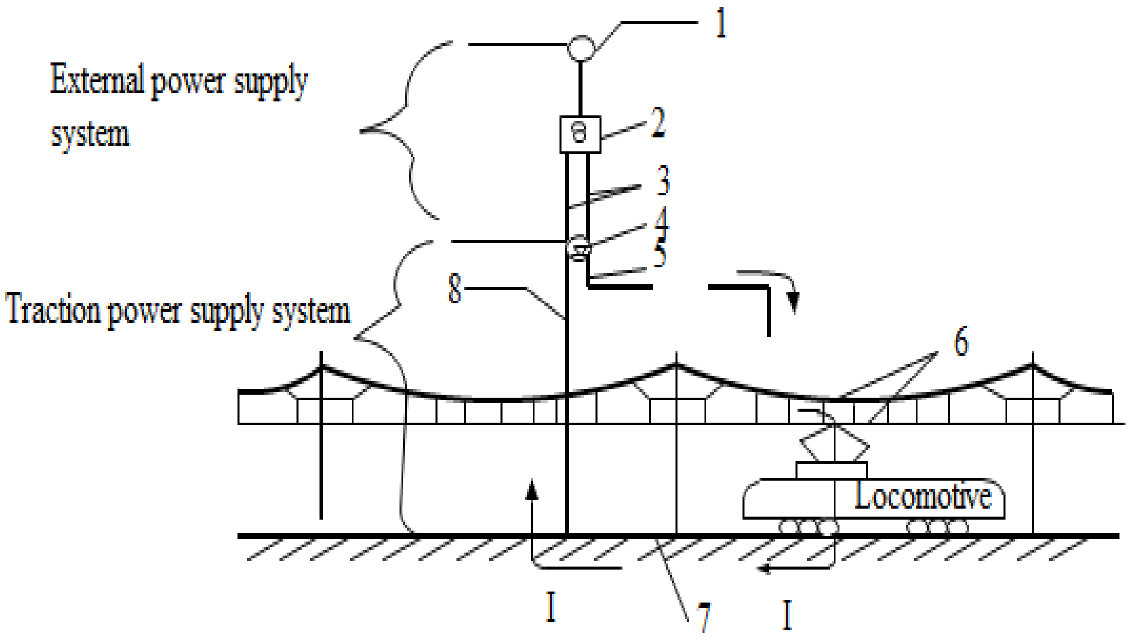


Figure 2.1 General Scheme of Railway Power Supply System and its Elements [12, 13]

1. Power generation station
2. Step-Up substation
3. High voltage transmission line
4. Traction substation
5. Feeder cable
6. Overhead contact system (OCS)
7. Rails
8. Return path/cable

Traction Network

Traction power supply system consists of traction substation, section post and traction electric network. Traction substation is three-phase with external power supply system of 132kV power receiving equipment brings in high-voltage current supplied by external power transmission line that controls opening and closing. Then the traction transformer transforms incoming three-phase electricity into 27.5kV single phase electricity. Finally electric energy feed into traction network with single-phase feeder equipment. The section post construct down and up feeders of electrified railway in parallel to increase the voltage level of feeding sections which is at the end of the feeders and balance the current of up and down feeding sections and reduce the loss of electrical energy [6]. The substation is a part of an electrical generation transmission and distribution system. The functions of the substations is change the voltage from high to low or to the reverse or perform any of several other relevant functions. The interval of generating station and consumer electric power may flow through several substations at different voltage levels. [14].

AC electric traction systems are mostly operated as single phase systems. Electric traction systems, which are supplied via the public transmission grid, operate at a nominal voltage and frequency. This voltage is 25 kV and at frequencies of 50Hz or 60Hz. An overhead contact system (OCS) supplies the power to the electric trains. In order to reduce the unbalance imposed by the single phase traction load neighboring overhead contact system (OCS), feeding points are often connected to different phase pairs of the transmission system. At the midpoint between the feeding points the OCS sections are separated by a neutral section (NS). A result of this arrangement is single end fed OCS sections. The running rails and earth act as return circuit. Amongst others the OCS usually consists of a catenary, which is a contact wire held level to the track by a suspension wire. The catenary wires are electrically paralleled. Along the contact wire the current collecting pantograph of the trains establish the conductive connection between the OCS and the traction drives on the trains. Overhead contact systems serve two main purposes; firstly they distribute the power to the electric trains and secondly they establish the electrical connection between the stationary power supply and the moving traction load. Hence, the strains imposed onto the OCS are not only due to thermal effects of the current flowing through the catenary conductors but also caused by the contact force and friction of the pantographs [15].

Power for AC railway traction is obtained from utility supply system, at transmission or sub-transmission voltage level, through traction feeding substations as illustrated in figure 2.1. The rail line is usually divided in to a number of isolated feeding sections and each section is feed by single phase supply from transformer with in the section power is carried to the train through overhead catenary and current takes the rails as return paths. Traction power supply system can apply several feeding arrangements. Different AC feeding systems in railways lead to different conductor layouts and current supply involving different approaches on load flow calculation [16]. Ethiopia traction power system adopts power frequency of 50Hz 25kV AC system and direct feeding system with return wire. And also, there are many transformer connection schemes that are commonly used in railroad substations; such as single-phase connection, single-phase (3-phase) Vv type connection, 3-phase YNd11 (three-phase and two-phase with different capacity) connection, Scott connection and impedance-matching balance connection [17]. The connection schemes and the balancing of the two transformer loads of a traction substation that are the most important factors that affect the voltage unbalances and performance of its power supply system therefore should be taken into account in the substation models [18]. In Ethiopia Sebeta adopts single-phase traction transformers with three-phase Vv conditions remained and the others implements three-phase Vv connection traction transformers, and also all the traction substations adopt fixed alternate.

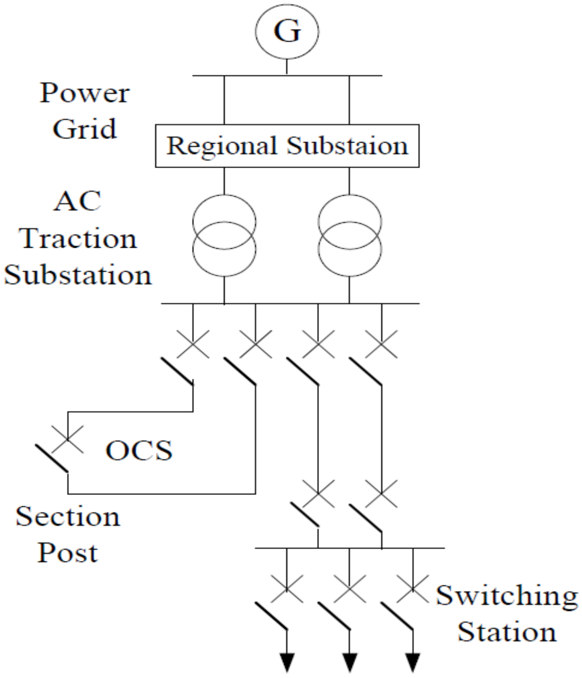


Figure 2.2 AC Traction Power Supply System [5]

2.2 External Power Grid for Traction Power Supply System

The single phase 50Hz power supply for railway traction at 27.5kV is obtained, from 132kV three phase grid systems through a step up transformer, the primary winding of which is joined to two of the phase of the three phases efficiently earthed transmission line network of the state electricity board. The primary voltage of traction transformer is: 132kV and no load secondary voltage being 27.5kV [19]. With the purpose of reduce the imbalance on the three phase grid system; the two phases of the three phase transmission line are tap, in a cyclic order for feeding the consecutive traction sub-stations. The distance between adjacent traction substations is normally between 35km and 50km depending upon density of traffic, gradients in the sections and other factors. In Ethiopia every traction substation have two independent and reliable 132kV voltage level power supply.

2.3. Overview of AC Electrified Traction System Addis Ababa-Djibouti Railway

Electrified railway systems (RES) are used widely around the world as a significant means of mass and public transportation. They are expanding at great speed throughout the world. Like many other nations, Ethiopia is also working to have the worldwide High Speed/High Capacity (HS/HC) railway lines that use the AC power supply system. The SEBETA - ADAMA section is double track, with a length of 110.298km; the ADAMA - MIESO section presents single track, with a length of 208.663km. It is temporarily suggested that: single-phase traction transformers shall be used in both SEBETA and MIESO （terminations） traction substations with conditions for 3-phase V/V connection reserved, and 3-phase V/v connection traction transformers shall be used in other traction substations. Fixed back-up transformer shall be applied for all traction transformers. Totally 11 new traction substations i.e. SEBETA, INDODE, BISHOFTU, MOJO,WACHULALU, CHISA, HARO, AJO TERE, AWASHISHT, ADELE and MIESO traction substations and 4 new section posts i.e. LABU, DK48, DK82 and ADAMA section posts are proposed to be built along the Line [20]. One power dispatching office is proposed to be set at LABU in the new traction power supply system. Two dispatching consoles will be set for dispatching control of traction substation facilities in SEBETA-MIESO section. The two most common electrification power supply systems for high speed rail are: 1x25kv and 2 x 25kv In Ethiopia the single-phase power frequency 50Hz) AC 25kV and the direct feeding system with return wire is applied for the power supply system [21].

In this system, the traction transformers are supplied from state grid, normally at 132 kV voltage levels. This voltage is further step down to 27.5 kV nominal voltage at traction substation of using 132/27.5kV transformers. Distribution of the traction power supply facilities shall meet the requirements of long-term traction load and shall be designed with a capacity to meet passenger and freight transportation. Voltage of OCS shall be as follows: nominal voltage: 25kV; Feeding no load voltage: 27.5kV, maximum short-time voltage: 29kV, minimum working voltage: 20kV and working voltage under abnormal conditions: 19kV. The electric traction substation with load Level-1(it is mainly includes the load closely related to train operation such as communication, signal, informatization and integrated dispatching as well as emergency lighting etc.) Load shall be supplied by two independent and reliable power supplies and those two power supplies shall be hot backup for each other i.e. each traction substation has two 132kV independent power lines. Power system voltage loss of traction substation is calculated by imputing to the traction substation 132kV of system line side and the minimum short circuit capacity is 400MVA [20].

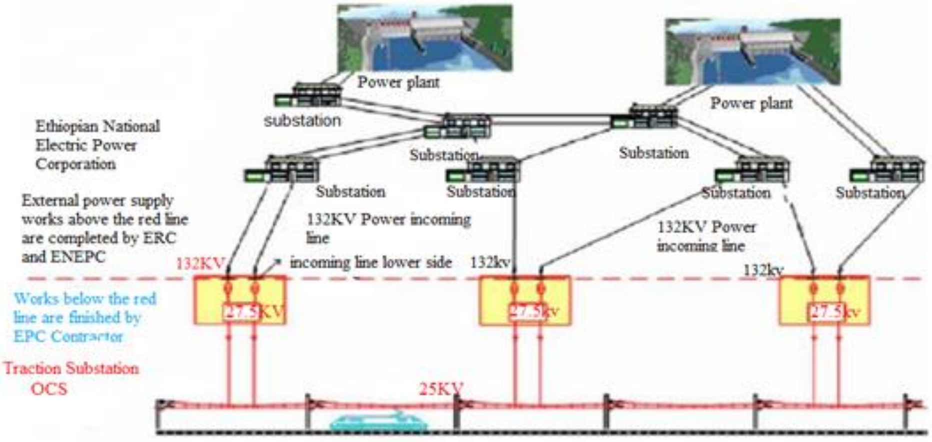


Figure 2.3 Traction Power Supply System Configuration [20]

2.4 Power Supply Mode for Traction System

Some basic feeding configurations are widely used for feeding electric energy to electric trains in mainline AC railways. These are:

2.4.1 Direct Feeding Configuration

Direct connection of the feeding transformer to the overhead catenary and the rails at each substation, in this configuration traction current goes through train and returns to traction substation from rail and earth. Direct feeding configuration is quite simple and it has less investment and maintenance cost. However, there are some disadvantages to this scheme (high impedance of feeders with large losses, high rail-to-earth voltage and the interference to neighboring communication circuits). To reduce those effects, the addition of an extra conductor (Return Conductor) paralleled and tied to the rails at typically 5 or 6 km is needed and this can reduce electromagnetic interference in parallel communication lines by 30%.

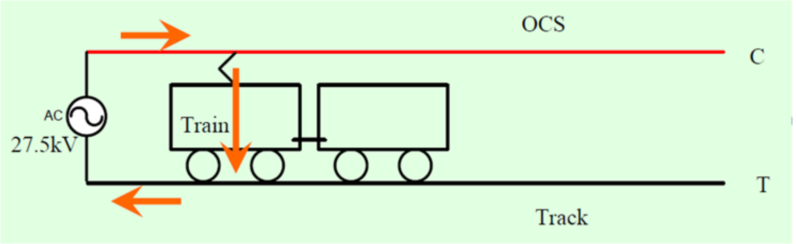


Figure 2.4 Direct Feeding Configuration

2.4.2 Booster Transformer Feeding Configuration

In this configuration boost transformer is serial connected between catenary and negative return line. Traction current returns to traction substation through negative return line (N).The flow return current in the return conductor rather than in the rails suppress the magneto-motive force resulting from the catenary current, the turn ratio needs to be unity. Although this feeding reduces electromagnetic interference with about 0.025 screening factor, the leakage inductance of BTs with a return conductor increases the total feeding impedance by approximately 50% compared with the direct feeding. Thus, the distance of two adjacent feeder substations is reduced because of the voltage drop along the contact wire

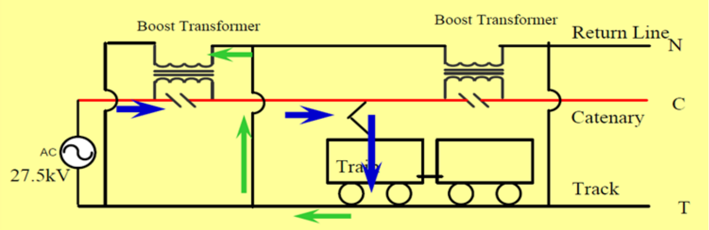


Figure 2.5 Booster Transformer Feeding Configuration

2.4.3 Direct Feeding with Return Line Mode: in this power supply configuration major part of the traction current returns from negative return line and the remaining current returns from rail. It has simple structure, less investment, maintenance and high reliability as directly power mode. Compared with direct power supply mode, in direct power supply with return line configuration rail potential and communication interference are improved. Because of low rail potential and traction network impedance is reducing, power feeding length is increased to extend 30% and it has less interference on extra low voltage(ELV) system.

Compared with boost transformer power supply configuration, direct power supply with return line configuration has Simple structure, less investment and maintenance. In direct power supply with return line configuration traction network impedance is reducing and feeding length is increased.

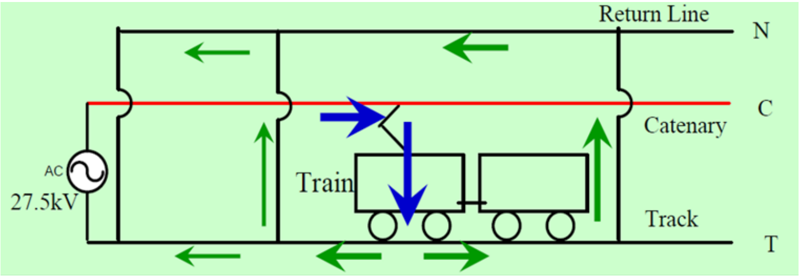


Figure 2.6 Direct Feeding with Return Line Mode

2.4.4 Autotransformer Feeding Configuration: Adding autotransformer (AT) at every 8-15 km intervals can increase substation distance up to 50-100 km. The AT has two equal-turn windings, whose middle tap is connected to the rails to provide earth potential for balancing a voltage between the contact wire and the return conductor. The electromagnetic interference in an AT system is normally lower than that in the BT system. However, the size and MVA rating of the AT are much larger and more expensive than the BT. In addition, its protection equipment is more complicated and it needs more installation space. Compared with direct power supply configuration, system is voltage is doubled i.e. 2×25kV, Voltage drop is reduced to 1/4. Impendence per unit length is about 1/4 of direct power supply. Power loss is reduced. And distance between traction substations is increased.

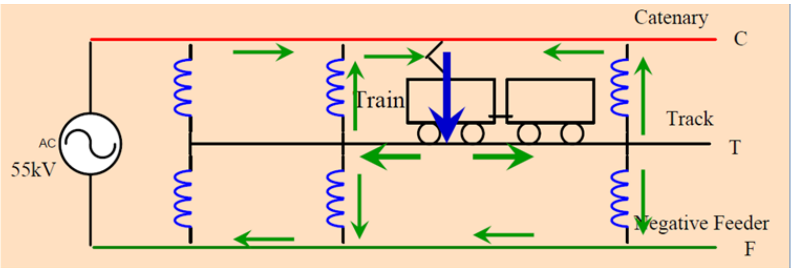


Figure 2.7.Autotransformer Feeding Configuration

2.5 Types of Railway Services

There are three types of passenger services offered by the railways,

2.5.1 City or urban service: in this case, there are frequent stops, the distance between stops being nearly 1km or less. Hence, high acceleration and retardation are essential to achieve moderately high schedule speed between the stations.

2.5.2 Sub-urban service: in this case the distance between stops averages from 3 to 5 km over a distance of 25 to 30 km from the city terminus. Here also, high rates of acceleration and retardation are necessary.

2.5.3 Main line services (Inter Urban): it involves operation over long route where stops are infrequent. Here, operating speed is high and accelerating and braking periods are relatively unimportant.

On goods traffic side also, there are three types of services (i) mainline freight service (ii) local or pick-up fright service and (iii) shunting service [24].

Chapter Three

Train Data Analysis and Modeling of Train Movement

Train dynamics (i.e. the changes of train position, velocity, and acceleration with respect to the change of time) analysis is a basic planning task in railway operation under different circumstances [22]. During the trip between two successive stations by alternating powering, coasting, and braking operation modes train dynamics has four operation regimes; namely: acceleration, constant speed, deceleration and braking [22].

Train, as a load is on the move and their power demand and hence the effects on supply system depend on its operation and location. A relationship between power demand of a train and its mobility is crucial in load flow studies. Train speed and operation mode are the decisive factors of the immediate amount of power required by the train as a load. They are however determined by the traction equipment characteristics, train weight, aerodynamics, and track geometry and drive control. For an inter-station run, a train goes through different speeds and operation modes and the power demand may thus vary significantly within a short period of time. A simple and quick reference linking train speed and operation mode to the power required is essential to load flow calculation [8].

Table 3.1 Train Acceleration and Retardation for Various Train Transportation Services

s.no	Parameter of comparsion	Urban service	Sub-urban service	Mainline service
1	Acceleration	1.5 to 4kmphps	1.5 to 4kmphps	0.6 to 0.8kmphps
2	Retardation	3 to 4kmphps	3 to 4kmphps	1.5kmphps
3	Maximum speed	120kmph	120kmph	100kmph
4	Distance beteween station	1 km	2.5 to 3.5 km	>10 km
5	Special remark	Free running period is abesnt coasting period is small	Free running period is abesnt coasting period is long	Long free running and coasting period acceleration and breaking period is small

3.1 Speed Time Curve of the Train

The line from Sebeta to Mieso has 19 stations (depart and stop) and 11 substations having an average distance of 16km and 29km respectively. Let's consider two substations and one section post from SEBETA to LEBU section post and LEBU section post to INDODE substation with distance coverage of 14.4km and 18.8 km respectively, a station is considered midway between two consecutive substations having 14.4km or 18.8km distance alternatively.

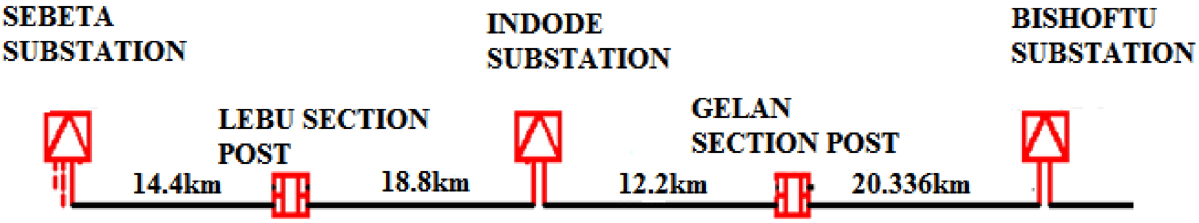


Figure 3. 1 Samples Station and Feeding Sections [20]

During trains operation, the service brake deceleration value is equal to 0.525 [m/s^2] (1.89kmphps) for the passenger trains and to 0.225 [m/s^2] or (0.81kmphps) for freight trains. The acceleration is limited to 0.8 [m/s^2] or (2.88kmphps) for the passenger train and to 0.5 [m/s^2] (1.8kmphps) for the freight train. [25]

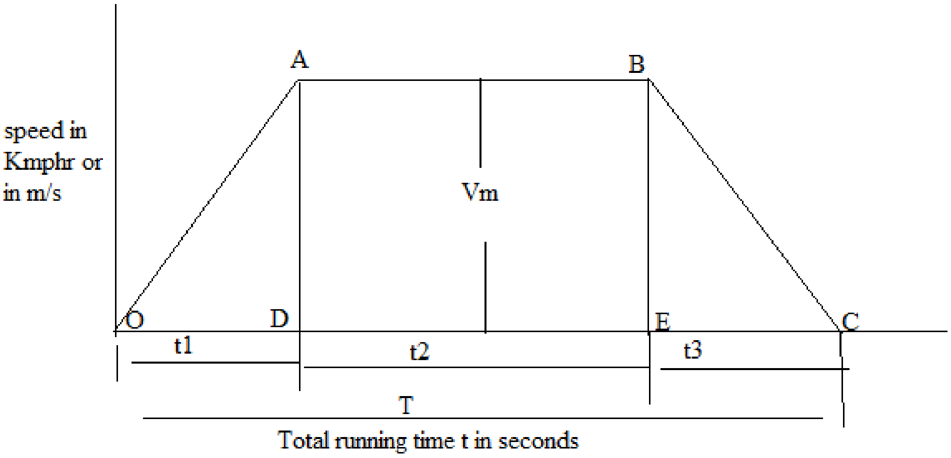


Figure.3.2 Speed Time Curve of the Train [24]

For passenger train

$$\alpha = \frac{V_m}{t_1} \quad \text{and} \quad \beta = \frac{V_m}{t_3} \tag{3.1}$$

D=Area OABC

=Area OAD + Area ABED + Area BCE

$= \frac{1}{2} V_{max}\ t_1 + V_{max}\ t_2 + \frac{1}{2} V_{max} t_3,$ where $t = t_1 + t_2 + t_3$

$= V_{max}\ [\frac{1}{2} V_{max}\ t_1 + t - t_1 - t_3 + \frac{1}{2} t_3,$ $t_2 = t - [t_1 + t_3]$

$= V_{max}\ [t - \frac{V_{max}}{2}(\frac{1}{\alpha} + \frac{1}{\beta}),$ $K = \frac{1}{2}[\frac{1}{\alpha} + \frac{1}{\beta}]$

$$D = V_{max}\ [t - V_{max} * K] \tag{3.2}$$

$$t = [\frac{D}{V_{max}} + K * V_{max}] \tag{3.3}$$

For the Freight Train: $t_1 = {V_m}/{\propto} = {80kmph}/{1.8kmphps} = 44.44\ sec$

For the Passenger train: $t_1 = {V_m}/{\propto} = {120kmph}/{2.88kmphps} = 41.67\ sec$

Time for Deceleration (t_3) from Sebeta to INDODE (Double traction)

Time for Freight Train $t_3 = {V_m}/{\beta} = {80kmph}/{0.81kmphps} = 98.765 sec$

Time for Passenger Train $t_3 = {V_m}/{\beta} = {120kmph}/{1.89kmphps} = 63.492\ sec$

Time for Free running (t_2) from Sebeta to INDODE (Double traction):

Before calculating the time (t_2) first we need to calculate the distance S_1 , S_2 and S_3 from the speed-time curve as follows :

The area under the speed-time curve is the distance, so that

$$S_1 = {1}/{2} * V_m * t_1 \tag{3.4}$$

For Freight train $S_1 = {1}/{2} * {44.44}/{3600} * 80 = 0.494km$

And for the passenger train

$S_1 = {}^{1}/_{2} * {}^{41.67}/_{3600} * 120 = 0.695km$

Distance (S_3) for deceleration period is,

Braking distance For Passenger train

$$S_3 = {}^{1}/_{2} * V_m * t_3 \qquad (3.5)$$

$= {}^{1}/_{2}$ *120*(${}^{63.492}/_{3600}$) S_3 =1.06km

Braking distance For Freight Train $S_3 = {}^{1}/_{2} * V_m * t_3 = {}^{1}/_{2}$ *80*(${}^{98.765}/_{3600}$)

S_3 = 1.097km

Where D is the total run length (in Km)

$$D = Breaking\ distance + area\ of\ OABE \qquad (3.6)$$

Thus the total distance from SEBETA Substation to LABU section post is 14.4km, therefore the total distance over which the power remains ON $i.e\ D'\ is$:

D'=D-Breaking distance=14.4km-1.06km =13.34km for passenger train

D' =13.34km

D'=D-Breaking distance=14.4km-1.097km =13.303km for freight train

D' =13.303km

similarly, the total distance from LEBU section post to INDODE Substation is 18.8km,therefore the total distance over which the power remains ON is :-

D'=D-Breaking distance=18.8km-1.06km =17.74km for passenger train

D' =17.74km

D'=D-Breaking distance=18.8km-1.097km =17.703km for freight train

D' =17.703km

Train braking distance depends on:

- Train speed,
- Traction weight,
- Braking technology and
- Signal block system.

Distance (S_2) for the free running period, Since, this thesis consider from SEBETA substation to INDODE Substation, now ,first consider from SEBETA substation to LEBUE section post with the total running length of (D in Km) 14.4km. So that,

$D = S_1 + S_2 + S_3$ =14.4km

S_2 = D$-$(S_1 + S_3)=14.4-(0.695+1.06)

S_2 =12.645km, for the passenger train

And for the Freight train, S_2 =14.4-(0.494+1.097)

S_2 =12.81km

Now, the free running time from Sebeta to LEBU for the Freight Train: -

t_2 = ${}^{S_2}/_{V_m} = \frac{12.81}{80} * 3600$=576.41 sec

And, for the Passenger Train t_2 = ${}^{S_2}/_{V_m} = \frac{12.645}{120} * 3600$ =379.35 sec

And secondly, considering from LEBUE section post to INDODE Substation with a total distance (D) of 18.8km. So that, we have

$D = S_1 + S_2 + S_3$ =18.8 km

$S_2 = D - (S_1 + S_3$)=18.8 - (0.695+1.06)

S_2 =17.045km, for the passenger train

And for the Freight train, S_2 =18.8-(0.494+1.097)

S_2 = 17.21 km

Now, the free running time from Sebeta to LEBU for the Freight Train

$t_2 = {S_2}/{V_m} = \frac{17.21}{80} * 3600$=774.45 sec

And, for the Passenger Train $t_2 = {S_2}/{V_m} = \frac{17.045}{120} * 3600$ =511.35 sec

Total time running from SEBETA substation to LEBU section post

For passenger train

$$t = \left[\frac{D}{V_{max}} + K * V_{max}\right], K = \frac{1}{2}\left[\frac{1}{\alpha} + \frac{1}{\beta}\right] = \frac{1}{2}\left[\frac{1}{2.88} + \frac{1}{1.89}\right] = 0.438$$

$$t = \left[\frac{14.4km}{120km/h} + 0.438 * 120km/h\right]$$

$$t = 8.076\,min$$

Total time running from LEBU section post to INDODE substation

$$t = \left[\frac{18.8km}{120km/h} + 0.438 * 120km/h\right] = 10.276min$$

Similarly, for freight train

$$K = \frac{1}{2}\left[\frac{1}{\alpha} + \frac{1}{\beta}\right] = \frac{1}{2}\left[\frac{1}{1.8} + \frac{1}{0.81}\right] = 0.895$$

$$t = \left[\frac{14.4km}{80km/h} + 0.895 * 80km/h\right]$$

$$t = 11.993\,min\,total\ running\ time\ form\ sebeta\ substation\ to\ lebu\ section\ post$$

And

$$t = \left[\frac{18.8km}{80km/h} + 0.895 * 80km/h\right]$$

$t = 15.293\ min,$ is the total running time from Lebu section post to Indode substation

Therefore, the total running time from SEBETA to INDODE substation for passenger train is $t = 18.352min$ and the total running time from SEBETA to INDODE substation for freight locomotive is $t = 27.286\ min$

3.2 Models of Train in Motion

The motion of a train can be modeled and represented by the various force components and the motion quantities that act on it at a particular time and location. The force components that act on the train include weight of the train, Tractive Effort (TE), rolling resistance, air resistance, gradient resistance, curvature resistance, brake effort and adhesion. The resistance component is the sum of all kinds of resistances acting on the train including track resistance, rolling resistance and air resistance [26].

3.2.1 Forces acting on a Train

A net force on a train moving with speed v along a track inclined at an angle to the horizontal are determined by the forces shown in Figure below 3.3

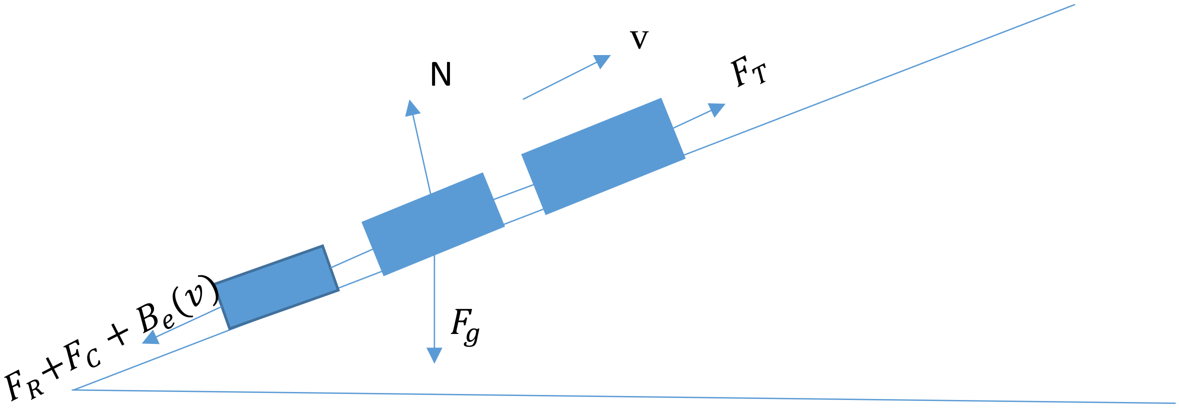


Figure 3.3 Forces Acting on Moving Train [26]

By Newton's first law of motion, the Net force is given by:

$$F_{net}(v) = F_T(v) - F_R - F_C \pm F_g - B_e(v) \tag{3.7}$$

Where

F_T is the tractive force of the locomotive

F_r is the resistance force

F_c is the curve force

F_g is the gravitational force due to the profile of the line

$B_e(v)$ is the braking effort of the locomotive

3.2.2 Tractive force F_T

Tractive force F_T is the force which a locomotive can exert when pulling a train is called its tractive effort, and depends on the speed of the train.

1. Tractive or accelerating modes

By this time the traction force $T(v)$ and running resistance F_R Applied to the train in addition to the gravitational and curve resistance force thus, their resultant force F is:

$$F_{net}(v) = T_E(v) - F_R(v) - F_C \pm F_g$$

2. Coasting mode /constant speed: by this time running resistance $F_R(v)$, and curve resistance force F_C are applied to the train in addition to the gravitational force, therefore the resultant force $F_{net}(v)$ is:

$$F_{net}(v) = -F_R(v) - F_C \pm F_g$$

3. Braking mode/decelerating: by this time, running resistance $F_R(v)$ and braking force $B_e(v)$ are applied to the train in addition to the gravitational force, thus their resultant force $F_{net}(v)$ is:

$$F_{net}(v) = -\, B_e(v - F_R(v)$$

Therefore, when $F_{net}(v)$>0, the train accelerates

$F_{net}(v)$<0, the train decelerate or braking mode

$F_{net}(v)$=0 the train operates constantly moving

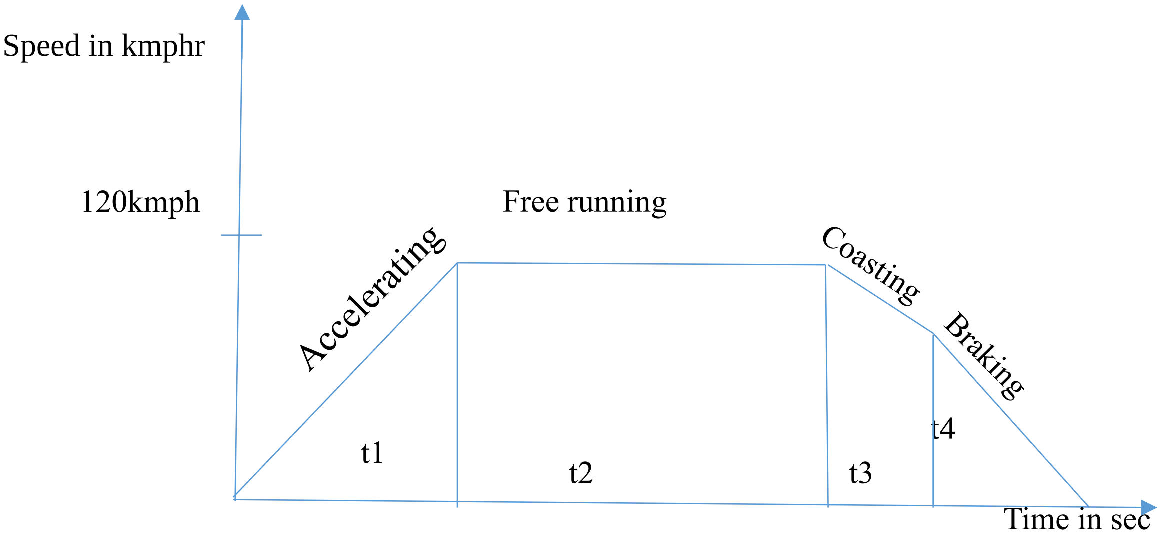


Figure 3.4.Speed Time Profile Curve Sebeta to Indode

3.2.3 Train Resistance

Train movement along the rail suffers from various resistance forces which opposes longitudinal traverse of the train. These resistances are a fundamental essence which affects the top speed achieved by the train and ability to accelerate. Therefore, traction resistance must be known to determine type of locomotive applied for that track. For determining power requirement's, energy consumption and running times of trains, it is important to know the amount of force acting on the train and direction of the force applied [27, 28].

Train resistance can be running resistance (mechanical resistance and aero dynamic resistance), curve resistance, gradient resistance and tunnel resistance [27]. Some of the resistance varies with the weight of the train [29].

- ✓ Journal resistance
- ✓ Friction between journal and bearing
- ✓ Rolling Friction
- ✓ Friction between wheel and rail due to "creepage" at interface
- ✓ Minute elastic deformation of wheel and rail surfaces
- ✓ Track Resistance
- ✓ Deformation of track structure
- ✓ Consequent "uphill" running

And others vary with speed of the train

- ➢ Flange contact
- ➢ consequent friction and impacts
- ➢ rail lubrication reduces resistance on both curved and tangent track
- ➢ Wheel/rail interface friction
- ➢ lateral movement between wheel tread and rail head
- ➢ Oscillation can also induce various other energy losses into:
  - vehicle suspension system (sway, bounce, buff, draft
  - track structure

These resistances being added to the train resistances give the total train resistance. There are a lot of analytical relations (empirical formulas) which have been in use to estimate train resistances. The best admired formulae for train resistance evaluation are Davis‘s Equation, Modified Davis Equation and the Canadian National (CN) Equation that differ from each other by the regression coefficients (A, B and C) evaluated using fitting test data, running resistance of the train can be expressed as [27]:

$$F_R = F_{Rolling} + F_{airdynamic} = A + BV + CV^2 \text{ (kN)} \quad (3.8)$$

Where A= from journal resistance, track resistance and rolling resistance, B= from flange friction, flange impact, rolling resistance of wheel/rail and wave action of the rail and C= from head-end wind pressure, turbulence between cars, yaw angle of wind tunnels and rear drag [27].Those coefficients are dependent on the type of train, type of track and length of train [30, 31].

For passenger train

$$A = 1880 + 70 * n_{ax} \text{(N)} \quad (3.8a)$$

Where, n_{ax} *is number of axles*, L_t *is total length of locomotives* and ρ *is rotating mass factor*

$$B = 1 + 0.19 L_t \, {sN}/{m} \quad (3.8b)$$

$$C = \frac{\rho * (8.3 + 0.057 L_t)}{2} \left(S^2 \frac{N}{M^2} \right) \quad (3.8c)$$

For freight train

$$A = 2540 + 175 * n_{ax} \text{ (N)} \quad (3.8d)$$

$$B = -22 + 0.58 L_t \left(S \frac{N}{M} \right) \quad (3.8f)$$

$$C = \frac{\rho * (8.2 + 0.133 L_t)}{2} (s^2 \frac{N}{M^2}) \quad (3.8g)$$

3.2.4 Curve Resistance

Is due to the presence of curve along the track. When a vehicle travels on a curve section of its travel way, external forces act on the vehicle. Certain components of these forces tend to retard the forward motion of the vehicle. The sum of these components is the curve resistance. In train motion this resistance depends on the friction between wheel flange and rail, the wheel slippage on the rails, and the radius of curvature [32].

$$F_{Cr} = M * g \frac{6.5}{R - 55}, R > 300 \quad (3.9)$$

$$F_{Cr} = M * g \frac{5}{R - 30}, R \leq 300 \quad (3.10)$$

3.2.5 Breaking Force $\mathbf{B_e(v)}$

The brake force available depends on two factors: first, the adhesion between the rail and the wheels being braked, and second, and the normal reaction of the rail on the wheels being braked (and hence on the weight per braked wheel).

3.3 Mathematical Analysis (Models) of Train in Motion

Table 3.2 HXD1C Freight and SS9 Passenger Electric Locomotives Parameter Specification

	HXD1C freight locomotive	SS9 passenger locomotive
Model	HXD1C	SS9
Traction system	Electric	Electric
Starting traction effort	570 kN	570kN
Standard gauge	1435mm	1435mm
Continuous traction effort	400 kN	400kN
Traction power at wheel rim	7200kW	7200kW
The maximum speed of the locomotives	80kmph	120kmph
Continuous speed of the locomotives	65kmph	72kmph
Rated speed of the locomotives	43.5kmph	43.5kmph
Radius of curvature	800m	800m
Axle load	25tonne	25tonne
No .of axles	6	6
Loco weight	150tonne	150tonne
No of traction motors	6,3-Φ AC traction motors	6,3-Φ AC traction motors
Loco brake systems	Regenerative braking system	Regenerative braking system
Length of the locomotives		22.6m
Max.Brake effort	400KN	400KN

Table 3.3 and Table 3.4 Summarize the Main Data of Freight Wagons and Passenger Coaches.

Table 3.3 Freight Wagons Data

Types	No load weight(t)	Load capacity(t)	Design speed(km/h)	Length (m)	Bogie axle load(t)
Box car	25.0	70	100	1704	25
Gondola car covered	24.0	70	100	14.0	25
Gondola car uncovered	24.0	70	100	14.0	25
Hopper car-covered	24.8	69	100	16.50	25
Hopper wagon uncovered	23.8	70	100	14.4	25

Flat wagon	23.0	70	100	13.5	25
Tank wagon	25.0	70	100	13.0	25
Bi level auto carrier	37.4	22	100	26.1	25
Refrigerated car	40.5	38	120	21.0	NA
Center Beam car	23.8	70	100	14.4	NA

Table 3.4 Passenger Coach Data

Type	No load weight(t)	Rated seats	Design speed(km/h)	Length (m)	Bogie axle load (t)
YZ25G Hard-seat	NA	118	120	25.5	17
YW25G Hard sleeper	NA	66	120	25.5	17
RW25G soft berth	NA	36	120	25.5	17
RW25G Dinner passenger	NA	50	120	25.5	17

Table 3.5 summarizes the data of the freight trains. This thesis calculate the data, starting from the assumptions below:

The value of the no load weight of the freight wagons is indicated in Table 3.5 for the simulations, an average value of 25.7 tonne will be considered. The payload of the freight wagon is equal to the maximum load capacity (i.e. 69.3 tons) increased by 5 tons as worst condition, the total weight is equal to 100 tonne.

Table 3.5 Total Freight Train Data

	Single locomotives/wagon values				# of locomotives and wagons	Total values				
	Length (m)	No load weight (t)	Pay load (t)	Rotating masses (%)		Length (m)	No load weight (t)	Pay load(t)	Total weight(t)	Rotating masses (t)
HXD1C loco	23	150	0	9	2	46	300	0	300	27
Freight wagons	20	25.7	74.3	6	28	560	720	2080	2800	43.2
					Freight Trains Data	606	1020	2080	3100	70.2

Table 3.6 summarizes the passenger's trains data, now, this thesis calculate these data starting from the assumptions, it assumes that:

- The single passenger weight is equal to 0.075tonne including luggage,
- The no load weight of the passenger coaches is equal to 46 ton.
- And the rotating masses of the passenger coaches are equal to 6% of the load weight. And the average value of the auxiliary load of each passenger coach, continuously absorbed at train pantograph, is equal to 60 kVA with a power factor equal to 0.8,

Table 3.6 Total Passenger Trains Data

	Single loco/wagon values					# of loco & coaches	Total values					
Passenger trains	Length (m)	No load weight(t)	# of passengers	Payload (t)	Rotating masses		Length (m)	No load weight(t)	# of passengers	Payload (t)	Total weight (t)	Rotating masses(t)
HXD1C Loco	23	150	0	0	9	1	23	150	0	0	0	13.5
Hard seat	25.5	46	118	8.85	6	3	76.5	138	354	26.6	164.6	8.3
Hard sleep	25.5	46	66	4.95	6	3	76.5	138	198	14.9	152.9	8.3
Soft bed	25.5	46	36	2.7	6	2	51	92	72	5.4	97.4	5.5
Dinner	25.5	46	0	0	6	1	25.5	46	0	0	46	2.8
Service coach	25.5	46	0	0	6	1	25.5	46	0	0	46	2.8
Passenger trains data							278	610	624	46.8	656.8	41.1

The freight train maximum speed is assumed equal to 80kmph and the maximum speed of the passenger trains is assumed equal to 120kmph.

3.3.1 Calculation of resistance force using Davis equation

$F_R = F_{rolling} + F_{Airodynamic\ resistance}$ (kN)

$F_R = A + BV + CV^2$

For passenger train

$A = 1880 + 70n_{ax}$ (N)

Where

$n_{ax}\ \ is\ number\ of\ axles$

$B = 1 + 0.19L_t$ ($S\frac{N}{M}$)

Where

L_t *is total length of locomotives*

$C = \frac{\rho*(8.3+0.057L_t)}{2}$ $(S^2\frac{N}{M^2})$ Where

ρ *is mass correction factor or*

$M_e = \rho M;$

ρ *is rotating mass factor usually use* 1.1

Now, substituting the value from Table 3.5 above the following result obtained

A=2300, B=53.82, C=13.28

Therefore, from equation (3.8)

$$F_R = 2.3 + 5.389 * 10^{-2}V + 1.33 * 10^{-2}V^2 \quad \text{(kN)} \qquad (3.11)$$

The starting tractive effort is given to be 570kN and speed corresponding to this tractive effort value is calculated under the assumption of 0.95motor efficiency as follows

$$F_t = \eta * \frac{P}{V} \; (kN) \qquad (3.12)$$

$$570kN = 0.95 * \frac{7200kW}{V_r}$$

$V_r = 12\,{}^{m}/_{s} = 43.3\ kmphr$, until the speed of the train reaches this speed value maximum tractive effort take the value given in Table 3.2

Now taking the rated speed of the locomotive the resistance force becomes:

$$F_R = 2.3 + 5.389 * 10^{-2}V + 1.33 * 10^{-2}V^2 \quad \text{(kN)}$$

F_R=29.57 kN resistance force of passenger locomotives

For freight train

$A = 2540 + 175 * n_{ax}$ (N)

$B = -22 + 0.58L_t$ $(S\frac{N}{M})$

$C = \frac{\rho*(8.2+0.133L_t)}{2}(s^2\frac{N}{M^2})$

Now, substituting the value from table above we get the following result for fright locomotive

A=3590, B=329.48, C=48.84

$F_R = 3.59 + 0.3295V + 0.0488V^2$ (kN)

$F_R = 109.352\ kN$ Resistance force for fright locomotives

3.3.2 Calculation of Curve Resistance force

For passenger locomotives

Now, for this thesis from Sebeta to Indode substation the curvature distribution fulfill equation (3.9) thus this thesis use the these formula,

$$F_{Cr} = M * g\frac{6.5}{R-55}, R > 300$$

Table 3.7 Curve Distribution along SEBETA TO INDODE Substation

For the first line		Radius	For second line		Radius
2798.26	4136.08	1600	2808.68	4126.49	1600
4637.04	5543.39	1600	4563.52	5497.98	1595.79
5993.44	6963.37	1600	5948.51	6890.48	1604.19
8471.1	9218.68	3500	8388.22	9185.04	3495.9
10725.9	11612.9	1600	10682.2	11541.1	858.865
12287.8	12882.5	1600	12246	12811.8	1604.19
13037.2	14201.1	800	12967.3	14151.2	800
17328.5	17921.1	1600	17253.3	17876	1600
18122.6	18803.4	800	18043.6	18751.6	795.59

Using equation (3.9) i.e. $F_{Cr} = M * g\frac{6.5}{R-55}, R > 300$ to obtain the resistance force this thesis considers three cases:

Case1.when radius of curvature is R=800m, g=9.81$^{m}/_{s^2}$ and the Total Weight or mass of the passenger locomotives is 656.8 ton

$$F_{Cr} = M_{tot} * g\frac{6.5}{R-55}, R > 300$$

$$F_{Cr} = 56.22N$$

Case 2 when radius of Curvature R =1600m,

$$F_{Cr} = M_{tot} * g\frac{6.5}{R-55}, R > 300$$

F_{Cr}=27.11N

Case 3 when radius of Curvature R= 3500m

$$F_{Cr} = M_{tot} * g\frac{6.5}{R-55}, R > 300$$

$$F_{Cr} = 12.157N$$

Therefore, from result the maximum curve resistance force is obtained at minimum radius of curvature R equal to 800m, in order to determine the total tractive force and energy consumption. i.e. F_{Cr} =56.22N

For fright locomotives

Case1.when radius of curvature is R=800m, g=9.81$^{m}/_{s^2}$ and Total Weight or mass of the locomotives in ton is 3100 ton for fright locomotives

$$F_{Cr} = M_{tot} * g\frac{6.5}{R-55}\ , R > 300$$

$$F_{Cr} = 265.33N$$

Case 2 when radius of Curvature R =1600m,

$$F_{Cr} = M_{tot} * g\frac{6.5}{R-55}\ , R > 300$$

$$F_{Cr} = 127.943N$$

Case 3 when radius of Curvature R= 3500m

$$F_{Cr} = M_{tot} * g\frac{6.5}{R-55}\ , R > 300$$

$$F_{Cr} = 57.379N$$

Thus, from result the maximum curve resistance force is obtained from the minimum radius of curvature R equal to 800m, therefore, the total tractive force and energy consumption is determined by this force i.e. F_{Cr}=$265.33N$ for fright locomotive.

3.3.3 Force due to profile or gradient resistance

Gradient resistance is the other force which acted on the train and it is independent of the speed of train but weight. The location of gradient play prominent role in the application of tractive effort and may cause over heating of the motor due to motor overloading or favors the motor by providing the required effort of driving. It is proportional to the angle (in degree) of the inclined track and can be directly derived from the relationship between train weight and the track grade [27, 28].

This force exists due to the profile of the railway line on which the train is moving. It is the sum of gravitation force due to inclination of the profile and/or horizontal curve of the profile. When train is on an up gradient, gravity component of dead weight of a train parallel to the track (W sin Ө) will be responsible for the train to come down. In order to prevent this, tractive effort has to be applied in upward direction whose magnitude is given by equation (3.13).

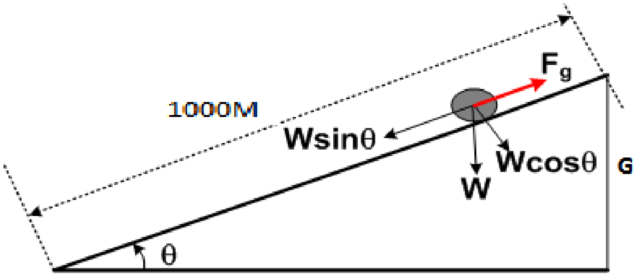


Figure 3.5 Train on up gradient [3 H. PARTAB, "Modern Electric Traction", DHANPAT RAI & CO., Chapter three: Traction Mechanics]

In railway practice, gradient is expressed as rise in meters in a track distance of 1000 meter and is denoted by letter (percentage gradient) G%.

Table 3.8 Gradient Distribution along SEBETA to INDODE substation

From	To	Gradient (‰)	Sin(α)
0	700	0	0
700	1100	10.6	0.0106
1100	3400	0	0
3400	3800	12	0.012
3800	5500	18.1	0.0181
5500	5900	18.5	0.0185
5900	7000	18.1	0.0181
7000	8321.07	18.5	0.0185
8321.07	9221.07	18.3	0.0183
9221.07	10621.1	18.5	0.0185
10621.1	11621.1	18.1	0.0181
11621.1	12121.1	18.85	0.01885
12121.1	12521.1	8.5	0.0085
12521.1	12921.1	-3.5	-0.00035
12921.1	13321.1	-10.5	-0.0105
13321.1	14621.1	-5.9	-0.0059
14621.1	16421.1	0	0

16421.1	17022.1	6	0.006
17022.1	17471.1	-6	-0.006
17471.1	18821.1	-17.7	-0.0177

Force due to inclination or slop when a train moves on a segment of railway line with inclination angle θ, a force proportional to the weight of a train and the sine of the inclination angle θ act on the train i.e.

$F_g = M * g\,sin(\theta)$, Since angle θ small enough (3.13)

$sin\,\theta \approx tan\,\theta = i$

$F_g = Mgi$, where, i is the gradient or slope of particular segment. If the gradient is positive the force opposes the train movement and if otherwise the force is in the direction of train movement, now along Sebeta to Indode substation the gradient distribution is Tabulated in Table 3.8, from the gradient distribution of zero, negative and positive and also determination of the gradient force at each gradient segment and gradient value is so tedious work. Therefore, to minimize the long calculation at each gradient point this thesis try to use a technique called equivalent gradient approximation i.e. determining the equivalent gradient.

Case 1 equivalent gradient of the positive gradient in the distribution

$$g_{eq1} = \frac{l_1 g_1 + l_2 g_2 + l_3 g_3 + \cdots \dots \dots \dots l_n g_n}{l_1 + l_2 + l_3 \dots \dots \dots \dots . l_n} \quad (3.14)$$

Where, n is, 0, 1, 2, 3……N

L is length of the track segment

Case2 equivalent gradient of the negative gradient in the distribution

$$g_{eq2} = \frac{l_{21} g_{21} + l_{22} g_{22} + l_{23} g_{23} + \cdots \dots \dots \dots l_{2n} g_{2n}}{l_{21} + l_{22} + l_{23} \dots \dots \dots \dots . l_{2n}} \quad (3.15)$$

Therefore, for the gradient distribution from sebeta to indode substation the equivalent gradient become as follows

Case1, from starting point of sebeta substation to 12.521Km length of track segment

$$g_{eq1} = \frac{l_1 g_1 + l_2 g_2 + l_3 g_3 + \cdots \dots \dots \dots \dots \dots \dots l_n g_n}{l_1 + l_2 + l_3 \dots \dots \dots \dots \dots . l_n}$$

$g_{eq1} = (700 * 0 + 400 * 10.6 + 2300 * 0 + 400 * 12 + 1700 * 18.1 + 400 * 18.5 + 1100 * 18.1 + 1321.07 * 18.5 + 900 * 18.3 + 1400.03 * 18.5 + 1000 * 18.1 + 500 * 18.5 + 400 * 8.5)/$ 12,521.07

g_{eq1}=13.152‰

Case 2, from 12.521Km length of track segment to 14.621km length i.e. negative gradient distribution thus the equivalent gradient becomes

$$g_{\mathrm{eq}2} = \frac{l_{21}g_{21} + l_{22}g_{22} + l_{23}g_{23} + \cdots \ldots\ldots\ldots\ldots\ldots\ldots l_{2n}g_{2n}}{l_{21} + l_{22} + l_{23} \ldots\ldots\ldots\ldots\ldots . l_{2n}}$$

$$g_{eq2} = \frac{400 * -3.5 + 400 * -10.5 + 1300 * -5.9}{2100}$$

$g_{eq2} = -6.32$‰

Case3, from 14.621Km length of track segment to 16.421km length that is already the LEBUE section post with gradient of zero

$g_{eq3} = 0$‰

Case4, from 16.421Km length of track segment to 17.022km length

g_{eq4} =6‰

Case5, from 17.022km length of track segment to 18.821km length

$$g_{eq5} = \frac{-449 * -6 + 1350 * -17.7}{1799}$$

$g_{eq5} = -14.779$‰

For passenger train

Now, this thesis determine the gradient force with equivalent gradient from the profile of the railway lines

$$F_{g1} = 9.81 W_{tot}\, G_{eq1} \qquad (3.16)$$

Where, W_{tot} is the total weight of the passenger locomotives i.e. W_{tot} =656.80ton,

$G_{eq1} = 13.152$‰ $= 0.0135$ is for positive equivalent gradient 1

Thus, substituting the corresponding value this thesis obtain the following result,

F_{g1}=86.98N

$$F_{g2} = 9.81 W_{tot}\, G_{eq2} \qquad (3.17)$$

Where

G_{eq2} =-6.32‰ = -0.00632

$F_{g2} = -40.72N$

When, $G_{eq3} = 0‰$

$F_{g3} = 9.81 W_{tot}\, G_{eq3}$

$F_{g3} = 0\ N$, This means that it's on station i.e. for this thesis LEBUE section post.

When, $G_{eq4} = 6‰$=0.006

$$F_{g4} = 9.81 W_{tot}\, G_{eq4} \qquad (3.18)$$

$F_{g4} = 38.66N$

When, $G_{eq5} = -14.779‰ = -0.014779$

$$F_{g5} = 9.81 W_{tot}\, G_{eq5} \qquad (3.19)$$

$F_{g5} = -95.224$N

Therefore, the total force due to gradient of the railway line is the sum of each force i.e.

$$F_{gtot} = F_{g1} + F_{g2} + F_{g3} + F_{g4} + F_{g5} \qquad (3.20)$$

$F_{gtot} = -10.304N$, this result implies that the gradient force assist in the direction of train movement.

Similarly, for fright locomotives this thesis determine the gradient force from the profile of the railway lines

$F_{g1} = 9.81 W_{tot}\, G_{eq1}$

Where,

W_{tot} is the total weight of the passenger locomotives i.e. $W_{tot} =$ 3100ton, $G_{eq1} = 13.152‰ = 0.0135$ is for positive equivalent gradient 1

Thus, substituting the corresponding value this thesis obtain the following result,

F_{g1}= 410.55N

$F_{g2} = 9.81 W_{tot}\, G_{eq2}$

Where, G_{eq2} =-6.32‰ = -0.00632

$F_{g2} = -192.197N$When, $G_{eq3} = 0‰$

$F_{g3} = 9.81 W_{tot}\, G_{eq3}$

$F_{g3} = 0\ N$, This means that it's on station LEBUE section post

When, $G_{eq4} = 6‰=0.006$

$F_{g4} = 9.81W_{tot}\, G_{eq4}$

$F_{g4} = 182.47N$

When, $G_{eq5} = -14.779‰ = -0.014779$

$F_{g5} = 9.81W_{tot}\, G_{eq5}$

$F_{g5} = -449.475$N

Therefore, the total force due to gradient of the railway line is the sum of each gradient force i.e.

$F_{gtot} = F_{g1} + F_{g2} + F_{g3} + F_{g4} + F_{g5}$

$F_{gtot} = -48.652N$, thus the total gradient force for fright locomotives and this result implies that this gradient force assist in the direction of train movement.

3.4 Energy consumption by gradient force

For passenger locomotives

Energy consumed by the gradient force is determined as $E_{g1} = F_{g1} * D_{\mathrm{n}}$,

Where

D_n is the total distance cover starting from point of the gradient to the next gradient distribution n =1, 2, 3…….

When, $D_1 = 12.5211km$

$$E_{g1} = F_{g1} * D_1, \tag{3.21}$$

$$E_{g1} = 9.81 * WGD_1 \text{ (Joule)} \tag{3.22}$$

$$= F_{g1}D_1\left(\frac{1000}{3600}\right) \text{ (W-h)}$$

$$E_{g1} = 0.2777F_{g1}D_1\text{(W-h)} \tag{3.23}$$

$E_{g1} = 302.439\ kwh$

When, D_2 =2.1km

$$E_{g2} = 0.2777F_{g2} * D_2 \tag{3.24}$$

$E_{g2} = -23.75\ kwh$

When, $D_3 = 1.8km$

$E_{g3} = 0\ kwh$, Because the gradient force at the segment is zero

$when, D_4 = 0.601km$

$E_{g4} = 0.2777F_{g4}D_4$ (W-h) (3.25)

$E_{g4} = 6.4523\ kwh$

When, $D_5 = 1.799km$

$E_{g5} = 0.2777F_{g5}D_5$ (W-h) (3.26)

$E_{g5} = -47.572kwh$

Therefor the energy consumption from SEBETA substation to LEBUE section post due to the gradient force is:

$E_{g,Sebeta-Lebue} = E_{g1} + E_{g2}$ (3.27)

$E_{g,Sebeta-Lebue} = 278.689kwh$

Therefor the energy consumption from LEBUE section post to INDODE substation due to the gradient force is

$E_{g,Lebu-Indode} = E_{g3} + E_{g4} + E_{g5}$ (3.28)

$E_{g,Lebu-Indode} = -41.12kwh$

The total energy consumption from SEBETA substation to INDODE substation due to the gradient force that is consumed by passenger train is:

$E_{g,Sebeta-Indode} = E_{g1} + E_{g2} + E_{g3} + E_{g4} + E_{g5}$ (3.30)

$E_{g,tot} = E_{g,Sebeta-Indode} = 237.569kwh$

For fright locomotives

Energy consumed by the gradient force, where D_n is the total distance cover from point of the gradient starting to the next gradient distribution n =1, 2, 3…

When, $D_1 = 12.5211km$

$E_{g1} = F_{g1} * D_1$, for

$E_{g1} = 9.81 * WGD_1$ (Joule)

$= F_{g1}D_1\left(\frac{1000}{3600}\right)$ (W-h)

$E_{g1} = 0.2777F_{g1}D_1$ (W-h)

$E_{g1} = 1427.53\ kwh$

When, D_2 =2.1km

$E_{g2} = 0.2777F_{g2} * D_2$

$E_{g2} = -112.112\ kwh$

When, $D_3 = 1.8km$

$E_{g3} = 0\ kwh$, Because the gradient force at the segment is zero

$when, D_4 = 0.601km$

$E_{g4} = 0.2777 F_{g4} D_4$ (W-h) $= 30.454kwh$

When, $D_5 = 1.799km$

$E_{g5} = 0.2777 F_{g5} D_5$ (W-h)

$E_{g5} = -224.55kwh$

Therefore, the energy consumption from SEBETA substation to LEBUE section post due to the gradient force is:

$E_{g,Sebeta-Lebue} = E_{g1} + E_{g2}$

$E_{g,Sebeta-Lebue} = 1{,}315.42kwh$

Therefore, the energy consumption from LEBUE section post to INDODE substation due to the gradient force is

$E_{g,Lebu-Indode} = E_{g3} + E_{g4} + E_{g5}$

$E_{g,Lebu-Indode} = -194.096kwh$

The total energy consumption from SEBETA substation to INDODE substation due to the gradient force consumed by fright locomotive is:

$E_{g,Sebeta-Indode} = E_{g1} + E_{g2} + E_{g3} + E_{g4} + E_{g5}$

$E_{g,tot} = E_{g,Sebeta-Indode} = 1121.324kwh$

3.5 Power of a traction motor

Power is the rate of doing work and is given by:-

$$\text{Output power} = F_T * V \left(\frac{1000}{3600}\right) Watt \quad (3.31)$$

Now, consider an instant at point p in Figure 2.2, the speed remain constant but tractive effort required is less, the tractive effort required is maximum when the speed is approaching maximum value. Therefore, at instant D power output required from the deriving axle to propel the train is maximum and it is given below [33].

$$P_{max} = F_T * V_{max} \left(\frac{1000}{3600}\right) Watt$$

$$= 570000*120*\frac{1000}{3600} = 19MW$$

P_{max}= 19MW

If η be the efficiency of a transmission gear, maximum power output of the motors [29]

$$P_{max} = \frac{F_T * V_{max}\left(\frac{1000}{3600}\right)}{\eta}\ Watt \tag{3.32}$$

The train efficiency is assumed equal to 0.85, both in traction and in braking, for all range of pantograph voltage (17.5÷31 kV) and train speed (0÷120 km/h). [25]

Output Power required for continuous motion of a locomotive is given below, where continuous speed is 72 km/hr. of the train it is possible to get, using equation (4).

Thus, the continuous power consumption of a train is:-

Output power = $F_T * V\ \left(\frac{1000}{3600}\right) kW$

$= \frac{359048*72}{3600}$ = 7,180.96 kW

$P_{out} = 7{,}180.96kw \approx= 7200\ kw$

Number of motor of the train is 6, thus the maximum power consumption by each traction motor of the locomotive becomes $\frac{19MW}{6} = 3.17MW$

3.6 Specific energy consumption

It is energy consumed in watt hours per ton kilometer of a train. We will first find out specific energy output of deriving wheels. When this is divided by overall efficiency of transmission gear and motor we will get specific energy consumption.

Total energy output of driving axles is spent as follows:

1. for accelerating the train
2. for overcoming the gradient
3. for overcoming the train resistance

- Energy required for train acceleration(E_a)

$$E_a = F_A\text{*Distance OAD} \tag{3.33}$$

$$E_a = 277.8 * M_e * \frac{1}{2} * V_m * t_1 \text{ (Joule)} \tag{3.34}$$

$$E_a\text{=}277.8 * M_e * \frac{1}{2} * V_m * \frac{V_M}{\alpha}\text{, where } t_1 = \frac{V_M}{\alpha} \tag{3.35}$$

It will be seen that since V_m is in km/h, it has been converted into m/s by multiplying it with the conversion factor of (1000/3600).in the case of (V_m/t), conversion factor for V_m and being the same, they cancel out since 1wh=3600J

Therefore, $E_a = 277.8 * M_e \left[\frac{1}{2}\frac{V_m * 1000}{36000} * \frac{V_M}{\alpha}\right]$ w-h

$$E_a = 0.01072\,{V_m}^2 * W_e \text{ (w-h)} \tag{3.36}$$

2. Energy required for overcoming gradient (E_g)

$$E_g = F_g * D' \tag{3.37}$$

Is assumed trapezoidal speed time curve of figure (3.2), where D' is the total distance over which power remains ON, Its maximum value equals the distance represented by the area OABE in figure 3.2 i.e. from the start to the end of the free running period in the case of trapezoidal curve

$E_g = 9.81 * WGD'$ (Joule)

$= 9.81 * WGD' \left(\frac{1000}{3600}\right)$ (W-h)

$$E_g = 2.725WGD' \text{ (W-h)} \tag{3.38}$$

3. Energy required for overcoming resistance (E_r)

$E_r = F_r * D'$

$=$ W$* r * D'$ (joules)

$= W * r * D'(\frac{1000}{3600})$ (W-h)

$$E_r = 0.2778WrD' \ (Wh) \tag{3.39}$$

Therefor the total energy output of the driving axles is

$E_{out} = E_a + E_g + E_r$

$$E_{out} = 0.01072\,{V_m}^2 * W_e + 2.725WGD' + 0.2778WrD' \text{(W-h)} \tag{3.40}$$

3.7 Specific energy output

$$E_{SPO} = \frac{E_{Output}}{W * D} \qquad (3.41)$$

Where D is the total run length in km

$$= \frac{0.01072\, {V_m}^2\ * W_e}{WD} + \frac{2.725WGD'}{WD} + \frac{0.2778WrD'}{WD}$$

$$E_{SPO} = \frac{0.01072\, {V_m}^2}{D}\ \frac{W_e}{W} + \frac{2.725GD'}{D} + \frac{0.2778rD'}{D}\left(\frac{Wh}{tonne-km}\right) \qquad (3.42)$$

It may be noted that if there is no gradient then

$$E_{SPO} = \frac{0.01072\, {V_m}^2}{D}\ \frac{W_e}{W} + \frac{0.2778rD'}{D}\quad \left(\frac{Wh}{tonne-km}\right) \qquad (3.43)$$

3.8 Energy consumption

It is equals the total energy input to the traction motors from the supply .it is usually expressed in W-h by dividing which is equals 3600J. It can be found by dividing the energy output of the driving wheels with the combined efficiency of transmission gear and motor [24].

$$energyy\ consumption = \frac{Output\ driving\ axles}{\eta_{motor} * \eta_{gear}} \qquad (3.44)$$

3.9 Overall Specific energy consumption

It is the energy consumed (in W-h) per ton mass of the train per km length of the run.

$$Specific\ energy\ consumption = \frac{Total\ energy\ consumed\ in\ Wh}{train\ mass\ in\ tonne * run\ length\ \ in\ km} \qquad (3.45)$$

$$= \frac{specific\ energy\ out\ put}{\eta} \qquad (3.46)$$

Where η is overall efficiency of transmission gear or motor $=\eta_{motor} * \eta_{gear} = 0.85$

Therefore, the specific energy consumption is

$$E_{Spc} = \frac{0.01072\, {V_m}^2}{\eta * D}\ \frac{W_e}{W} + \frac{2.725GD'}{\eta * D} + \frac{0.2778rD'}{\eta * D}\left(\frac{Wh}{tonne-km}\right) \qquad (3.47)$$

Thus, the specific energy consumption of the train running at a given schedule speed is influenced by, distance between stops, acceleration, retardation, maximum speed, types of train and its equipment and also the Track configuration [29,33].

Now, by engineering assumption taking (η = 0.85) i.e. overall efficiency of transmission gear and motors and the equivalent gradient from sebeta to LEBU section post is $G_{eq\ sebtea\ to\ Lebu} = g_{eq1} + g_{eq2} = 13.152‰ - 6.32‰ = 6.832‰ = 0.006832$ and total running distance of 14.4km.

For passenger locomotive

Thus, the specific energy consumption in the section from SEBETA substation to LEBU section post at the up track is:-

$$E_{Spec} = \frac{0.01072 * 120^2 * 1.1}{0.85 * 14.4} + \frac{2.725 * 0.006832 * 13.34}{0.85 * 14.4} + \frac{0.2778 * 29.57 * 13.34}{0.85 * 14.4}$$

$E_{Spec} = 22.846 \, {}^{whr}/_{tonne - km}$, Specific energy consumption of passenger locomotive from sebeta to LEBU section post

Thus, the overall specific energy consumption from SEBETA substation to LEBU section post is given as

$$E_{Overall\_cons} = [E_{Spec} * W * D]whr \tag{3.48}$$

Where, W is the weight of the passenger locomotive 656.8 ton

$$= 22.846 \, {}^{whr}/_{tonne - km} * 656.80ton * 14.4km$$

$E_{Overall_{cons}} = 216{,}075.64 \, whr = 216.076kwhr$, overall specific energy consumption of passenger train from sebeta to LEBU section post.

For freight train

Thus, the specific energy consumption in the section from SEBETA substation to LEBU section post at the up track is: where $D' = 13.303km, V_m = 80kmph, F_R = 109.352\ KN$ is resistance force for fright locomotives from Davis‘s Equation

$$E_{Spec} = [\frac{0.01072*80^2 *1.1}{0.85*14.4} + \frac{2.725*0.006832*13.303}{0.85*14.4} + \frac{0.2778*109.352*13.303}{0.85*14.4}]$$

$E_{Spec} = 39.202 \, {}^{whr}/_{tonne - km}$, Specific energy consumption of freight locomotive from sebeta to LEBU section post

Thus, the overall specific energy consumption from SEBETA substation to LEBU section post is given as $E_{Overall\_cons} = [E_{Spec} * W * D]whr.$

Where, W is the weight of the passenger locomotive 3100 tonne

$$= 39.202\, {}^{whr}/_{tonne - km} * 3100tonne * 14.4km$$

$E_{Overall_{cons}} = 1{,}749{,}996.674\, whr = 1{,}749.99kwhr,$ overall specific energy consumption of freight train from sebeta to LEBU section post

For passenger locomotive

Thus, the specific energy consumption in the section from LEBU section post to INDODE substation at the up track is:-

With the equivalent gradient from LEBU section post to INDODE substation is $G_{eq\ Lebu\ to\ Indode} = g_{eq3} + g_{eq4} + g_{eq5} = 0‰ + 6‰ - 14.779‰ = -8.779‰$

$= -0.008779, D' = 17.74km, F_R = 29.57KN$ And the total running distance of D =18.8km

$$E_{Spec} = [\frac{0.01072 * 120^2\ * 1.1}{0.85 * 18.8} + \frac{2.725 * -0.008779 * 17.74}{0.85 * 18.8} + \frac{0.2778 * 29.57 * 17.74}{0.85 * 18.8}]$$

$E_{Spec}\ = 19.719\, {}^{whr}/_{tonne - km}$, Specific energy consumption of passenger locomotive from LEBU section post to Indode substation

Thus, the overall specific energy consumption from LEBU section post to INDODE substation is given as:-

$$E_{Overall\_cons} = [E_{Spec} * W * D]whr\ ,$$

Where, W is the weight of the passenger locomotive 656.8 ton

$$= 19.719\, {}^{whr}/_{tonne - km} * 656.80tonne * 18.8km$$

$E_{Overall_{cons}} = 243{,}483.562\, whr = 243.484kwhr,$ overall specific energy consumption of passenger train from LEBU section post to Indode substation

For freight train

Thus, the specific energy consumption in the section from LEBU section post to INDODE substation at the up track is, where $D' = 17.703km, V_m = 80kmph, D = 18.8km$

$F_R = 109.352\,KN$ is resistance force for fright locomotives from Davis's Equation, and $G_{eq\ Lebu\ to\ Indode} = g_{eq3} + g_{eq4} + g_{eq5} = 0‰ + 6‰ - 14.779‰ = -8.779‰$

$$E_{Spec} = [\frac{0.01072 * 80^2\ * 1.1}{0.85 * 18.8} + \frac{2.725 * -0.008779 * 17.703}{0.85 * 18.8} + \frac{0.2778 * 109.352 * 17.703}{0.85 * 18.8}]$$

$E_{Spec}\ = 38.35\,{}^{whr}/_{tonne - km}$, Specific energy consumption of freight locomotive from LEBU section post to Indode substation

Thus, the overall specific energy consumption from LEBU section post to indode substation is given as

$E_{Overall\_cons} = [E_{Spec} * W * D]whr$, Where, W is the weight of the passenger locomotive 3100 tonne

$$= 38.35\,{}^{whr}/_{tonne - km} * 3100ton * 18.84km$$

$E_{Overall_{cons}} = 2{,}239{,}788.097\ whr = 2{,}239.8kwhr$, overall specific energy consumption of freight train from LEBU section post to INDODE substation

Therefore, the total specific energy consumption of the passenger locomotive from SEBETA SUBSTATION TO INDODE Substation is the summation of sebeta substation to LEBU section post and LEBU section post to INDOD substation of the passenger locomotive i.e.:-

$E_{SPEC\ tot} = 216.076kwhr + 243.484kwhr = 459.56kwhr$, it is the overall energy consumption from SEBETA to INDODE Substation of the passenger locomotives. And the total specific energy consumption of the freight locomotive from SEBETA SUBSTATION TO LEBU section post is the summation of sebeta substation to LEBU section post and from LEBU section post to INDOD substation of the freight locomotive i.e.:-

$E_{SPEC\ tot} = 1{,}749.99kwhr + 2{,}239.8kwhr$ = 3,989.8kWhr it is the overall energy consumption from SEBETA to INDODE Substation of the freight locomotives.

Chapter Four

Modeling Traction Power Supply System

4.1 Transmission Line Modeling

AC transmission line transmits electrical power from national grid network to the railway substation. AC lines are modeled using its series resistance, series inductance, shunt capacitance, and shunt conductance. There are three ways in common practice to model power transmission lines. The three models are the short line model, medium line model and the long line models. A line is defined as a short-length if its length is less than 80 km (50 miles), or medium length for the length between 80 km (50 miles) and 240 km (150 miles), and long line for length above 240km [34]. Both short and medium-length lines are approximated by lumped-parameter models [34]. However, if the line is larger than 240 km, the model must consider parameters uniformly distributed along the line [34, 35]. Since the length of transmission line from three phase grid substation to the traction substation of sebeta, is around 1.40km, it is modeled using the short line model method. Assuming there is a balanced three phase transmission line, the section is modeled using three phase pi circuit with lumped parameters.

The power transmission line is one of the major components of an electric power system. Its major function is to transport electric energy, with minimal losses, from the power sources to the load centers, usually separated by long distances. The design of a transmission line depends on four electrical parameters:

1. Series resistance
2. Series inductance
3. Shunt capacitance
4. Shunt conductance

The series resistance relies basically on the physical composition of the conductor at a given temperature. The series inductance and shunt capacitance are produced by the presence of magnetic and electric fields around the conductors, and depend on their geometrical arrangement. The shunt conductance is due to leakage currents flowing across insulators and air. As leakage current is considerably small compared to nominal current, it is usually neglected, and therefore, shunt conductance is normally not considered for the transmission line modeling.

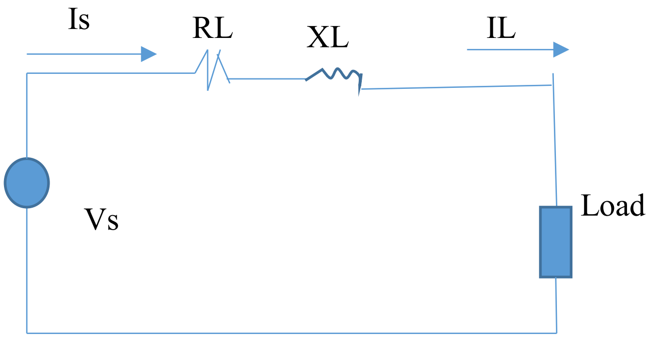


Figure 4.1 Equivalent Circuit of a Short-Length Transmission Line

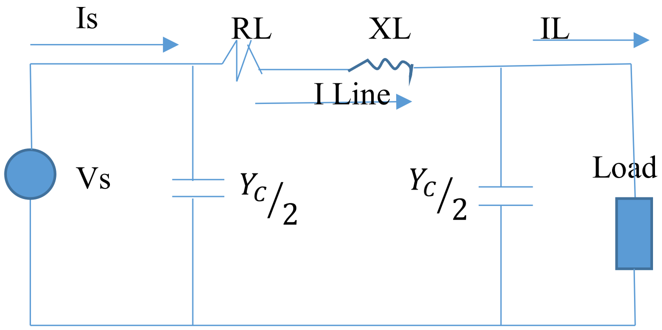


Figure 4.2 Equivalent Circuit of a Medium Length of Transmission Line

THE PER-UNIT SYSTEM

An interconnected power system typically consists of many different voltage levels given a system containing several transmission line, transformers and/or rotating machines. The per-unit system simplifies the analysis of complex power systems by choosing a common set of base parameters in terms of which, all systems quantities are defined. The different voltage levels disappear and the overall system reduces to a set of impedances. The primary advantages of the per-unit system are:

(1) The per-unit values for transformer impedance, voltage and current are identical when referred to the primary and secondary (no need to reflect impedances from one side of the transformer to the other, the transformer is a single impedance).

(2) The per-unit values for various components lie within a narrow range regardless of the equipment rating.

(3) The per-unit values clearly represent the relative values of the circuit quantities. Many of the ubiquitous scaling constants are eliminated.

(4) Ideal for computer simulations. The definition of any quantity (voltage, current, power, impedance) in the per-unit system is:

$$\text{Quantity (per unit)} = \frac{Quantity(normal\ unit)}{Base\ value\ of\ Quantity(normal\ unit)}$$

The complete characterization of a per-unit system requires that all four base values be defined. Given the four base values, the per-unit quantities are defined as:

The complete characterization of a per-unit system requires that all four base values be defined. Given the four base values, the per-unit quantities are defined as:

$$\left.\begin{aligned} V_{PU} &= \frac{V}{V_{base}} \\ I_{pu} &= \frac{I}{I_{base}} \\ S_{pu} &= \frac{S}{S_{base}} \\ Z_{pu} &= \frac{Z}{Z_{base}} \end{aligned}\right\} \qquad (4.1)$$

Note that the numerator terms in the previous equations are in general complex while the base values are real-valued. Once any two of the four base values ($V_{base}, I_{base}, S_{base}$ and Z_{base}) are defined, the remaining two base values can be determined according their fundamental circuit relationships.

Usually the base values of power and voltage are selected and the base values of current and impedance are determined according to:

$$\left.\begin{aligned} I_{base} &= \frac{S_{base}}{V_{base}} \\ Z_{base} &= \frac{V_{base}}{I_{base}} = \frac{V^2{}_{base}}{S_{base}} \end{aligned}\right\} \qquad (4.2)$$

To convert a per unit impedance from old to new base value,I use

$$Z_{pu,new} = \frac{Z_{actual}}{Z_{base\ new}} = \frac{Z_{\mathrm{pu}.old} Z_{base,old}}{Z_{base,new}}$$

Substituting Z_{base} $from\ the\ abov\ equation$

$$Z_{pu,new} = Z_{pu,old} \left(\frac{V_{base,old}}{V_{base\ new}}\right) 2 \frac{S_{base\ new}}{S_{base\ old}} \qquad (4.3)$$

Also assume that:

(1) The value of S_{base} is constant for all points in the power system, and

(2) The ratio of voltage bases on either side of a transformer is chosen to equal the ratio of the transformer voltage ratings, and then the transformer per-unit impedance remains unchanged when referred from one side of a transformer to the other. This will allow me to eliminate the ideal transformer from the transformer model (i.e., I will not have to reflect impedances from one side of the transformer to the other.)

4.2 Substation Model

Description

A typical AC railway power feeding system receives the electric energy at the substation. For technical reasons, like feeding reliability, protection, rotation of phases, and so on, any feeding section is isolated from the others and supplied with only one power substation. A Sebeta Lebu feeding section is about 14.4km long. Conventionally, the power substation is modeled by a combination of an infinite bus bar (ideal voltage source) in series with equivalent high-voltage grid impedance connected to a feeder transformer with on-load tap changer. The tap changer is assumed to give the nominal voltage ratio. In a 1x25 kV system, the model of the feeding transformer is straightforward and is as shown in Figure 3.1. The excitation admittance is usually neglected [10].

Conventionally, the power substation is modeled by a combination of an infinite bus bar (ideal voltage source) in series with equivalent high-voltage grid impedance connected to a feeder transformer with on-load tap changer as shown in Figure 4.3a. This circuit is then simplified to either Thevenin or Norton equivalent circuits as shown in Figure 4.3b and Figure 4.3c, respectively.

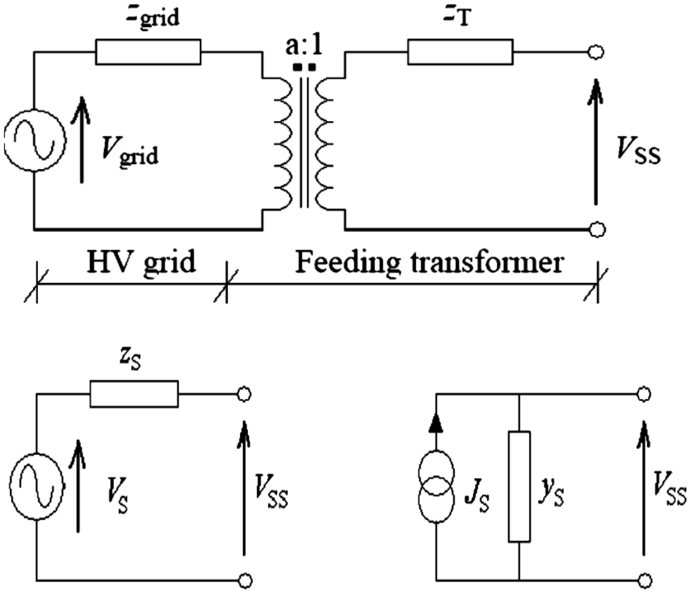


Figure 4.3 Power Substation model [10] a) Simplified Substation Model b) Thevenin Equivalent Circuit c) Norton Equivalent Circuit

4.3 Mathematical Modeling of Traction Power Supply System Component

4.3.1 Traction Power Transmission Line Modeling

The impedance value of the cables and other connection elements (overhead contact lines, bus-bar etc.) depends on different factors (constructional techniques, temperature, etc....) which influence the line resistance and the line reactance. These two parameters expressed per unit of length are given by the manufacturer of the cable.

Feeding line parameter

The impedance is generally expressed by the following formula:

$$Z=(R+X)*L \tag{4.4}$$

Where

Z = Line impedance

R = Line resistance

X = Line reactance

L = Length of the cable

The per unit value of transmission line impedance:

The per-unit values for transmission line impedance lie within a narrow range regardless of the line rating.

The actual value of the transmission line impedance will be converted to it per unit value as follows

$$\left.\begin{aligned} Z_{base} &= \frac{V^2{}_{base}}{S_{base}} \\ Z_{pu} &= \frac{Z_{Transmission}}{Z_{base}} \end{aligned}\right\} \tag{4.5}$$

Taking S_{base}= 100MVA which is constant throughout the system and V_{base} = 132kV at the grid side this thesis determine the per unit value as follows:

$$V_{base(primary\ side\ voltage)} = 132KV$$

$$V_{base(secondary\ side\ voltage)} = 27.5\text{KV}$$

$$Z_{base} = \frac{V^2{}_{base}}{S_{base}} = \frac{27.5^2}{100} = 7.5625\Omega$$

$$Z_{pu(transmission\ line)} = \frac{Z_{Transmission}\ line\ actual\ value}{Z_{base}} \quad (4.6)$$

Therefore, per unit value will be calculated using the above equation as follows:

The feeding line equvalent actual impedance and the per unit value of frrom SEBETA substation to LABU Section post for length of 14.42km with length of feeding section is

Z = (R+ X)* L= (0.080668+j0.303805)*14.42=1.1632+j4.3809Ω

$$Z_{pu(transmission\ line)} = \frac{Z_{Transmission}\ line\ actual\ value}{Z_{base}}$$

$$Z_{pu} = \frac{1.1632 + j4.3809\Omega}{7.5625\Omega} = 0.1538 + j0.5793$$

$Z_{pu=}$0.1538+j0.5793

The feeding line equivalent actual impedance and the per unit value of from LEBU Section post to INDODE substation with length of 18.10km length of feeding section is

Z = (R+ X)* L= (0.080668+j0.303805Ω)*18.10=1.299+j4.891Ω

$$Z_{pu(transmission\ line)} = \frac{Z_{Transmission}\ line\ actual\ value}{Z_{base}} = \frac{1.299 + j4.891\Omega}{7.5625\Omega}$$

$$= 0.1718 + j0.6468$$

4.3.2 Modeling of Traction Power Feeding Section (Catenary System) Network.

4.3.2.1 Overhead Contact System Traction Impedance Modeling

Electrical characteristics such as the impedance, current distribution and current capability determine the energy transmission behavior of an OCS. The electrical characteristics of contact line and the corresponding protection required for the electric installations and operating equipment are designed in view of the current to be transmitted via the contact line system. Once the transmission characteristics and currents are known, it is possible to evaluate the electromagnetic interferences being emitted by an electric railway line. The contact line system can be assumed to act as a long conductor installed above ground [36, 37, and 38]. Figure 4.4 shows the basic supply scheme.

The basic relationships within the contact line system are:

- The substation supplies the electric energy with a source voltage and the current $I_{traction}$.
- The energy is transmitted from the substation to the traction vehicles via the contact line. The line impedance of OCS is designated as Z_{eq}.
- The electric power depends on the conditions of the train at the respective time.
- The traction current Itraction returns to the substation through the return circuit consisting of the rails and return conductors. In OCS, the earth is part of the return circuit.

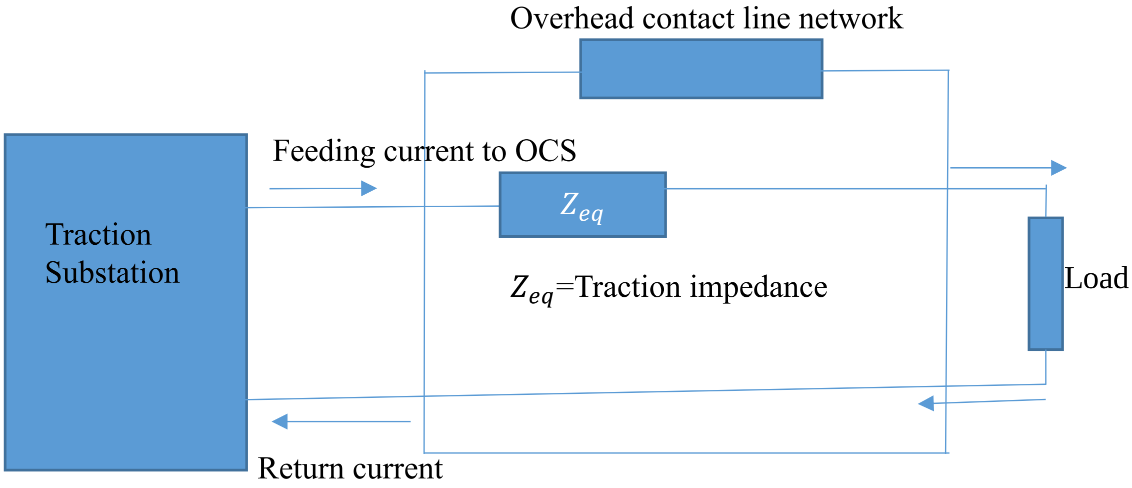


Figure 4.4.Equivalent Network of OCS

Components of Impedance

The impedance of the loop comprising the contact line and the return circuit is commonly called the line impedance. In DC railway installations, the line impedance is obtained from the resistances of all parallel contact lines, reinforcing feeder conductors or cables and the return circuit comprising the track resistance including all parallel return conductors. The impedances of AC contact line consist of active resistance and internal and external reactance of the conductor, and usually expressed in relation to the length [39] [40].

Resistance of OCS Conductors per unit Length

The resistance per unit length of conductors, wires, cables and rails is determined by the electrical properties of the materials that these components are made of. The resistance per unit length of wires, conductors, rails and earth is determined in the following:-

Wires and conductors resistance

The resistance per unit length of the wires and conductors is calculated by:

$$R' = {}^{R}/_{l} = \rho\, {}^{l}/_{Al} = \frac{\rho}{A} \qquad (4.7)$$

Where:

R' *is per unit resistance of the conductor*, ρ *is specific resistivity of the conductor in* Ωm,

l *is length of the conductor and* $A =$ *cross sectional area of the conductor*

Impedance of conductor-earth loop per unit length

Overhead contact lines differ from the common type of transmission line because of the various asymmetric wire arrangements of OCS. For example, a single trolley type OCS consists of one contact line and two rails to form a three conductor overhead contact line with asymmetric wire arrangement. For single track catenary OCS, there will be one catenary wire, one contact wire and two rails to a four wire overhead contact line with asymmetric wire arrangement. For double track line, similarly, there will be two contact line, two catenary wire and four rails, to form eight conductors overhead contact line with asymmetric wire arrangement.

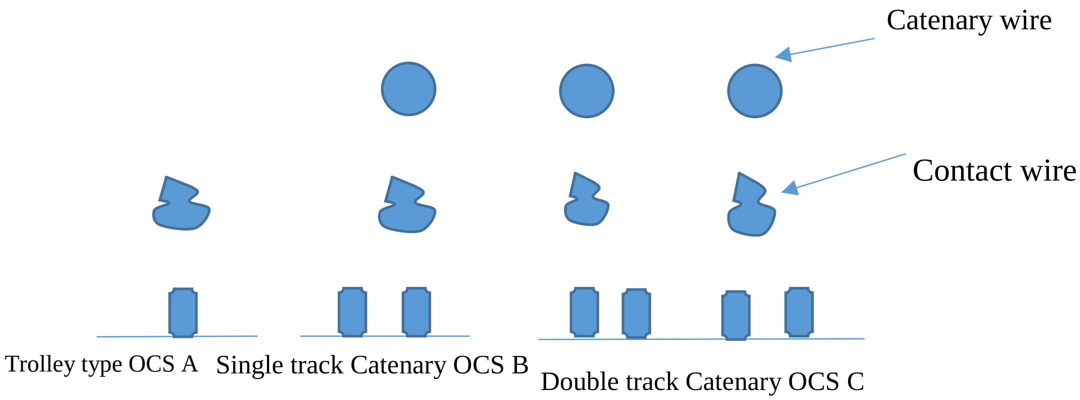


Figure 4.5 Various Types of Conductor Arrangement [38]

The current in the overhead contact network distribute unevenly on the contact wire, catenary wire and rails. This is because, not only the three conductor type is different but also their cross section area is different. This makes the overhead contact line very much different and complex than the common transmission line network.

Trolley type OCS

To calculate the impedance of OCS, first, it is easy to develop the impedance model for trolley type OCS and analogously develop the model for other type of OCS.

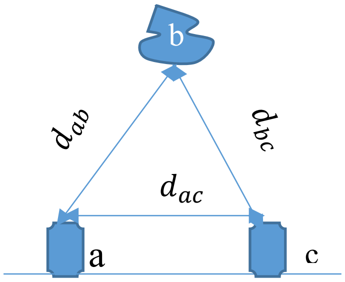


Figure 4.6 Trolley Type OCS Conductor Arrangements [38]

The above trolley type overhead contact line network, consists of a loop containing the contact line b. the rail a, and rail c. the current on each of the rails designated as I_a and I_c.and the current on the contact line is designated as I_b.

The current I_a creates a flux linkage on contact line b and this forms a conductor-earth loop a-b.

The value is calculated for 1km of conductors as follows [38]

$$\Psi_{ab} = \frac{\mu_o I_a 10^3}{2\pi} \int_{R_a}^{d_{ab}} \frac{ds}{\rho} + \Psi_a = \frac{\mu_o I_a * 10^3}{2\pi} ln \frac{d_{ab}}{R_a} + \psi_a \quad (4.8)$$

Where,

$\Psi_{ab} - is\ flux\ linkage\ along\ counter\ a\_b\ due\ to\ I_a, current\ on\ rail\ a.$

$\Psi_a - is\ self\ linkage\ flux\ inside\ the\ rail\ a\ due\ to\ I_a\ .$

$R_a - is\ equivlaent\ radius\ of\ the\ rail\ a.$

$\mu_o - is\ magenetic\ permitivity\ of\ free\ space$

The voltage drop along the loop a-b, created by the current $I_a, on\ the\ rail\ a, wil\ be;$

$$\Delta V_{ab} = r_a I_a + j\omega[\frac{\mu_o I_a * 10^3}{2\pi} ln \frac{d_{ab}}{R_a} + \Psi_a] \quad (4.9)$$

Where, $r_a - is\ per\ unit\ active\ resistance\ of\ the\ rail\ a, in\ {}^{\Omega}/_{km}$

$\omega = 2\pi f - angular\ frequency\ in\ radian\ per\ second$

Taking $\mu_o = 4\pi \text{ x } 10^{-7}\ {}^{H}/_{m}$, the above equationcan be re-written as;

$$\Delta V_{ab} = [r_a + j2\omega * 10^{-4}\ ln\frac{d_{ab}}{R_a} + \frac{j\omega\psi_a}{I_a}]I_a \tag{4.10}$$

The inner linkage flux creats a self reactance of the rail a,$x_a = \frac{\omega\psi_a}{I_a}$ [9]and since the active resistanc is r_a, then the total self impedance of the rail a will be;$Z_a = r_a + jx_a$considering this and re –writing equation (4.10)

$$\Delta V_{ab} = \left[r_a + x_a + j2\omega * 10^{-4}\ ln\frac{d_{ab}}{R_a}\right] I_a = (Z_a + jmln\frac{d_{ab}}{R_a})I_a \tag{4.11}$$

Where,$m = 2\omega\ x\ 10^{-4}$,it is known that for aluminum and copper wire.irrespective of the conductor length and geometery [37].

$x_a = 0.25m$

To simplify the above equation .it is represented as;$\Delta V_{ab} = Z_{ab}I_a$

Then, the impedance of the loop is; $Z_{ab} = Z_a + jm\ ln\frac{d_{ab}}{R_a}$

Analogously, the impedance of the loop b-a, b-c, c-b, a-c, c-a will be;

$$\left.\begin{aligned} Z_{ba} &= Z_b + jm\ ln\frac{d_{ba}}{R_b} \\ Z_{bc} &= Z_b + jm\ ln\frac{d_{bc}}{R_b} \\ Z_{cb} &= Z_c + jm\ ln\frac{d_{cb}}{R_c} \\ Z_{ac} &= Z_a + jm\ ln\frac{d_{ac}}{R_a} \\ Z_{ca} &= Z_c + jm\ ln\frac{d_{ca}}{R_c} \end{aligned}\right\} \tag{4.12}$$

Where,$R_b\ the\ radius\ of\ contact\ wire, b\ and\ R_c\ equivalent\ radius\ c,$

Z_b – The total self-impedance of contact wire,

The two impedance are not equal,$Z_{ab} \neq Z_{ba}$, because the rail and the contact wire are not only different on cross section but also the type of conductor.

To determine the impedance on the loop a-b due to the current I_C *on the rail c; voltage drop relation is used* [37]

$$\Delta V_{ab}^{c} = \Delta V_{cb} - \Delta V_{ca}$$

Since,

$$\left.\begin{aligned} \Delta V_{cb} &= (Z_c + jmln\frac{d_{cb}}{R_c})I_C \\ \Delta V_{ca} &= (Z_c + jmln\frac{d_{ca}}{R_c})I_C \end{aligned}\right\} \qquad (4.13)$$

Then,

$$\Delta V_{ab}^{c} = (\, jmln\frac{d_{cb}}{d_{ca}})I_C$$

Representing, the mutual impedance between loop a-b, due to current I_c on the rail c; by x_{ab}^{c} then,

$$\Delta V_{ab}^{c} = jx_{ab}^{c}I_c$$

$$x_{ab}^{c} = mln\frac{d_{cb}}{d_{ca}}$$

The total voltage drop of along the loop a-b will be,

$$\Delta V_{ab} = Z_{ab}I_a - Z_{bc}I_b + jX_{ab}^{c}I_c \qquad (4.14$$

Catenary OCS

Generalizing, the above scenario for catenary OCS with catenary wire and contact wire in addition to the two rails, then, the total voltage drop caused by all conductor current will be,

$$\Delta V_{ab} = Z_{ab}I_a - Z_{bc}I_b + jX_{ab}^{c}I_c + jX_{ab}^{d}I_d \qquad (4.15)$$

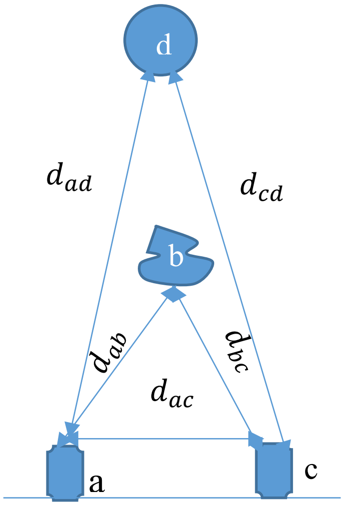


Figure 4.7 Catenary Type OCS Conductor Arrangements [38]

If we take the voltage drop between the loops, d-b, i.e. the voltage drop between the contact wire and catenary wire, then this value equate to zero, since there is no voltage drop between contact wire and catenary wire, then,

$$\Delta V_{bd} = Z_{bd}I_b - Z_{bd}I_d + jX_{bd}^{c}I_c + jX_{bd}^{a}I_d = 0 \qquad (4.16)$$

Where: Z_{bd} - is the total impedance of the loop between contact wire and catenary wire

Z_{db} - is the total impedance of the loop between catenary wire contact wire

$I_a and\ I_b$ – is the current on the rail a and rail b respectively

$I_b and\ I_d -\ \ is\ the$ Current on the contact wire and catenary wire respectively

Note: in the above formulas, the magnetic effect of the earth and resistance of the soil, is not considering the current on contact wire and catenary wire as a combined current:

$$I_o = I_b + I_d \qquad (4.17)$$

Where, I_o is the total current on the contact and catenary wire,

Substituting the above equation in place of $I_a$and I_b in equation (4.16)

Then,

- The total current on contact wire is calculated as:

$$I_b = \frac{Z_{db}I_o - jX_{bd}^{c}I_c - jX_{bd}^{a}I_a}{Z_{db}+Z_{bd}}$$

- The total current on the catenary wire is

$$I_d = \frac{Z_{bd}I_o - jX_{bd}^{c}I_c - jX_{bd}^{a}I_a}{Z_{bd}+Z_{db}} \qquad (4.18)$$

Since, the mutual reactance between the contact wire and catenary wire caused by the current in rails, rail a, and rail c, is small due to relatively large distance between rails and overhead lines then the value of X_{bd}^{a} and X_{bd}^{c} is approximately zero. Then the above equations, (4.17) and (4.18) can be written as:

$$I_b = \frac{Z_{db}}{Z_{db}+Z_{bd}} I \qquad (4.19)$$

$$I_d = \frac{Z_{\mathrm{bd}}}{Z_{db}+Z_{bd}} \mathrm{I} \qquad (4.20)$$

As previously discussed,

- The total impedance of the loop between contact wire and catenary wire is :-

$$Z_{bd} = Z_b + jm\,ln\frac{d_{bd}}{R_b} \qquad (4.21)$$

- The total impedance of the loop between catenary wire and contact wire is:

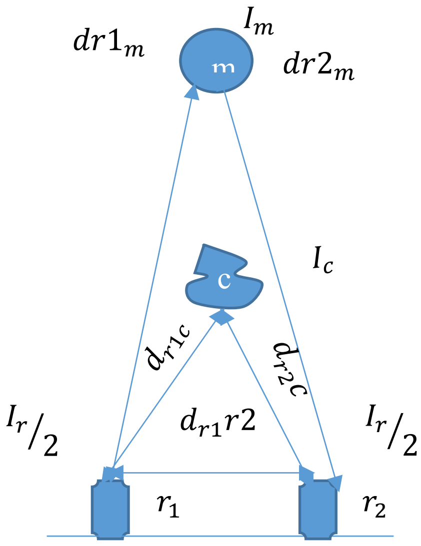
$$Z_{db} = Z_d + jm\,ln\frac{d_{db}}{R_d} \qquad (4.22)$$

Traction and equivalent impedance of OCS

When a current from the traction substation flows to the overhead contact system to feed a locomotive moving along the track; there will be some value of voltage drop in the network due to the resultant or equivalent impedance of the network as, shown in the figure 4.8 below. The resultant impedance which creates, the total voltage drop, is called the traction impedance [36, 37, and 41].

Traction impedance of single track catenary OCS

To calculate the traction impedance of single track catenary OCS; the voltage drops on the loop between the rail r1 and contact wire c is need to be calculated.



$$I_m + I_c = I_o$$

$I_{r1} + I_{r2} = I_r$,then

$$I_{r1} = I_{r2} = {}^{I_r}/_2$$

Figure 4.8 Single Track Catenary Type OCS Conductor Arrangement [38]

Then using equation 2 and the above diagram, the voltage drop on the loop between rail r_1 and contact wire c

$$\Delta V_{cr1} = Z_{cr1} I_c + Z_{r1c} \frac{I_r}{2} + jX_{cr1}^{m} I_m + jX_{r1c}^{r2} \frac{I_r}{2} \qquad (4.23)$$

Then substituting the formula for I_c and I_m from equation 6 and 7 to equation 8

$$\Delta V_{cr1} = Z_{cr1} \frac{Z_{mc}}{Z_{mc} + Z_{cm}} I_0 + Z_{r1c} \frac{I_{r1}}{2} + jX_{cr1}^{m} \frac{Z_{cm}}{Z_{mc} + Z_{cm}} I_o + jX_{r1c}^{r2} \frac{I_r}{2}$$

$$\Delta V_{cr1} = \frac{Z_{cr1} Z_{mc} + jX_{cr1}^{m} Z_{cm}}{Z_{mc} + Z_{cm}} I_0 + \frac{Z_{r1c} + jX_{r1c}^{r2}}{2} I_r \qquad (4.24)$$

The above equation can be re –written as:

$$\Delta V_{cr1} = Z_o I_o + Z_r I_r \qquad (4.25)$$

Where:

Z_o-is the equivalent impedance of the combined contact and catenary wire,

Z_r-is the equivalent impedance of the both rails,

$$Z_o = \frac{Z_{cr1}Z_{mc} + jX_{cr1}^{m}Z_{cm}}{Z_{mc}+Z_{cm}} \qquad (4.26)$$

$$Z_r = 0.5(Z_{r1c} + jX_{r1c}^{r2}) \qquad (4.27)$$

It is assumed that, the total current on the combined overhead lines flows to the combined rails,$I_o = I_r = I_{tracion}$, Then, the total equivalent impedance i.e. the traction impedance of a single track catenary OCS will be:

$$\left.\begin{aligned} I_o &= I_r = I_{tracion} \\ \Delta V_{cr1} &= (Z_o + Z_r)I_{traction} \\ \Delta V_{cr1} &= Z_{equ}I_{tracion} \\ Z_{equ} &= Z_o + Z_r \end{aligned}\right\} \qquad (4.28)$$

Note: In the above equation, it is assumed that, the current flowing in the overhead contact line directly return to the substation through the two rails, without current lose as in side the earth or Soil.

Traction impedance of double track catenary OCS

To calculate the traction impedance of double track catenary OCS; the voltage drops on the loop between the rail r_1 and contact wire $c_1$is need to be calculated.

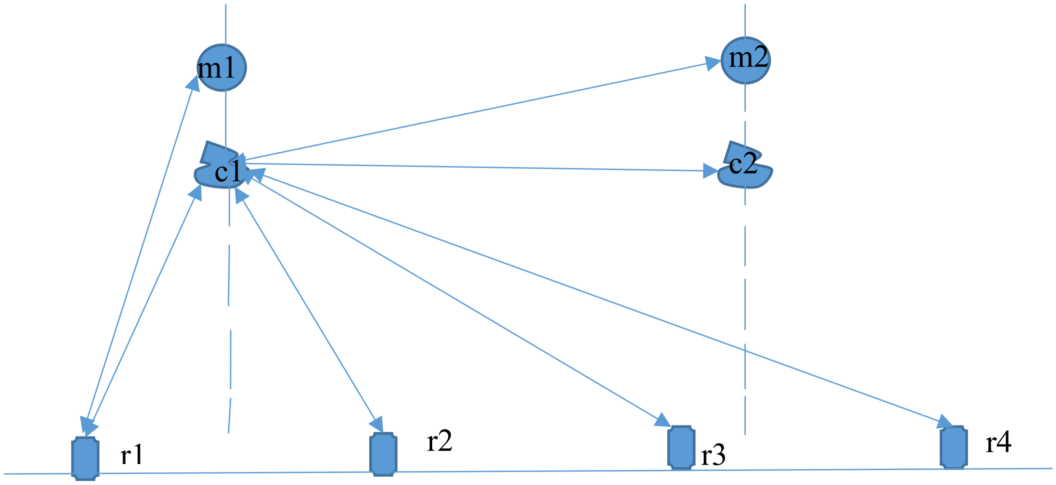


Figure 4.9 Double Track Catenary Type OCS Conductor Arrangement [38]

Similarly, like single track OCS, the traction impedance for double track OCS, is calculated by assuming, $I_1 = I_2 = I_3 = I_4 = \frac{I_r}{4}$ Then, using equation 1 and figure 2, the voltage drop on the loop between rail r_1 and contact wire c_1,

$$\Delta V_{c_1 r_1} = \frac{Z_{c1r1} Z_{mc} + jX_{c1r1}^{m1} Z_{cm}}{Z_{mc} + Z_{cm}} I_{o1} + \frac{jX_{c1r1}^{c2} Z_{mc} + jX_{c1r1}^{m2} Z_{cm}}{Z_{mc} + Z_{cm}} I_{o2} + \frac{Z_{r_1 c_1} + jX_{r1c1}^{r2} + jX_{r1c1}^{r3} + jX_{r1c1}^{r4}}{4} I_r$$

(4.30)

Where: I_{01-} is the total current on combined contact and catenary wire of the first track OCS.

I_{02-} is the total current on combined contact and catenary wire of the second track OCS.

$I_{r-}is$ the total current on the parallel connected rails of both tracks

The above equation can be re written as:

$$\Delta V_{c_1 r_1} = Z_{o_1} I_{o_1} + Z_{o_1}^{o_2} I_{O_2} + Z_r I_r \qquad (4.31)$$

Where:

Z_{o_1} *is the equivalent impedance of the combined contact and catenary wire of first track OCS*

$Z_{o_1}^{o_2}$ *is the mutual impedance between the first track and second track combined overheadlines*

Then, $Z_{o_1} = \frac{Z_{c_1 r_1} Z_{mc} + jX_{c_1 r_1}^{m1} Z_{cm}}{Z_{mc} + Z_{cm}}$

$$Z_{o_1}^{o_2} = \frac{jX_{c_1 r_1}^{c2} Z_{mc} + jX_{c_1 r_1}^{m2} Z_{cm}}{Z_{mc} + Z_{cm}} \qquad (4.32)$$

$$Z_r = 0.25(Z_{r_1 c_1} + jX_{r_1 c_1}^{r_2} + jX_{r_1 c_1}^{r_3} + jX_{r_1 c_1}^{r_4})$$

Since double track catenary wire and contact wire are parallel connected, the following relation exists;

$$\left. I_{o_1} = I_{o_2} = \frac{I_o}{2} \right\}$$

Then equation (4.31) can be re-written as;

$$\Delta V_{c_1 r_1} = Z_{o_1} \frac{I_o}{2} + Z_{o_1}^{o_2} \frac{I_o}{2} + Z_r I_r \qquad (4.33)$$

$$\Delta V_{c_1r_1} = \left(\frac{Z_{o_1} + Z_{o_1}^{o_2}}{2}\right) I_o + Z_r I_r$$

It is assumed that, the total current on the combined overhead lines flows to the combined rails,$I_o = I_r = I_{traction}$ (4.34)

Then, the total equivalent impedance i.e. the traction impedance of double track catenary OCS will be:

$$\Delta V_{c_1r_1} = \left(\frac{Z_{o_1}+Z_{o_1}^{o_2}}{2} + Z_r\right) I_{traction} = Z_{equ} I_{traction} \quad (4.35)$$

$$Z_{equ} = \frac{Z_{o_1}+Z_{o_1}^{o_2}}{2} + Z_r \quad (4.36)$$

Table 4.1 Summary of OCS Traction Impedance Modeling and Calculation ($^{\Omega}/_{km}$*)*

Conductor self-impedance	$Z_c = R' + j0.5\omega 10^{-3}$
	$Z_m = R' + j0.5\omega 10^{-3}$
	$Z_{r_1} = R' + \left(\frac{\pi}{4}\right).\mu_o.f.10^{-3} + j0.5\omega 10^{-4}$
	$Z_{r_2} = R' + \left(\frac{\pi}{4}\right).\mu_o.f.10^{-3} + j0.5\omega 10^{-4}$
Mutual impedance	$X_{cr_1}^{m} = 2\omega.10^{-4}\ln\frac{d_{mr_1}}{mc}$
	$X_{r_{1c}}^{r_2} = 2\omega.10^{-4}\ln\frac{d_{r_{2c}}}{dmr_1}$
Loop impedance	$Z_{cr_{21}} = Z_c + j2\omega.10^{-4}\ln\frac{d_{cr_1}}{R_c}$
	$Z_{r_1c} = Z_{r_1} + j2\omega.10^{-4}\ln\frac{d_{cr_1}}{R_{r_1}}$
	$Z_{cm} = Z_c + j2\omega.10^{-4}\ln\frac{d_{cm}}{R_c}$
	$Z_{mc} = Z_m + j2\omega.10^{-4}\ln\frac{d_{cm}}{R_c}$
Combined impedance	$Z_o = \frac{Z_{cr_1}Z_{mc} + jX_{cr_1}^{m}Z_{cm}}{Z_{mc} + Z_{cm}}$
	$Z_r = 0.5(Z_{r1c} + jX_{r1c}^{r2})$
Equivalent or traction impedance	$Z_{equ} = Z_o + Z_r$

After traction impedance is calculated after current distribution and capability are known, voltage drop, power loss short circuit condition and protection system on OCS system is determined and safety and electromagnetic emissions issue for OCS system is fully addressed. Therefore all the above remaining tasks must be addressed by future work.

Now, for this thesis only consider double track OCS traction impedance calculation. Equivalent impedance of double track from Summary of OCS traction impedance modeling and Calculation can be determined by first listing constants, known line parameters and space Distribution of OCS conductor from each other. Track gage is standard track gage=1435mm=1.435m and distance between track center line=5m.Assume OCS is above the center line of the Track. The minimum and maximum contact line Height is from the rail is 5.75m and 6.5m respectively [42]. From this value contact wire height is taken an average value of 5.9m.The distance between catenary and contact wire at the mast (System height) is 1.4m [43] and minimum dropper length is 0.5m [42]. From this the distance between contact and messenger line is taken an average value of 1m.

1. Conductor self-impedance

$\rho = 0.01777\, {}^{\Omega mm^2}/_{km}$, $\omega = 2\pi f = 2\pi * 50\text{Hz}$

I. Messenger line JTMH 95,$Z_m = R' + j0.5\omega \times 10^{-3}\, {}^{\Omega}/_{km}$

$\rho = 0.02778\, {}^{\Omega}/_{km}$

$$R' = \frac{\rho}{A} = \frac{0.02778}{95} = 2.9242 * 10^{-4}\, {}^{\Omega}/_{m} = 0.2924\, {}^{\Omega}/_{km}$$

Then, $Z_m = 0.2924 + j0.5\omega \times 10^{-3}\, {}^{\Omega}/_{km}$, $Z_m = 0.2924 + j0.517\, {}^{\Omega}/_{km}$

II. Contact line CTAH 120,$Z_c = R' + j\omega * 10^{-3}\, {}^{\Omega}/_{km}$

$$R' = \frac{\rho}{A} = \frac{0.01777}{120} = 1.481 * 10^{-4}\, {}^{\Omega}/_{km} = 0.1481\, {}^{\Omega}/_{km}$$

$Z_c = R' + j\omega * 10^{-3}\, {}^{\Omega}/_{km}$, $Z_c = 0.1481 + j0.157\, {}^{\Omega}/_{km}$

Running rails

The resistance of steel running rails can be obtained from table below which shows the characteristic properties of commonly used running rails. Where rail joints are used, the resistance R_c is increased according to the material and cross section. A commonly accepted value is 0.5% per joint.

Table 4.2. Resistances per Unit Length of Conductors at 20 °C and 40 °C, values in $^{m\Omega}/_{km}$

Conductor	A(mm^2)	$R_c{}'$at 20℃		$R_c{}'$ at 40℃	
		New	20% worn	New	20% worn
Cu AC-80	80	223	278	240	300
Cu AC-100	100	179	223	193	240
Cu AC-120	120	149	186	160	200
CA BzII	70	422	-	455	-
CA BzII	95	298	-	321	-
CA BzII	120	237	-	255	-

Table 4.3 Characteristics Properties of Commonly used Running Rails Types

Rail type	m' $^{kg}/_{m}$	H (mm)	Fw (mm)	A (mm^2)	U (mm)	$r_{eq'}$ A (mm)	$R'\ ^{m\Omega}/_{km}$ Wear 0%	$R'\ ^{m\Omega}/_{km}$ Wear 15%
R_{50}	50	152	132	6450	620	45.31	34.5	40.6
R_{65}	65	180	150	8288	700	51.36	25.2	29.9

Note:m-mass per unit length, H-height of rail, Fw-foot width, A-cross sectional area

r_{eq-}cross secion area- equivalent radius; r_{eq}=$\sqrt{\frac{A}{\pi}}$, R'- resistance at 20 ℃

I. Rails R50 $Z_{r_1} = Z_{r_2} = R' + \left(\frac{\pi}{4}\right) * \mu_o * f ** 10^{-3} + j0.5\omega * 10^{-4}\ ^{\Omega}/_{km}$

R' =0.0345$^{\Omega}/_{km}$

$\mu_o = 4\pi \times 10^{-7}\ ^{H}/_{m} = 4\pi \times 10^{-4}\ ^{H}/_{km}$

Then, substituting the value and this thesis obtain the following result

$Z_{r_1} = Z_{r_2} = 0.0345 + j0.01571\, {}^{\Omega}/_{km}$

2. Mutual impedance

$$X^{r_2}_{r_1c} = 2\omega \text{ x } 10^{-3} ln \frac{d_{r_{1c}}}{mr_1}, X^{m}_{cr_1} = 2\omega \text{ x } 10^{-3} ln \frac{d_{mr_1}}{d_{mc}}$$

$d_{mr_1} = \sqrt{0.7175^2 + 6.9^2} = 6.937m,$

$and, d_{mc} = 1m$

$d_{r_2c} = \sqrt{0.7175^2 + 5.9^2} = 5.943m$

$X^{m}_{r_1c} = 0.122\, {}^{\Omega}/_{km}, X^{r_2}_{r_1c} = -0.00097\, {}^{\Omega}/_{km}$

3. Loop impedance

i. $Z_{cr_1} = Z_c + j2\omega * 10^{-4} ln \frac{d_{cr_1}}{R_c}$

$d_{cr_1} = 5.943m\ and\ equivalent\ radius\ of\ the\ rail\ R_c$

$R_c = 0.0453m$

$Z_{cr_1} = 0.1481 + j0.4639\, {}^{\Omega}/_{km}$

ii. And $Z_{r_{1c}} = Z_{r_1} + j2\omega * 10^{-4} ln \frac{d_{cr_1}}{R_{r_1}}$

$Z_{r_{1c}} = 0.03455 + j0.3221\, {}^{\Omega}/_{km}$

iii. $Z_{cm} = Z_c + j2\omega * 10^{-4} ln \frac{d_{cm}}{R_c}$

$Z_{cm} = 0.1481 + j0.3515\, {}^{\Omega}/_{km}$

iv. $Z_{mc} = Z_m + j2\omega * 10^{-4} ln \frac{d_{cm}}{R_m}$

$Z_{mc} = 0.2924 + j0.3515\, {}^{\Omega}/_{km}$

4. Combined impedance

$$Z_o = \frac{Z_{cr_1} Z_{mc} + jX^{m}_{cr_1} Z_{cm}}{Z_{mc} + Z_{cm}}$$

Substituting each value from above we get the following:

$Z_0 = 0.0876 + j0.2467\, ^{\Omega}/_{km}$

$Z_r = 0.5(Z_{r_1c} + jX_{r_1c}^{r_2})$

Z_r =0.03455+j0.1562$^{\Omega}/_{km}$

Therefore, the equivalent or traction impedance becomes:-

$Z_{equ} = Z_o + Z_r$

$Z_{equ} = 0.12215 + j0.4029\, ^{\Omega}/_{km}$, equivalent traction impedance of the system.

Earth return path

Although the differing types of soil show a great variety of resistivity, the resistance of earth to DC currents is zero due to the huge cross section involved. However, in case of AC currents, the Earth possesses a resistance. The resistance per unit length of the earth return path, R'_E is a function of the frequency of the power supply [9].

$$R'_E = \frac{\pi}{4} * \mu_o * f \qquad (4.37)$$

I. Suspension type and wire material of OCS

1. The suspension type of OCS: adopt full compensation simplified catenary suspension.
2. Wire material of OCS

Table 4.4 Table of Wire Material and Tension

Type of wire material		Model of wire material	Tension (kN)
Contact wire	Main line	CTAH-120	13
	Station tracks	CTAH-85	9
Carrier cable	Main line	JTMH-95	15
	Station tracks	JTMH-70	15
Additional wire	Supply lines	LBGLJ-185/25	10
	Return line	LBGLJ-185/25	10
	Overhead ground wire	LBGLJ-70/10	6.5

Table 4.5 List of the Impedances of Traction Electric Network

	Trains / Project	SS9	HXD1C
Conduit composition 1		JTMH95+CTSH120	
Single line	Impedance of traction electric network ($^{\Omega}/_{km}$)	0.127449+j0.416534	
	Power factor	0.85	0.95
	Equivalent impedance of traction network($^{\Omega}/_{km}$)	0.3519	0.2511
Dual-line	Impedance of traction electric network ($^{\Omega}/_{km}$)	0.116155+j0.375627	
	Power factor	0.85	0.95
	Equivalent impedance of traction network($^{\Omega}/_{km}$)	0.4042	0.2840
	Conduit composition 2	JTMH95+CTSH120+LBGLJ185	
Single line	Impedance of traction electric network ($^{\Omega}/_{km}$)	0.091894+j0.342983	
	Power factor	0.85	0.95
	Equivalent impedance of traction network($^{\Omega}/_{km}$)	0.2793	0.1945
Dual-line	Impedance of traction electric network ($^{\Omega}/_{km}$)	0.080668+J0.303805	
	Power factor	0.85	0.95
	Equivalent impedance of traction network($^{\Omega}/_{km}$)	0.2468	0.1715

4.3.3 Traction Substation Modeling

The available data considering SEBETA SUBSTATION

Table 4.6 Electrical Parameter of Traction Network [44] and Analysis Data

Primary Voltage V_P	132KV
Secondary side of transformer no load (open circuit) voltage	27.5KV
Secondary side transformer load voltage	25KV
Minimum short circuit capacity of the grid	400MVA

Rated MVA capacity of single phase transformer SEBETA substation to LEBU section post	2 x16 MVA
Transformer percentage impedance or rated percentage reactance ukr	12%
Transformer reactance to resistance ratio is X/R	45

Rated secondary current

$$I_s = \frac{Rated\ MVA\ Capacity\ of\ single\ phase\ transformer}{Open\ circuite\ voltage\ of\ the\ secondary\ side} \quad (4.38)$$

$$= \frac{16MVA}{27.5} = 581.82A$$

Primary short circuit current

$$I_{PSC} = \frac{I_S}{Z\%} = \frac{335.91}{0.12} = 4.848\text{kA}$$

Three phase fault current I_{SC}

$$I_{SC} = \frac{Minimum\ short\ circuit\ capacity\ of\ the\ grid\ in\ MVA}{nominal\ primary\ side\ voltage\ in\ KV} \quad (4.39)$$

$$= \frac{400MVA}{132KV} = 3.030\text{k}A$$

But based on IEC 60909, the equivalent voltage source in RMS value is

$$US = \frac{C_{Max} * U_{grid}}{\sqrt{3}}\ in\ volt \quad (4.40)$$

This thesis Choose voltage factor of $C_{max} = 1.1$

$$Z_{grid} = \frac{C_{Max*}V_{grid}}{\sqrt{3} * I_{SC}} = \frac{1.1 * 132KV}{\sqrt{3} * 3030.23A} = 27.66\Omega$$

Now, converting to 25 KV side (no load 27.5kv) voltage is

$$Z_{grid} = a^2 * Z_{grid} \quad (4.41)$$

Where, a is the transformer turns ratio

$a^2 = (\frac{27.5KV}{132KV})^2 = 0.0434$

Thus, $Z_{grid} = 0.0434 * 27.66$

$=1.201\Omega$

Transformer impedance to LV (low voltage) side is:

$$Z_T = Z_{pu} * Z_{base} \tag{4.42}$$

Where $Z_{pu} = \frac{Z\%}{100} = 0.12$

$$z_{base} = \frac{KVbase^2}{MVAbase} \tag{4.43}$$

$$= \frac{25^2}{16} = 39.063\Omega$$

Therefore,$Z_T = Z_{pu} * Z_{base}$

$=0.12*39.063=4.688\Omega$

From IEC 60076 standard, X/R ratio for the transformer capacity of 16MVA is equal to 45. Thus, substituting the value X/R=45, X=45R,

$Z_T = \sqrt{R^2 + X^2} = \sqrt{R^2 + 2025R^2}$

$Z_T = \sqrt{2026R^2} = 45.011R$

Therefore,

R_T=0.1042Ω

X_T=j4.687 Ω

Thus, $Z_T = R + jX = 0.1042 + j4.687\ \Omega$

And, from IEC 60909 standard given in **appendix A,** the resistance and the reactance value of the grid impedance is multiplied by with factor of 0.1 and 0.995 respectively.

$$Z_{grid} = R_{grid} + jX_{grid} \tag{4.44}$$

R_{grid}=0.1*1.201=0.1201Ω

$X_{grid=}$ 0.995 $*$1.201=0.125Ω

$Z_{grid} = 0.1201 + j0.125\ \Omega$

Therefore, impedance at traction substation is give as the sum of the line impedance and the impedance of the transformer

$\sum R_S = \sum R_{grid} + \sum R_T$=0.1201+0.1042=0.2243 Ω

$\sum X_S = \sum X_{grid+} \sum X_T = j0.125 + j4.687 = j4.812\Omega$

$\sum Z_S$= $\sum R_S + \sum X_S$=0.2243+j4.812 Ω

Finally the model can be simplified into Thevenin equivalent form as shown belo

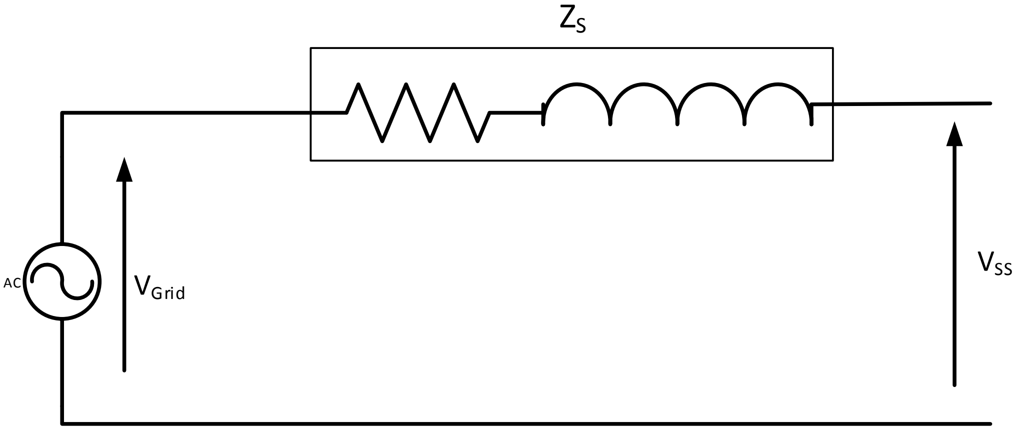


Figure 4.10 Equivalent Substation Model

4.3.4 Train (locomotive) Modeling

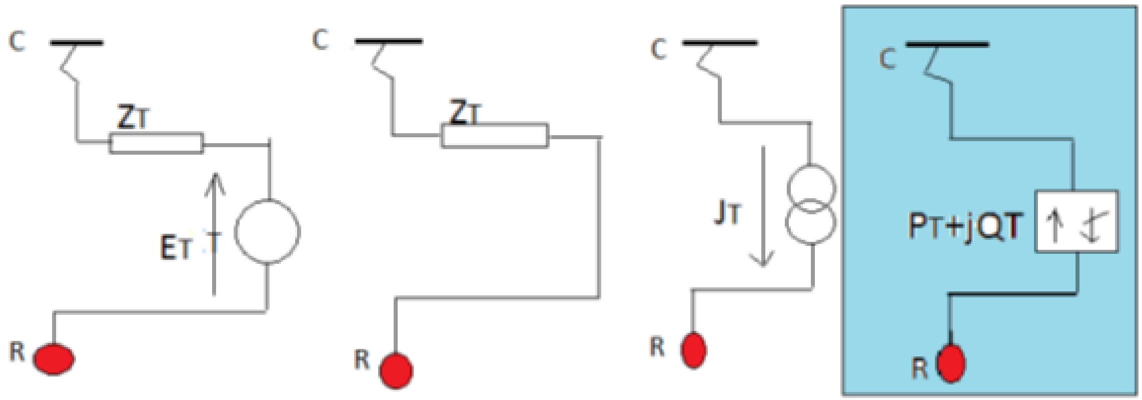
The other key component of traction power supply system is the electric train. It requires a simple model to reduce problem complexity and overall execution time; a direct method (integrating ordinary differential equations) used to obtain a model like that used in traction drive analysis is not appropriate for steady-state power flow calculations [10].

Power drawn from the load (train) depends upon the train's speed and operation mode which are in turn determined by the traction equipment characteristics, train weight, aerodynamics, track geometry and train control strategies etc. The power demand may thus vary significantly within a very short period of time during an inter-station run. The number of trains in a feeding section is also vital to the calculation as they may be running at different speeds, drawing (or feeding) different amount of power and thus posing different effects on the supply system. Nominal separation among trains is yet another important consideration and it should follow the timetables or dispatching schedules of the train services. As a summary of explanation determining load that takes power from catenary has lot of difficulties and several different conditions have to be taken care, these conditions can be listed as in below

- Size of load can change due to different vehicles and different traction motors.
- Changing speed of vehicles in time interval due to driver behavior and time scheduling.
- Load differences on different sections of catenary system

The train represents the load in the RES. Usually the MVA requirement of the train is determined for a specific speed, acceleration, and position of the train. The type of motor and drive on the train is usually considered also. And it requires a simple model to reduce problem complexity and overall execution time; directly applying differential equations to obtain a model is not appropriate for steady-state power flow calculations [10]. A train is modeled by Constant power model. This model is widely used in power flow problems. Also, it is mainly used in this research because powers and power factor are the two quantities that can be measured by the on-board traction controller. Furthermore, applying the Newton's second law of motion can alternatively calculate the modeled parameters through tractive effort vs speed and train running information data.

Figure 4.11(d) shows the constant power model. Due to the dynamic load nature of the train, traction model for each line subsection varies according to the requirement of the train movement in the subsection. Hence, the traction load model assuming 0.95 power factor and constant power model approach, is done as follows Having a fixed MVA at a certain node or nodes, renders the problem nonlinearity , according to [10] four methods are used to model a train:



4.11(a) Linear Model 4.11(b) Impedance Model 4.11(c) Current Model 4.11(d) Power Model Figure 4.11Types of Train Model [10]

4.3.4.1 Linear Model

The voltage source E_t and the series impedance Z_t representing this model can be determined as a function of speed, pantograph voltage and tractive effort over the whole range of operation. The direct calculation cannot be done because of the phase angle of the internal voltage source, which must be referenced to the substation. Thus, a look-up table is used to define the model parameters at any instance according to train speed, voltage and tractive effort. When the locomotive model is needed, the relevant values can be loaded and used in the power flow program. The inevitable disadvantage of this model is that a substantial database for each locomotive must be prepared for the simulation program. The linear model is shown in Figure. 4.11(a).

4.3.4.2 Impedance or Admittance Model

The effective model is the one that uses only the four measured quantities. The impedance magnitude is calculated by the ratio between the voltage and current magnitudes whereas the phase angle is simply determined from the power factor interpretation. The impedance model is given in Figure. 4.11(b).

4.3.4.3 The Current Model

The current model is not appropriate due to the unknown phase angle, a numerical database stored for this model with respect to train speed, pantograph voltage and tractive effort like the linear model is another effective way. The lookup table is required to obtain its parameters at any simulated time step. During simulation, the pantograph voltage is an unknown and needs to be solved for by a power flow program. The phase angle of the locomotive current must be specified with respect to the phase angle of the substation voltage. It cannot be specified unless the power flow solution has been successfully obtained. In practice, only four electrical quantities (Pantograph voltage-magnitude, input current-magnitude, power and power factor) can be measured on-board a train. The current model is given in Figure. 4.11 (c).

4.3.4.4 Constant Power Model

This model is widely used in three-phase power flow problems. Also, it is mainly used in this research because powers and power factor are the two quantities that can be measured by the on-board traction controller. Furthermore, applying tractive effort vs speed and train running information with the Newton’s second law of motion can alternatively calculate the model parameters [10]. Figure 4.11 (d) shows the power model. The train is modeled with a resistance and inductance and the motor size will be 7.2MW. Finally simulation will be done in several load conditions like different number of loads, different firing angles to investigate the performance of proposed system as much as possible. Due to the dynamic load nature of the train, traction model for each line subsection varies according to the requirement of the train movement in the subsection. Hence, the traction load model assuming 0.95 power factor and using constant power model, is done as follows:

Calculating the equivalent train impendence:

Train voltage=25KV

Train power=7.2MW

Power factor=0.95

The train current=$I_{tr} = \frac{P_{tr}}{V_{tr}\ COS\ \phi} = \frac{7.2MW}{25KV*0.95} = 303.1580A$

Reactive power =$Q_{tr} = P_{tr} * tan(\ cos^{-1}(\ \phi))$=2.3665MVar

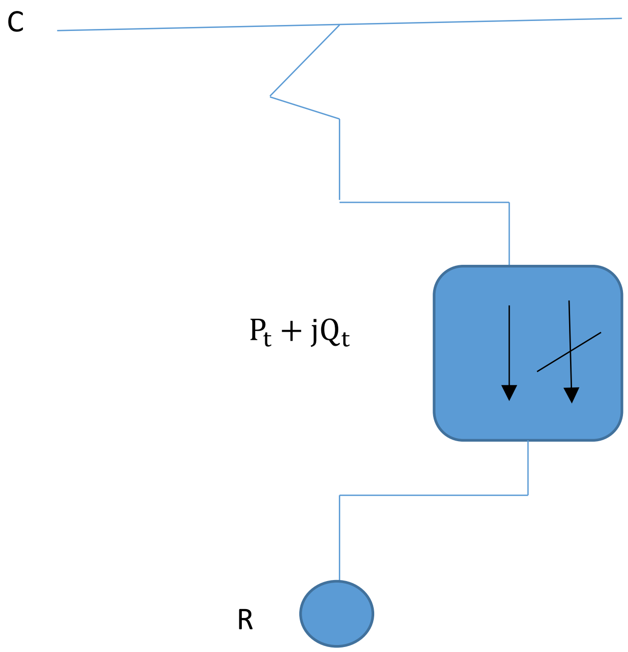


Figure 4.12. Train Model for Power Flow Calculation

4.4 Capacity of Traction Transformer

Capacity of traction substation shall be calculated according to conditions such as long term/short-term train pairs, type of locomotives, traction mass of a train and also shall be adjusted based on long-term/short-term conditions of freight train. The adjusted capacity shall be confirmed by full utilization of overload capacity of the traction substation to finally determine the installed capacity of the traction substation.

Transformer capacity calculation has three steps

A. Calculated capacity is determined by the requirements of the annual transportation volume size.

B. Transformers capacity check result is calculated, considering the train speed and intensive operation, the effective current of the power supply section and traction transformer overload ability. It is to ensure the required capacity of the transformer's safety operation.

C. After considering calculated capacity, capacity check result and other factors, installed capacity is determined as the selected number and capacity of the transformers selected according to the actual standards.

The situations of traction transformer capacity calculation: the calculation capacity of traction transformer depends on the load current of feeding section, mostly determined by traction calculation results, line transportation capacity conditions and the traffic volume. The train load density which is called line carrying capacity is calculated from annual transportation; so the main critical factor is annual transportation. The train current and feeding sections current can be calculated from train electricity consumption.

Calculating conditions of the number of trains or train density (N): It shall be calculated with the required carrying capacity of passenger and freight trains and the carrying capacity of lines. The required carrying capacity calculation depends on the following parameters:

- Traffic transportation requirement,
- Freight flow fluctuation coefficient: Based on the characteristics of this line and the freight transportation features along the line, the freight flow fluctuation coefficient

is taken as 1.3 and maintains some over designed capacity. The general consideration, designed coefficient: single line 20%, double track 15%.

- To consider the short term annual transportation is shown in equation 4.45

$$N = \frac{K_1 .K_2 .\Gamma \times 10^4}{365 .G.r} \; Trains /_{day} \qquad (4.45)$$

Where, K_1 is fluctuation coefficient, using 1.2 short term, K_2 is over designed coefficient single line uses 1.2, double track uses 1.15, r is freight trains net weight coefficient, weight ratio between freight net weight and gross weight, Γ is annual transportation $10^4 \, {}^{t}/_{year}$ and G is traction weight (t)

If the national regulation transportation required capacity is closed to line capacity, train number N can be calculated by the line transportation capacity. National regulation transportation required capacity is closed to the line transmission capacity as shown in equation 4.46

$$N = \frac{\Gamma \times 10^4}{365 \, G.r} Trains /_{day} \qquad (4.46)$$

If the national regulation transportation required capacity is less than half of the line capacity, train number N can be calculated by two times the transportation capacity as shown in equation (4.47)

$$N = \frac{2\Gamma \times 10^4}{365 \, G.r} Trains /_{day} \qquad (4.47)$$

Both cases are the variation coefficient and over designed coefficient is no longer consideration.

4.4.1 Train average current calculation

The train energy consumption, traction running time and transportation volume are the essential information of traction calculation result. This is the number of trains in the section is represented as; a fixed average train number and the location distribution of trains in the section are independent and unrelated to each other. The following formula is used to compute traction average current in feeding section shown as equation (4.50).

The train energy consumption (use i=f (t) curve

It is the product of average train current and traction network Voltage

$$E_{over\ all\_cons} = A = U\int_0^T i(t)dt \qquad (kVAh) \tag{4.48}$$

[0, T] divided into n equal parts Δt (minutes), corresponding current $i_0, i_1. i_2$ in the section running time T=$n\Delta t$.Total energy consumption at train running time

$$E_{over\ all\_cons} = U\int_0^T i(t) * d(t)\ kV.A.h = U\frac{n\Delta t}{60} * \frac{1}{n+1}\sum_{k=0}^{n} i_k$$

$= U\frac{n\Delta t}{60} I \qquad kV.A.h$ Excluding coasting or braking self-electricity energy consumption

$$A = \frac{U*I*t}{60} kV.A.h \tag{4.49}$$

4.4.2 Train average current

$$I_{avg} = \frac{1}{T}\int_0^T i * dt) = \frac{1}{n+1}\sum_0^n i_k\ (A)$$

$$I_{avg} = 60 * \frac{A}{U*t} + 7A \tag{4.50}$$

Where, 7A is self-electricity for locomotive, A is total energy consumption when the train travel through feeding section,$KV.A.h$, U is the average traction network voltage ,25kV, t is the traction running time of the train in (min).

The train effective current under traction running time can be expressed mathematically as following in equation (4.51)

For passenger train

Using equation 3.3, $t = [\frac{D}{V_{max}} + K * V_{max}]$

Total time running from SEBETA substation to LEBU section post

For passenger train

$$t = \left[\frac{D}{V_{max}} + K * V_{max}\right], K = \frac{1}{2}\left[\frac{1}{\alpha} + \frac{1}{\beta}\right] = \frac{1}{2}\left[\frac{1}{2.88} + \frac{1}{1.89}\right] = 0.438$$

$$t = \left[\frac{14.4km}{120km/h} + 0.438 * 120km/h\right]$$

$t = 8.076min$

$I_{avg} = 60 * \frac{E_{over\ all_{cons}}}{U * t} + 7A$

$E_{Overall_{cons}} = 216{,}075.64\ whr = 216.076kwhr$

Assuming Average power factor pf=0.85

$KVAh = \frac{kwh}{pf}$

$= \frac{216.076kwhr}{0.85} = \ 254.207kVAh\ = 60 * \frac{E_{over\ all_{cons}}}{V*t} + 7A$

$I_{avg} = 60 * \frac{254.207}{25*2*8.07} + 7A = \ 44.8001A$ Train average current per locomotive from SEBETA to LEBU section post

Table 4.7 Overall Energy Consumption, Time Taken and Train Average Current of Passenger and Freight Locomotive

For passenger train						
From	To	$E_{Overall_{cons}}$ MWhr	Train Power consumption in (MW)	$E_{Overall_{cons}}$ $(kVAh)$	$Running\ Time$ (min)	I_{avg}(A)
Sebeta	Lebu	0.2161	1.61	254.207	8.076	44.801
Lebu	Indode	0.2435	1.422	286.452	10.276	40.451
Sebeta	Indode	0.4596	1.503	540.659	18.352	42.353
For freight train						
Sebeta	Lebu	1.749	8.755	2,058.812	11.993	213.001
Lebu	Indode	2.240	8.788	2635.059	15.293	213.766
Sebeta	Indode	3.990	8.773	4,693.882	27.286	213.430

4.4.3 Feeder current

Traction load characteristics : fluctuation intermittence the traction load is movable as train change speed along the railway. The magnitude of traction load is variable with time. The higher the transportation density is, the larger the traction loads are, and vice versa. The train can be in arbitrary arrangement in the power supply section, arbitrarily distributed load on the power supply section. Traction load variation make the power supply system computation complex. The calculation of the feeder current is described by the three main values:

4.4.3.1 Feeder average current: is the average of the feeder current for day and night. Application:- estimation on the transformer capacity utilization, determination of the phase split and feeding section of catenary, and negative sequence calculation in primary system caused by traction power supply system .

4.4.3.2 Feeder effective current: is the RMS value of the feeder current for day and night. Application: to determine the temperature rise of the electrical equipment; transformer capacity calculation and heat calculation of catenary. Traction load characteristics make the power supply computation complexity. The calculation of the feeder current is described by the three main values.

4.4.3.3 Feeder maximum current: is maximum instantaneous operating current, and the maximum short-term operating current.

Application: the maximum instantaneous current is used for tuning relay protection. Over current protection setting value must be greater than the possible maximum operating current, and less than the possible minimum value of fault current. Maximum short-term operating current is used for the choice of electric equipment, such as the choice of transformer capacity.

The number of train which appeared at feeding sections in up and down direction is:-

- Train density N, Number of train operation per day (pairs).
- t- Train traction running time when travel through feeding section.
- Total train energy consumption when traveling through a feeding section $E_{overall\_cons}$

Assumption: trains average current in segment is equal and the traction running time is the same.

The train effective current under traction running time can be expressed mathematically as following in equation (4.51).

$$I_{\varepsilon g} = \sqrt{\frac{1}{t_g}\int_0^{t_g} i^2}\, dt = I_{\varepsilon g} = K_{\varepsilon g} I_g \tag{4.51}$$

Where, $K_{\varepsilon g}$ is the train effective current Coefficient.

$K_{\varepsilon g} = 1.04, {K_{\varepsilon g}}^2 = 1.08$

$$I_{\varepsilon g} = K_{\varepsilon g} I_g \tag{4.52}$$

$$I_1 = \ I_2 \dots\dots\dots\dots..I_{n=}\ I_{avg}, \qquad t_{g1} = t_{g2}\dots\dots\dots\dots\dots\dots\dots\dots t_{gn} = \frac{t_g}{n} \tag{4.53}$$

Where,

n is the feeding section starting from i=1, 2,……. n,

N (number of trains) daily train operation number (in pairs)

4.4.4 Calculation of capacity under normal operation

In this paper only consider the transformer capacity of single phase transformer of a Sebeta substation

Single phase transformer

Then, calculate with feeder effective I_ϵ current (whole-day average)

$$S = U * I_\epsilon \tag{4.54}$$

Feeder current,$i_F = i_1 + i_2$ where, i_1 & i_2 is the current in the first track and second track respectively.

Effective value,$${I_\varepsilon}^2 = {I_{\varepsilon 1}}^2 + {I_{\varepsilon 2}}^2 + 2I_1 I_2 \tag{4.55}$$

Transformer computing capacity (under normal operation)

$$\text{S}=U * \sqrt{{I_{\varepsilon 1}}^2 + {I_{\varepsilon 2}}^2 + 2I_1 I_2} \tag{4.56}$$

4.4.5 Capacity check result

Capacity check result is determined by the required maximum capacity. The maximum train number N_{max} is needed. Capacity check result on one hand, it is used for the requirement of the intensive operation alternatively it is to ensure safety operation of the traction transformer under overload condition.

$$S_{check} = \frac{S_{max}}{K} \tag{4.57}$$

Where, K is the overload coefficient if YND11, single-phase, Scott connection transformer, is set to 150%, 175%, and 200% separately. The largest train number under intensive operation short time peak hour transportation cannot be avoided under daily operation.at single line, each section consider one train ,at double track; departure interval is set to eight minutes at up and down direction. The number of trains running at the same time in the feeding section is the maximum number of trains .for the calculation of double track; the departure interval is set to eight or ten minutes, can calculate as shown formula (4.58)

$$N_{max} = \frac{1440}{8} \; 0r \; N_{max} = \frac{1440}{10} \tag{4.58}$$

To consider the overload performance of traction transformer: 1). the average daily load of traction transformer, during normal operation will not exceed the rated capacity. However, due to rapid fluctuation in the traction load, it may often appear to overload, but average value is small. The short-traction load fluctuation is not considered below 1-2 min. The reason of that limitation: the relationship between transformer windings temperature rise and the time is varied with exponential function. Thermal time constant of the transformer winding is 5 min - 10min; the thermal time constant of transformer oil is from 2h - 3h. The winding temperature changes caused by the traction load variation take about 15min to reach a steady value, and the winding of short time temperature rise allows up to 140℃ 2). During the intensive operation, the traction transformer may incidentally overload which last longer than the winding thermal time constant. This overload situation enables the winding insulation temperature rise rapidly, and increases the relative life loss. The design specification, if the traction transformer can overload 50% of the capacity, it can achieve the requirement of the short-term or long-term intensive operation.

4.4.6 Installed capacity

The traction transformer capacity calculation is to determine the transformer installed capacity and the numbers of transformer. The traction transformer installed capacity for normal speed electric railway to use, 20, 25, 31.5, 40 and 50 (MVA); for heavy load freight, 60 and 80(MVA) and dedicated high-speed passenger railway also use, 63.75 and 120(MVA).

Table 4.8 Standards of Traction Transformer Installed Capacity

	Normal speed electric railway					heavy load freight		Dedicated High-speed passenger Railway		
Traction transformer installed capacity S_r(MVA)	20	25	31.5	40	50	63	80	63	75	120

The traction transformer standby modes: in electrified sections with traction transformer: Movable stand by; each traction substation installs two traction transformer; two transformers operate in parallel normally. The substations are equipped with special railway branch lines. Standby transformer is placed in the special train, and parked in the middle position between traction substations or power supply section.

Fixed spare system; each traction substation installed two traction transformer, one for normal operation, another for standby. The permanent spare system increases traction transformer capacity; increases the number of traction transformer. Each traction transformer capacity should be able to design to achieve the largest traction load under normal traction transportation.

Calculation of installed capacity as shown below;

Substation, S_{normal}, S_{max}

Substation capacity=max $\{S_{normal}, {}^{S_{max}}/_{K}\}$ (4.60)

For the substation under parallel operation, need to check that one transformer can achieve the requirement of four hours normal operation.

4.4.7 Traction Transformer Capacity Calculation

Capacity of traction substation shall be calculated according to conditions such as long term/short-term train pairs, type of locomotives and traction mass of a train and shall be adjusted based on long-term/short-term conditions of freight train. The adjusted capacity shall be confirmed by full utilization of overload capacity of the traction substation to finally determine the installed capacity of the traction substation.

Conditions of traction transformer capacity calculation are:

- The calculation capacity of traction transformer depends on the load current of feeding section, mainly determined by traction calculation results, traffic volume and line passing capacity conditions.
- The most critical factor is annual transportation. Train load density which is called line carrying capacity is calculated from annual transportation. Train current and feeding section's current can be calculated from train's electricity consumption.
- For single phase transformer the transformer capacity is calculated by:

$$S_1 = U.\sqrt{I_{\varepsilon 1}^2 + I_{\varepsilon 2}^2 + 2I_1 I_2} \tag{4.61}$$

- Where, U is the secondary nominal voltage, $I_{\varepsilon 1}$ and $I_{\varepsilon 2}$ are the effective feeding current for the first and second track respectively and I_1 and I_2 the average feeding currents respectively.
- For other substation they are used three phase V_V transformer, hence its capacity is calculated as:

$$S_3 = 2U.I'_{\varepsilon 1}.k_t \tag{4.62}$$

Where: - K_t is temperature coefficient usually equal to 0.94.

Calculating conditions of the number of trains (N): It shall be calculated with the required carrying capacity of passenger and freight trains and the carrying capacity of lines. The required carrying capacity calculation depends on the following parameters:

- Traffic transportation requirement
- Freight flow fluctuation coefficient: Based on the characteristics of this line and the freight transportation features along the line, the freight flow fluctuation coefficient is taken as 1.3.

Number of train per day through Sebeta-Mieso: -

$$N = \frac{k1 * k2 * \Gamma * 10^4}{365 * G * r} train/day \qquad (4.63)$$

k_1 is fluctuation coefficient =1.15 for double line

k_2 is over designed coefficient=1.2, $\Gamma\ is\ anual\ transportation = 2400t$

G is traction weight 3500 in tonne

$r\ is$ Weight ratio between freight net weight and gross weight,

70t wagons with dead weight of 25.7t are operated for freight trains, with average net load of 74.3t. and The payload of the freight wagon is equal to the maximum load capacity (i.e69.3 tons) increased of 5 tones as worst condition, the total weight is equal to 100 tons, the traction tonnage is 3,500t and each train is composed of 28 wagons

$$\mathrm{r} = \frac{74.3}{100} = 0.743$$

Under short term situation $N = \frac{1.15 * 1.2 * 2400 * 10^4}{365 * 3500 * 0.743} train/day\ = 35 train/day$

Under long term situation $N = \frac{1.2 * 2400 * 10^4}{365 * 3500 * 0.743} train/day\ = 31 train/day$

During the intensive operation, the traction transformer may incidentally overload which last longer than the winding thermal time constant .This overload scenario enables the winding insulation temperature rise rapidly, and large increases the relative life loss. But under other situations, many factors (such as light load, winter, etc.) can reduce the relative life loss. Therefore, for design specification, if the traction transformer can overload 50% of the capacity, it can achieve the requirement of the short-term or long-term intensive operation.

$$S_{check} = {S_{max}}/{K}$$

Where K is overload coefficient and its value is 175% for our case. It have five section and single track; therefore maximum number of train can be calculated by assuming one train per feeding section. The number of trains running at the same time in the feeding section is the maximum number of trains.

Single line: empirical formula

$$N_{max} = \frac{1440}{t_{oi}+t'_{oi}+\tau} \tag{4.64}$$

Where: $t_{0i} + t'_{0i}$-Trains' net running time at up and down direction of the ith section.

τ- Stop time (at station), generally uses 7 minutes.

Then the capacity of the single phase traction transformer in sebeta substation is determined by the following formula

$$S_1 = U.\sqrt{I_{\varepsilon 1}^2 + I_{\varepsilon 2}^2 + 2I_1 I_2}$$

Now based on the following assumption train average current in segment equal and traction running is the same

$$I_1 = \cdots \ldots \ldots \ldots \ldots . I_n = I_{avg}, t_1 = \cdots \ldots \ldots \ldots . . t_n = {}^{t}/_{n}$$

$$I_{avg} = 60 * \frac{E_{over\ all_{cons}}}{V*t} + 7A\text{(Self-electricity)}$$

Feeder daily average current of Double track of unilateral power supply in appendix

$$I_F = npI_{avg} = \frac{Nt}{T} I_{avg}$$

$$P = \frac{Nt_{g1}}{n*T}$$

Feeder daily effective current of a double track of unilateral power supply is

$$I_{FE} = I_F \sqrt{1 + \frac{{K_{eg}}^2 - p}{n*p}}$$

Feeder daily average current at double track of unilateral power supply considering over zone feeding, n=2 because only one additional train is recommended according to the capacity of substation transformer, using equation (2.32) it is possible to calculate the probability of train in segment

$$P = \frac{2Nt_g}{2n * T}$$

Where, T=2Nt_g

Now from the Table 4.6 this thesis consider only for short term and take, N=14 trains per day and total sum of average time of freight train and passenger trains $t_g = 91.276min$

Therefore, $\text{P} = \frac{2*14*91.276min}{2*2*1440min}$

P=0.4437

Feeder current

$$I_F = npI_{avg}$$

$$= 2*0.4437*257.802$$

I_F =228.775A

Feeder average effective current

$$I_{FE} = I_F \sqrt{1 + \frac{{K_{eg}}^2 - p}{2n * p}}$$

$$I_{FE} = 228.775 \sqrt{1 + \frac{1.08 - 0.4437}{2 * 2 * 0.4437}}$$

I_{FE}=266.6499A

Thus, from the above data we can calculate maximum effective current as follows:

$$I_{\varepsilon max} = \sqrt{I_{\varepsilon 1}^2 + 2I_1I_2 + I_{\varepsilon 2}^2}$$

$$I_{\varepsilon max} = \sqrt{266.6499^2 + 266.65^2 + 2 * 228.775 * 228.775}$$

$I_{\varepsilon max} = $ 496.871A

$S_{max} = UI_{max}$

S_{max} = 25KV*496.871A=12,421.775KVA

$S_{check} = {}^{S_{max}}/_{K}$

Where, assuming, K=175%

$S_{check} = 7{,}098.157KVA = 7.098MVA$

Therefore, from the result this thesis deduce that the SEBETA substation transformer capacity is capable with the calculated capacity of 7.098MVA with the installed capacity of 16 MVA.

Table 4.9 Analysis Data of Train Total Passenger and Freight Train Power and Energy Consumption

For passenger train and freight train data analysis									
From	To	$E_{Overall_{co}}$ (MWhr)	$E_{Overall_{cons}}$ $(MVAh)$	Train Power consumption in (Mw)	Section distance (km)	I_{avg}(A)	I_F(A)	I_{FE}(A)	Section runtime $t(min)$
Sebeta	Lebu	1.970	2.313	10.365	14.4	257.802	228.77	266.65	20.069
Lebu	Indode	2.483	2.922	10.21	18.81	254.217	225.59	262.94	25.569
Sebeta	Indode	4.4590	5.235	10.276	33.21	255.783	226.98	264.56	45.638

Chapter Five

Power Flow and Short-Circuit Analysis

5.1 Introduction of Power Flow Calculation of AC Railway

The main function of AC railway power supply systems is to deliver electric energy to the electric locomotives that are connected to the system, and to do so, effectively and economically. Calculations related to AC railway power supply systems need basic tools such as power flow algorithms for obtaining voltage, current or power flows through each feeder section. As long as the AC railway power systems can be described by the conventional power supply analysis [10], classical power flow methods are applicable. The Newton-Raphson (NR) and the Gauss-Seidel (GS) methods are two well-known iterative techniques for solving power flow problems. With quadratic convergence [10], the NR method has been successfully developed and broadly accepted as the most powerful algorithm for several decades. Although these methods were originally developed for solving industrial power systems, they can be adapted to railway power distribution systems. In this thesis, analysis, modeling and simulation of the Newton Raphson power flow analysis of Sebeta to indode substation traction power supply system is explained in more detail.

5.2 Overview of DIgSILENT /*Power Factory*

DIgSILENT, is a computer aided engineering tool for the analysis of transmission, distribution, and industrial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization. “DIgSILENT " is an acronym for “DIgital SImuLation of Electrical NeTworks". DIgSILENT Version 7 was the world’s first power system analysis software with an integrated graphical single-line interface. That interactive single-line diagram included drawing functions, editing capabilities and all relevant static and dynamic calculation features. PowerFactory was designed and developed by qualified engineers and programmers with many years of experience in both electrical power system analysis and programming fields. The accuracy and validity of results obtained with PowerFactory has been confirmed in a large number of implementations, by organizations involved in planning and operation of power systems throughout the world.

Use of a single database, with the required data for all equipment within a power system (e.g. line data, generator data, protection data, harmonic data, controller data), means that *PowerFactory* can easily execute all power simulation functions within a single program environment functions such as load-flow, short-circuit calculation, harmonic analysis, protection coordination, stability calculation, and modal analysis. Although *PowerFactory* includes some sophisticated power system analysis functions, the intuitive user interface makes it possible for new users to very quickly perform common activities such as load-flow and short-circuit calculations.

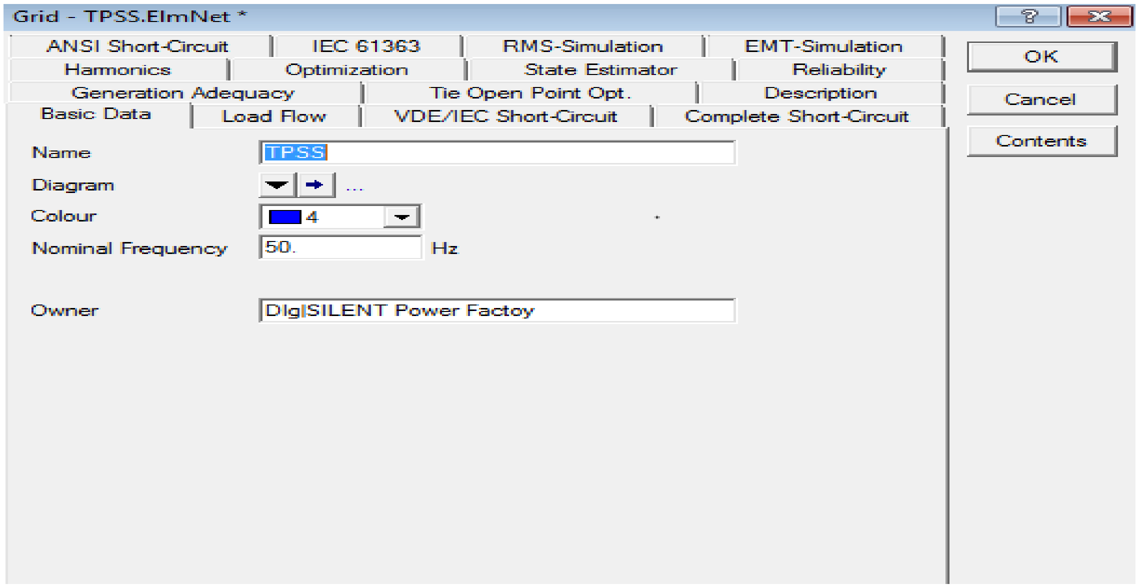
5.3 Network Representation and Calculation Methods

Electrical Buses

Buses are an electrical conductor, maintained at specific voltage and capable of carrying high current usually used to make a common connection between a several circuits in a system.

Three type of buses:

1. **Slack bus**: both voltage and angle settings are needed. Also the nominal voltage of the bus should be set. It is connected to the utility. The utility supply system is represented as a generator with unlimited capacity.



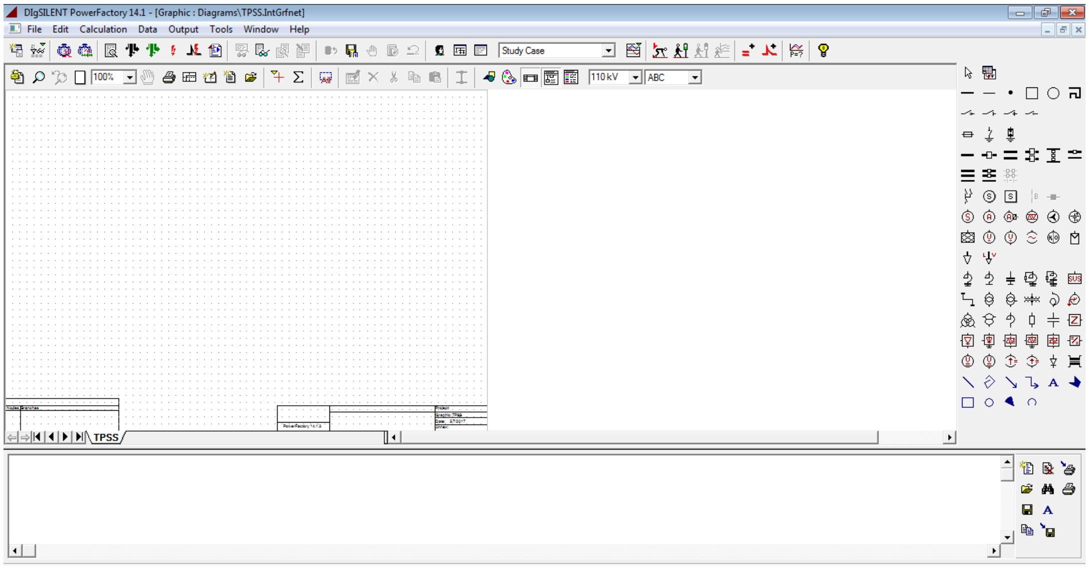
Grid - TPSS.ElmNet *

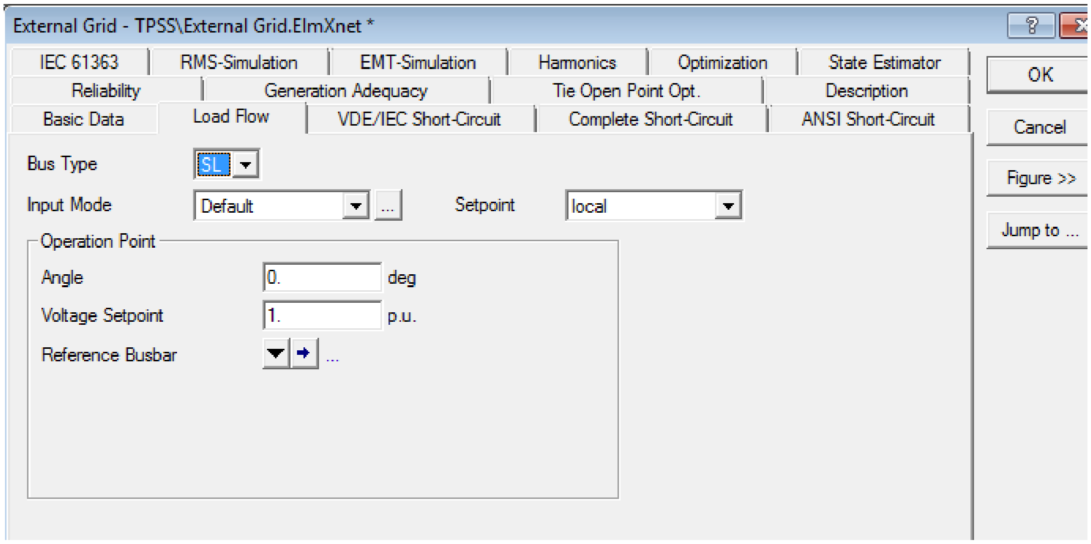
Name: TPSS

Colour: 4

Nominal Frequency: 50. Hz

Owner: DIgSILENT Power Factoy





Bus Type: SL

Input Mode: Default

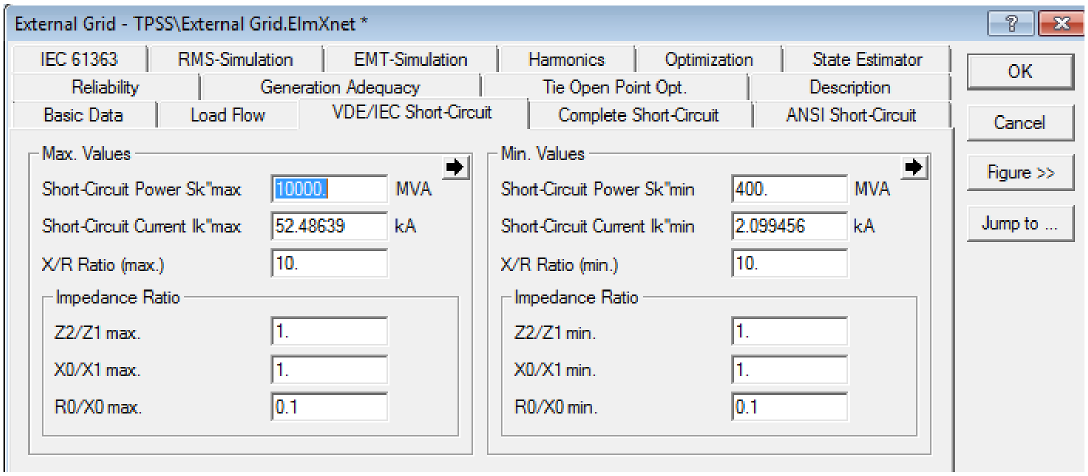
Setpoint: local

Operation Point

Angle: 0. deg

Voltage Setpoint: 1. p.u.

Reference Busbar



Max. Values

Short-Circuit Power Sk"max: 10000. MVA

Short-Circuit Current Ik"max: 52.48639 kA

X/R Ratio (max.): 10.

Impedance Ratio

Z2/Z1 max.: 1.

X0/X1 max.: 1.

R0/X0 max.: 0.1

Min. Values

Short-Circuit Power Sk"min: 400. MVA

Short-Circuit Current Ik"min: 2.099456 kA

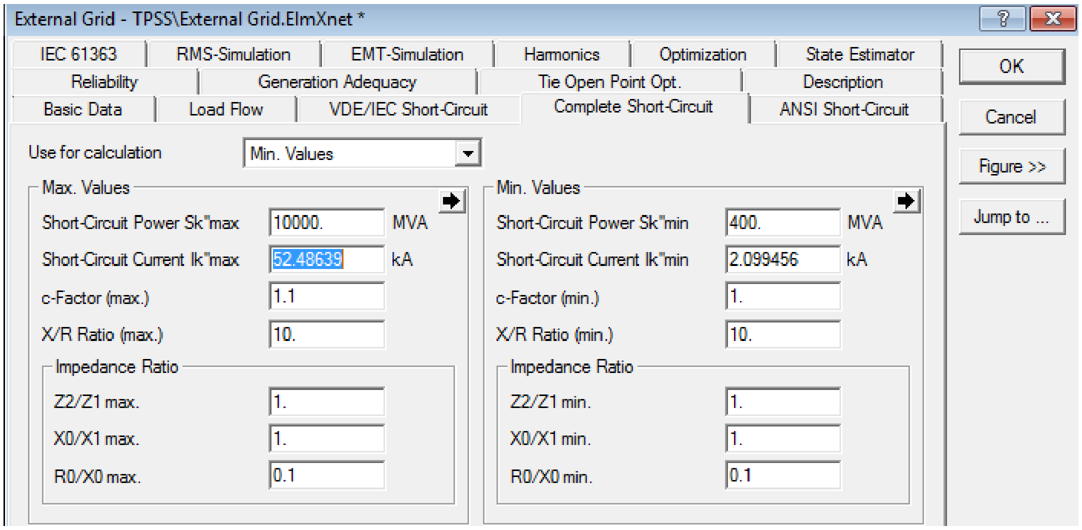
X/R Ratio (min.): 10.

Impedance Ratio

Z2/Z1 min.: 1.

X0/X1 min.: 1.

R0/X0 min.: 0.1



External Grid - TPSS\External Grid.ElmXnet *

Use for calculation: Min. Values

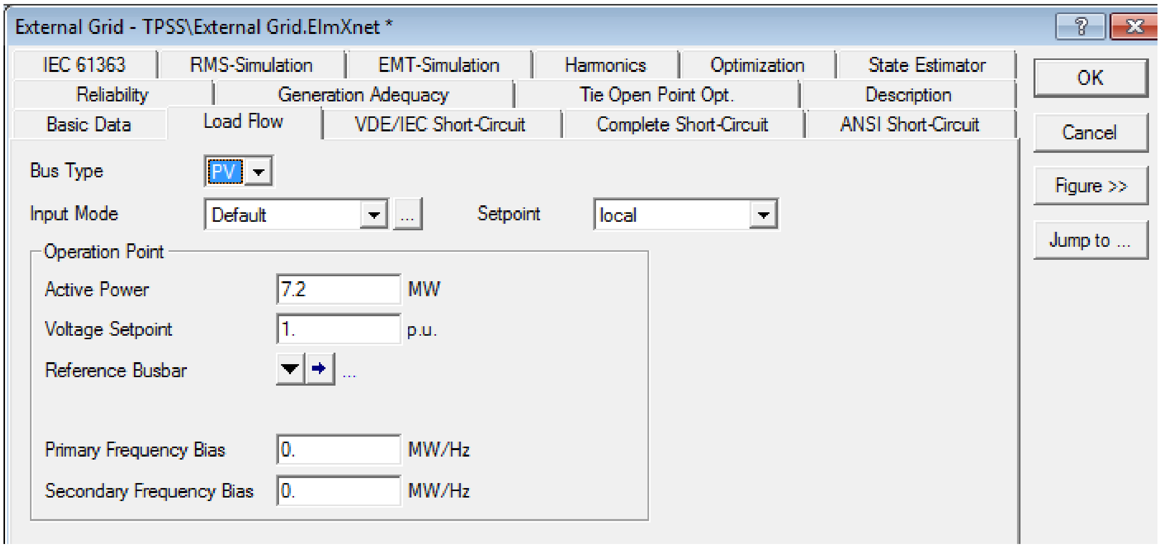
Max. Values
Short-Circuit Power Sk"max 10000. MVA
Short-Circuit Current Ik"max 52.48639 kA
c-Factor (max.) 1.1
X/R Ratio (max.) 10.
Impedance Ratio
Z2/Z1 max. 1.
X0/X1 max. 1.
R0/X0 max. 0.1

Min. Values
Short-Circuit Power Sk"min 400. MVA
Short-Circuit Current Ik"min 2.099456 kA
c-Factor (min.) 1.
X/R Ratio (min.) 10.
Impedance Ratio
Z2/Z1 min. 1.
X0/X1 min. 1.
R0/X0 min. 0.1

For slack bus, the actual MW output will be determined by the simulator. However, we must insert a Min MVars and Max MVars fields.

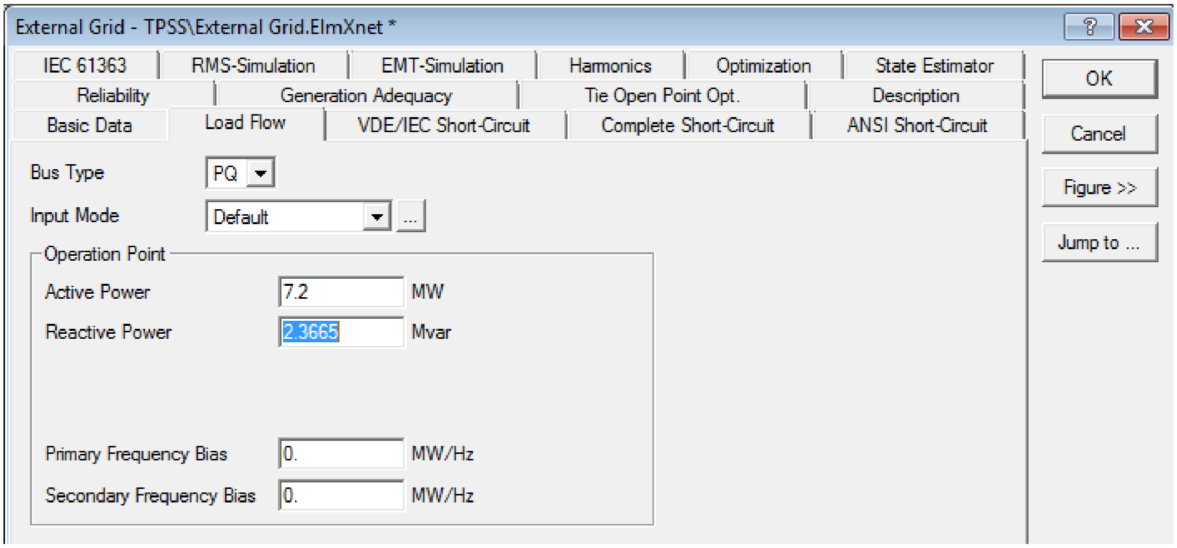
A load flow calculation determines the voltage magnitude (V) and the voltage angle (ϑ) of the nodes, as well as the active (P) and reactive (Q) power flow on branches. Usually, the network nodes are represented by specifying two of these four quantities. Depending on the quantities specified, nodes can be classified as:

2. **PV bus**: is connected to the generator. No need to input the angle setting box. Here the active power and voltage magnitude are specified. This type of node is used to represent generators and synchronous condensers whose active power and voltage magnitude are controlled (synchronous condensers P=0). In order to consider equipment limits under abnormal conditions, reactive power limits for the corresponding network components are also used as input information.



Bus Type: PV
Input Mode: Default
Setpoint: local
Operation Point
Active Power: 7.2 MW
Voltage Setpoint: 1. p.u.
Reference Busbar
Primary Frequency Bias: 0. MW/Hz
Secondary Frequency Bias: 0. MW/Hz

3. PQ bus: Neither voltage setting nor angle setting information is needed. Here the active and reactive power are specified. This type of node is used to represent loads and machines with fixed values. Loads can also be set to change (from their original Po and Qo values at nominal voltage) as a function of the voltage of the node to which the load itself is connected. Elements specified as PQ (for example synchronous machines, static generators PWM converters or SVS's) can be "forced" by the algorithm so that the P and Q resulting from the load flow are always within limits.



Bus Type: PQ
Input Mode: Default
Operation Point
Active Power: 7.2 MW
Reactive Power: 2.3665 Mvar
Primary Frequency Bias: 0. MW/Hz
Secondary Frequency Bias: 0. MW/Hz

4. Device nodes: special nodes used to represent devices such as HVDC converters, SVSs, etc., with specific control conditions (for example the control of active power flow at a certain MW threshold in a HVDC converter, or the control of the voltage of a bus bar by an SVS).

5.4 One-Line Diagram

The starting point of any power-flow problem is the development of a single-line diagram of the power system, from which computer solutions can be obtained. The one line diagram of the case study network, AC railway electric network, was thus drawn on the DIgSILENT Power factory simulator software platform for this study. All the organized data were then fed to the one-line diagram. Partial view of the one-line diagram is given chapter 6 simulation result in both edit and run modes of DIgSILENT Power factory simulator software.

5.5 Load Flow Problem

A load flow analysis can be utilized to solve the load flow problems and to determine total transmission loss in a system as well as losses in individual components. It provides real and reactive powers at different buses. Total transmission loss can be calculated from the algebraic sum of powers injected at all buses.

All necessary data like generators rated active power and output active power, minimum and maximum reactive power limits of generators, peak active and reactive loads of substations, transformer data, feeder line parameters, and all necessary and available data were collected from ERC concerned offices and analyzed in this section as required by the simulation software used.

In this research load flow analysis was used to determine the bus voltages profiles, active power flows, reactive power flows and losses on all lines and transformers of the AC railway network. The software used in carrying out this analysis is DIgSILENT Power factory simulator software.

5.6 Power Flow Solution

Power-flow problem starts with a single line diagram of the power system, from which computer solutions can be obtained. Data for the simulation include bus data, transmission line data, and generator data and load data. Computer simulation was used in this thesis to obtain the solutions to the grid Systems power flow based on the Newton-Raphson technique in DIgSILENT *PowerFactory* simulator software run mode. This is an iterative numerical method to find power flow solution until the specified convergence.

5.7 Short Circuit Analysis

Short-circuit studies should be performed as part of the design modeling of traction systems to determine the magnitude of the prospective currents flowing throughout the power system at various time intervals after a fault occurs. Much of the behavior of fault currents is determined by the characteristics and dynamics of the electrical system. During this time, the prospective system is called upon to detect, interrupt and isolate these faults.

The duty imposed on this equipment is dependent upon the magnitude of the current, which is dependent on the time from fault inception. The short circuit data is then used to select fuses, breakers and switchgear ratings in addition to selecting protective relays.

The short circuit study yields the following information:

I. The magnitude of short circuit currents throughout the traction power system
II. The maximum short circuit current seen by a circuit breaker, which is one of several pieces of information necessary in order to specify a circuit breaker
III. Voltages resulting from short circuit conditions.

Complex traction power systems, fed from multiple sources, and having multiple distribution paths typically requires the use of computers and specialized programs when performing short circuit analysis. Hand calculations are suitable for estimating the operating characteristics of a few individual circuits, but accurate calculation of voltages, power flows, or short circuit currents throughout a traction power system would be impractical without the use of computer programs.

The accuracy of the calculated fault currents depends primarily on accurate modeling of the system configuration and the system impedances used in the calculations. Short-circuit computer models for power system analysis can be based on mesh-current and node-voltage analysis methods. The behavior and value of the short circuit currents can be calculated for both transient and steady state conditions as required. Ordinary techniques of circuit analysis can be used to find the steady state value, and it may be possible to use a load flow program to compute the steady-state value.

5.7.1 Steady-State Short Circuit Analysis

A steady state short circuit analysis is typically considered as an extension of the load flow analysis. For a steady state short circuit calculation, the model built for the load flow analysis is sufficient. Once the model is built and the fault currents calculated, an examination of each feeder breaker steady state short circuit duty should be examined. Although the steady state current is not the current that the circuit breaker will interrupt, it does form a basis for calculating prospective peak current that the breaker must be capable of breaking. During a fault, there will be an initial transient peak that is greater than the steady state current, and the circuit breaker must be capable of interrupting the peak of the transient portion.

5.7.2 Circuit Breaker Calculation

A short circuit level for the selected different transformers varies between 400 MVA to 4000 MVA depending on the proximity of the generating station. Based on the short circuit levels the rated circuit breaking current values is as under. The method of calculating the fault current both for primary and secondary side of the substation is as follows.

$X_{smax} = \mathrm{j}\frac{{U_{2N}}^2}{S_{min}}$ = j1.89Ω where U_{2N}=27.5 kV

$X_{smin} = \mathrm{j}\frac{{U_{2N}}^2}{S_{max}} = j0.189\Omega$ Where S_{max} =4000MVA

$X_t = \mathrm{j}\frac{10\%}{100}\frac{{U_{2N}}^2}{S_T} = \mathrm{j}\frac{10\%}{100}\frac{27.5^2}{16MVA}$= j5.672Ω (for the single phase transformer at SEBETA)

The required transformer capacity is calculated $S_T = 7.04MVA,$ which is approximated to standard value of 16MVA. The transmission impedance is shown in the Table 4.5

Assuming the short circuit transformer capacity is 12%, then the maximum fault current is calculated as,

Max. Fault current $= \frac{U_{Lv}}{(j2X_{smin}+jX_t)} + Z_L$

= 4.271kA (for the SEBETA substation)

Where U_{LV} =27.5kV and Z_L (the line impedance for the different feeder lines) is shown in the table below

Min. Fault current =$^{\mathrm{U_{LV}}}/_{(\mathrm{j2X_{smax}} + \mathrm{jX_t}) + \mathrm{Z}}$ = 2.794 kA

Nominal rated current for the 16MVA single phase transformer at SEBETA is calculated for both the primary and secondary side, 132 KVA nominal voltages of HV side is:

$\mathrm{I_{rated}} = 16\mathrm{MVA}/_{132\ \mathrm{KV}} = 121.2121333\mathrm{A}$

The nominal rated current for 25kV, nominal voltages of LV side is:
$\mathrm{I_{rated}} = 12.667\mathrm{MVA}/_{27.5\mathrm{KV}} = 460.62\mathrm{A}$

Therefore, the short circuit breaker current for the secondary side is:

$\mathrm{I_{pickup}} = 1.2 * 460.62 = 552.742\mathrm{A}$ Thus the standard value will be 1kA

For the HV side the short breaking current is

$\mathrm{I_{pickup}} = \mathrm{I_{FOULTMIN}}$ =2.794 kA is standard current value is 6kA.Based on this the

standard SF6 circuit Braker with 6kA, 34.5kv rating is choosen for the low voltage side.

Thus it can be concluded that while deciding the ratings of the breakers used on the primary side, the rated short circuit breaking current is of importance and deciding factor and not the rated normal current which is generally much less. But for the breakers on the secondary side the situation is just the reverse while the deciding factor for the selection of the circuit breaker is the normal rated current and not the fault current.

5.7.3 Unsymmetrical faults

There are different type of unsymmetrical faults:

- Single line to ground (L-G) faults (70-80%)
- Line to line (L-L) faults (10%-8%)
- Double line to ground (L-L-G) faults (17%-10%)

Traction power supply system faults on OHE can be of two types:

1. Earth faults:-

- contact wire-to-rail
- feeder-to-rail;

2. Phase-to-phase faults:-

    - ✓ contact wire-to-feeder

Contact wire to the rail and feeder to rail faults are a type of single phase to ground faults while contact wire to feeder faults is a line to line type of faults. Single phase to ground is the most common type of faults. The second fault can occur by accidental closure of the bridging interrupter at the SP during normal feeding condition or by a short circuit at the insulated overlap opposite a traction substation at times of emergency feed conditions. This is termed as Wrong phase coupling (WPC) fault. It can also be occur when the pantograph of the train touch two different section at the same times. [46]

Chapter Six

Simulation and Result

In this thesis Power flow analysis can be conducted using Newton-Raphson and linear equation methods for the unbalanced power system feeding the traction substations. This thesis use Newton-Raphson (power ,classic iteration), the software is also capable of studying the fault calculations and transients in the AC distribution system feeding the traction system and the traction system itself according to IEC, VDE and ANSI standards. It is possible to define any type of fault at any location, Such as at the traction substations, at train overhead contact system or the AC network feeding the traction substations using this software. Therefore, the reliability of the traction system can be investigated. It is also necessary to study power dispatch in the system under faulty conditions. For increasing the reliability of the traction electrical system, it is necessary to design the structure of the power distribution system in a way that it would be able to still be fed from other feeders when a disconnection occurs in a feeder. For that reason, the electrical distribution system as shown in Figures 6.2 and 6.3 is designed to be able to feed all of the traction substations without any problems such as overloading.

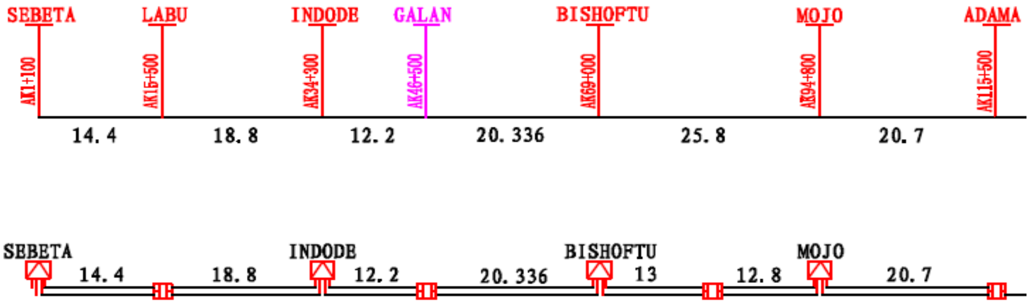


Figure 6.1 Double track from Sebeta to Adama provided with its distance between traction sub-station [20]

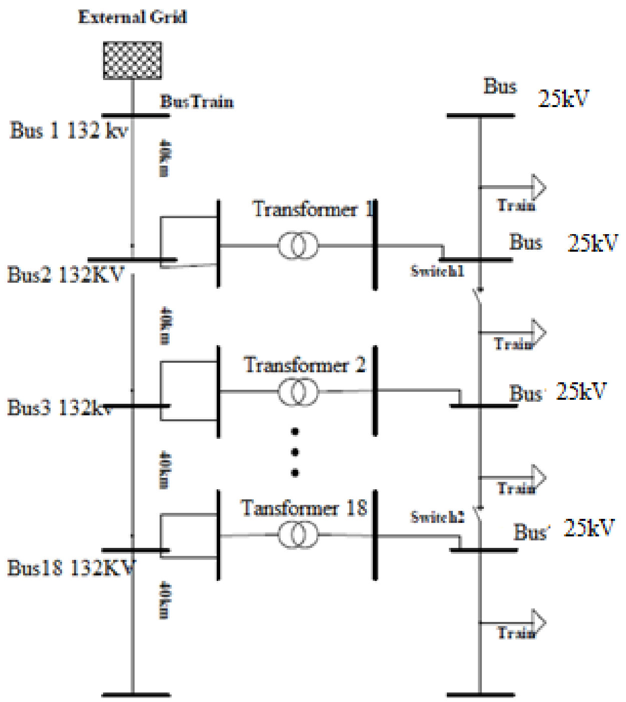
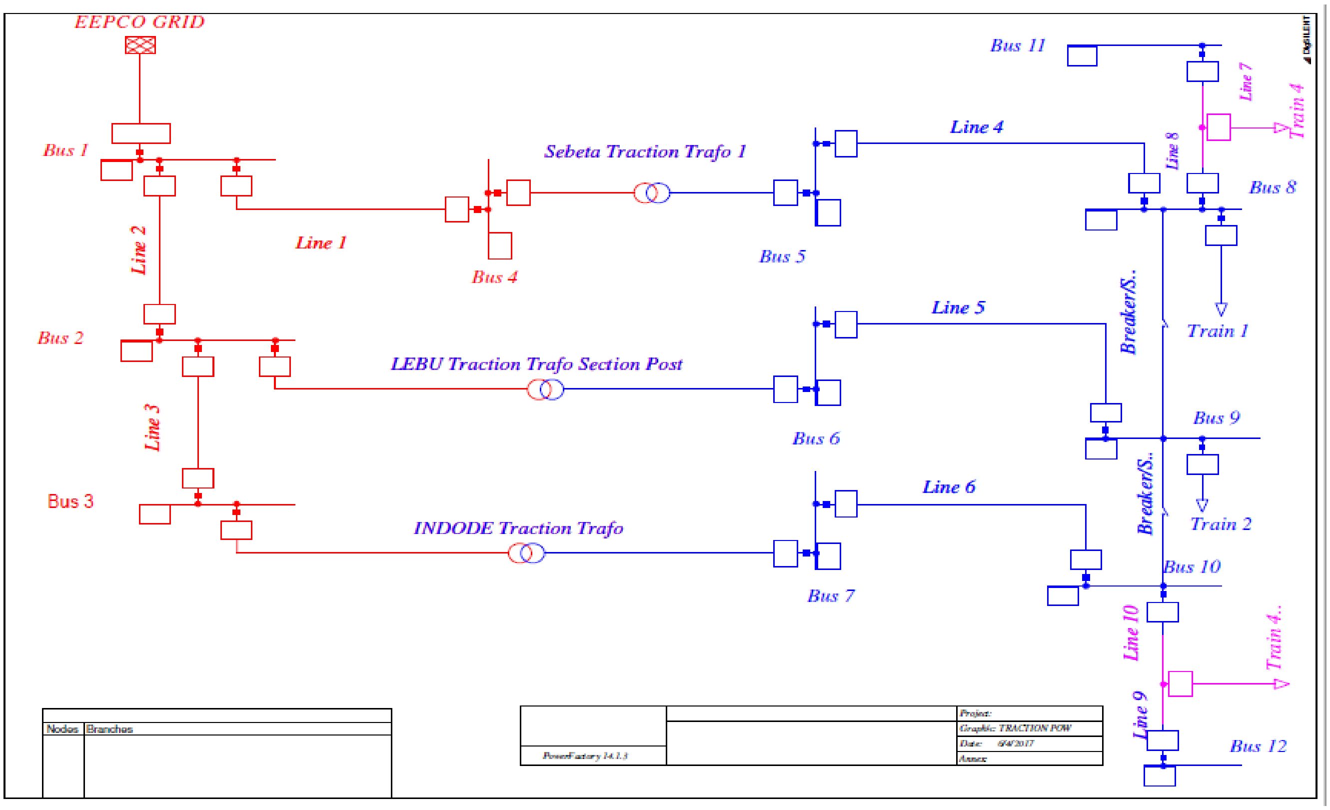


Figure 6.2. Railway Simulation Model in DIgSILENT Power Factory Simulator Software [45]

Case 1 When the load in the track consider only two passenger trains with P=3.22MW



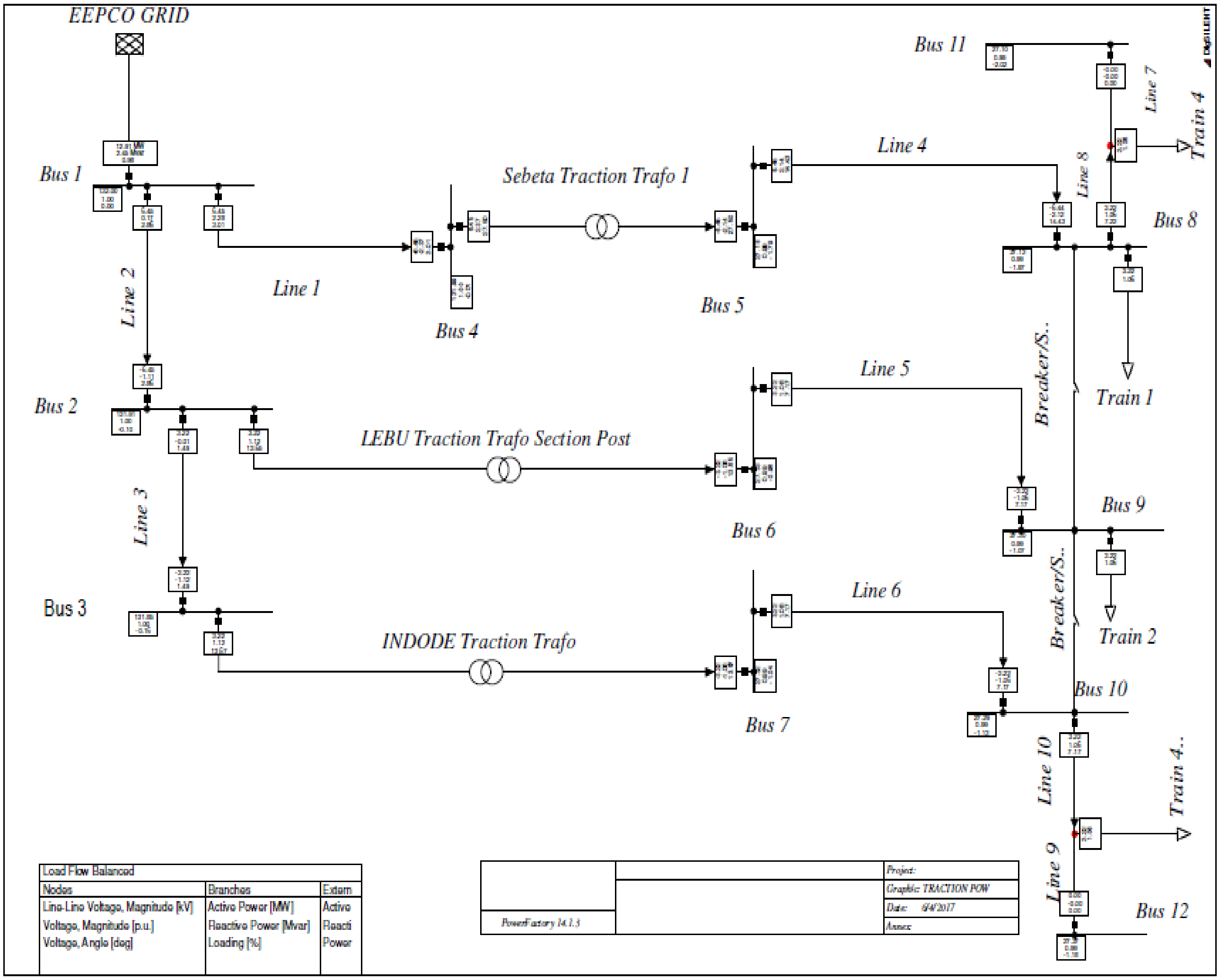
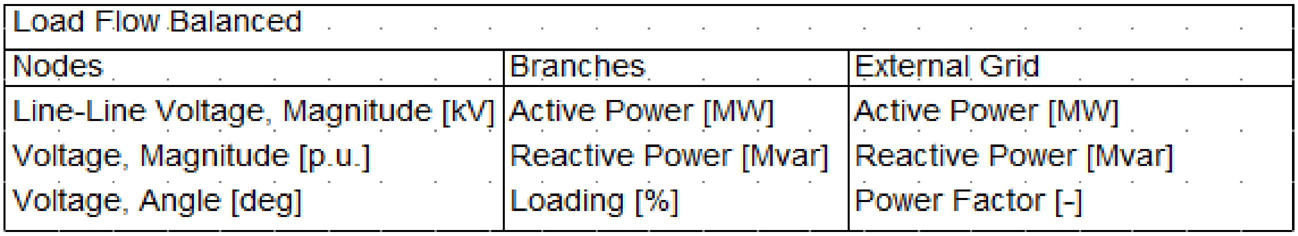


Figure 6.3 Load Flow Simulation Result from Sebeta to Indode Substation



Load Flow Balanced		
Nodes	Branches	External Grid
Line-Line Voltage, Magnitude [kV]	Active Power [MW]	Active Power [MW]
Voltage, Magnitude [p.u.]	Reactive Power [Mvar]	Reactive Power [Mvar]
Voltage, Angle [deg]	Loading [%]	Power Factor [-]

The above simulation result shows at the nodes of each buses the line to line voltage magnitude in kV, the phase voltage magnitude in p.u and the voltage angle in degree. Moreover at each branches of the buses and at the load side it shows active power in MW, reactive power in MVar, power factor and the percentage loading[%] of the system at each nodes and branches of the simulation result.

Case 2 When the load in the track consider one passenger train and one freight train with Total power consumption of P=10.365MW

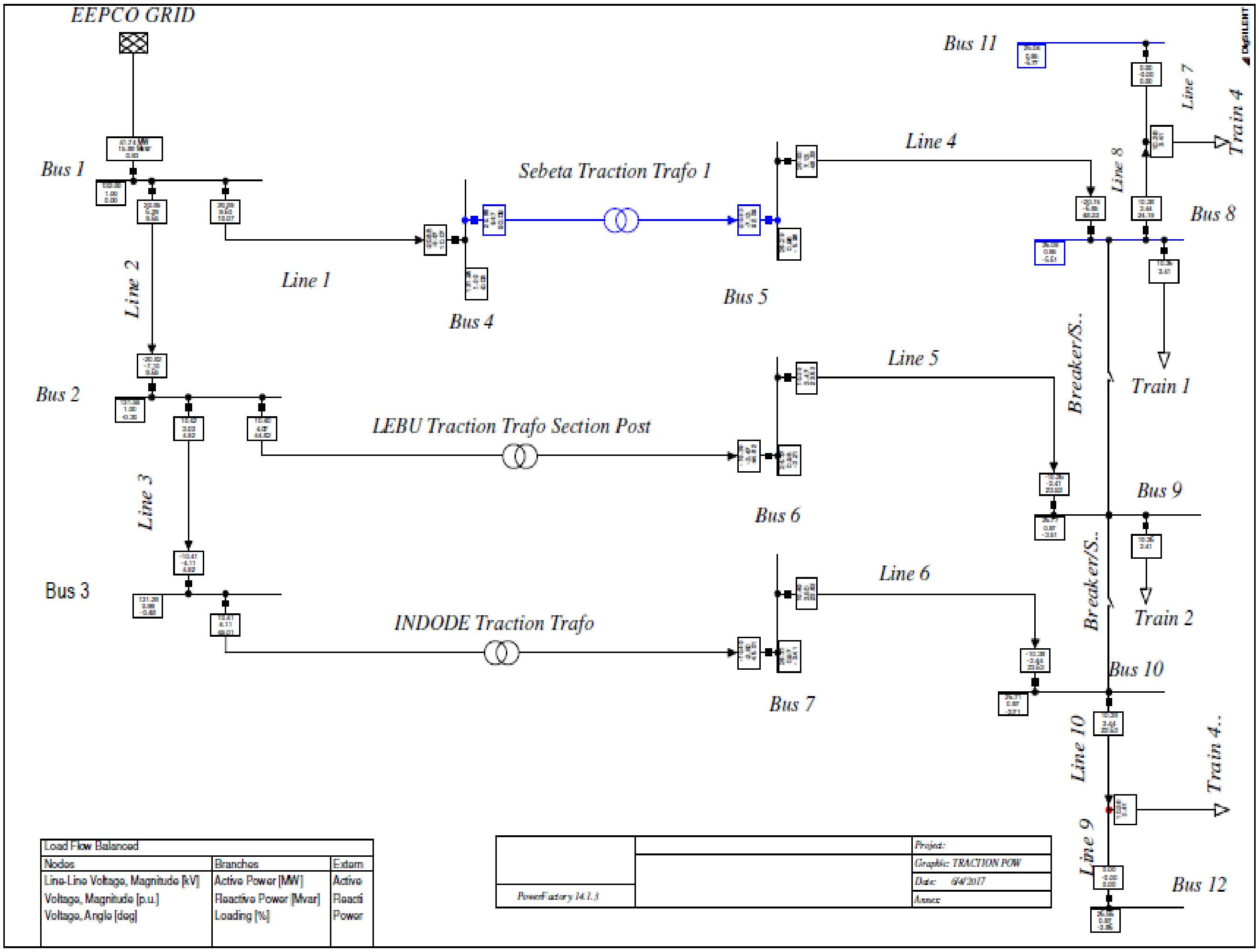


Figure 6.4 Single Line Diagram from Sebeta to Indode Traction Substation

Case 3. When power interruption occurred at sebeta substation and bus 8 opened

Load flow result 1, when the power interruption occurred at line four the circuit breaker at bus 8 opened the train 1 and train 4 becomes energized and they couldn't get power as shown below in the single line diagram representation

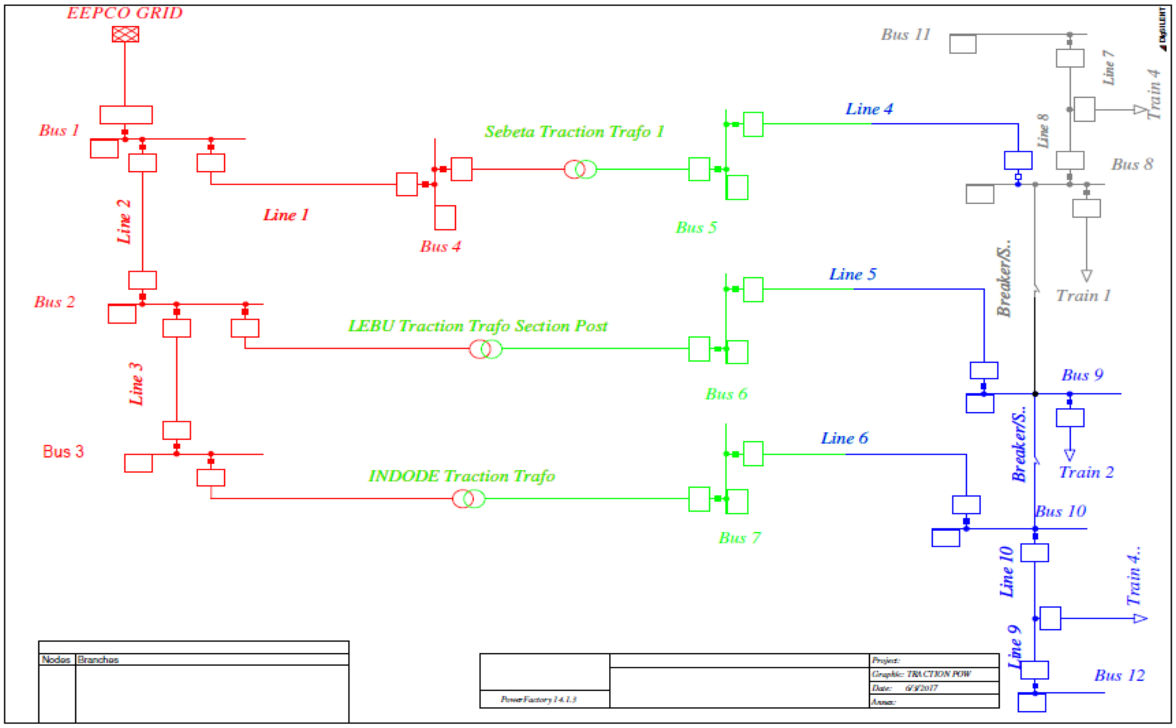


Figure 6.5 Single Line Diagram Representation when Power Cut at Line 4 /CB Opened at Bus 8

When the above scenario happened the circuit breaker or switch 1 automatically closed and train 1 and train 4 can get power from LEBU section post then train 1 and 4 become energized and get power as shown in figure below

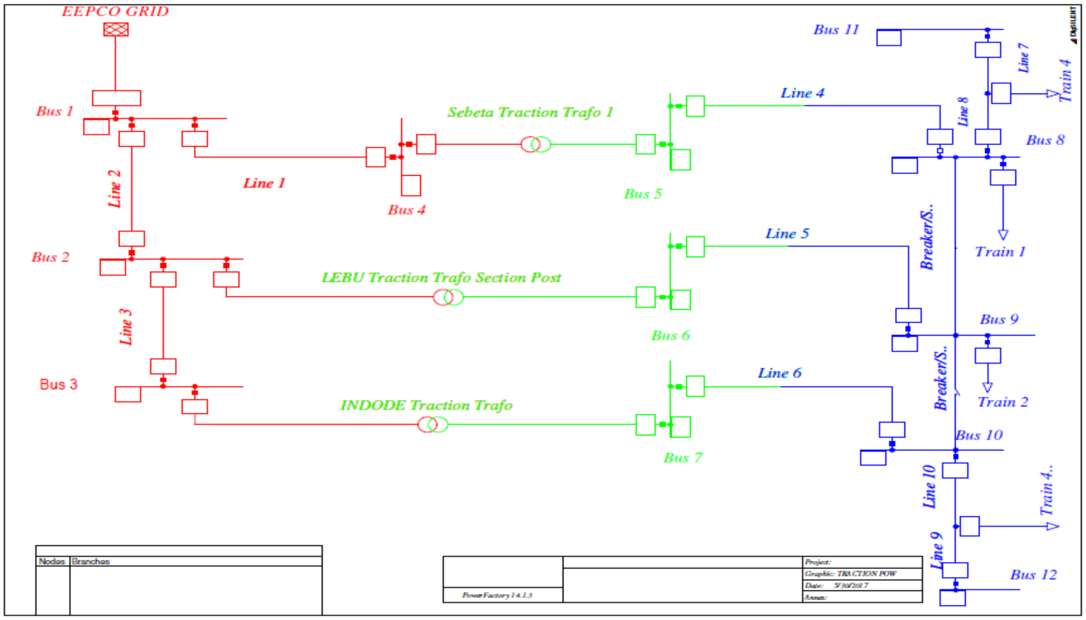


Figure 6.6 Power Feed from Lebu Section Post to the Load

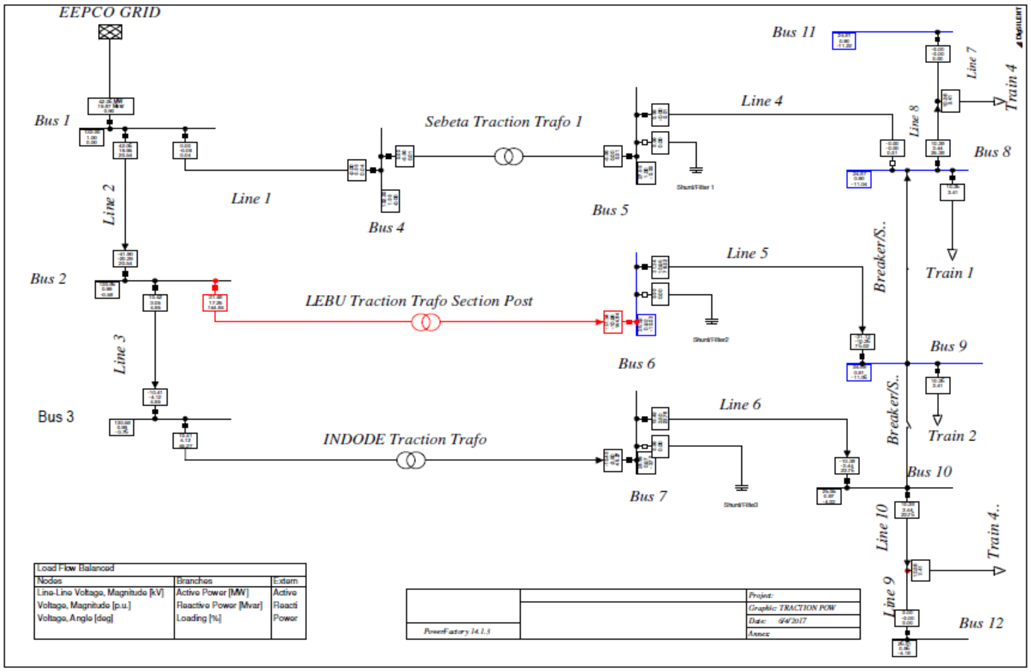


Figure 6.7 Power Feed from Lebu Section Post to the Train Load Flow Result

When power occurred at sebeta substation and power feed from lebu section post, the length becomes increased to supply power to the load, then the voltage deviation becomes high therefore, this thesis design a compensator (shunt capacitor /filter) at low voltage side and the result show an improved voltage.

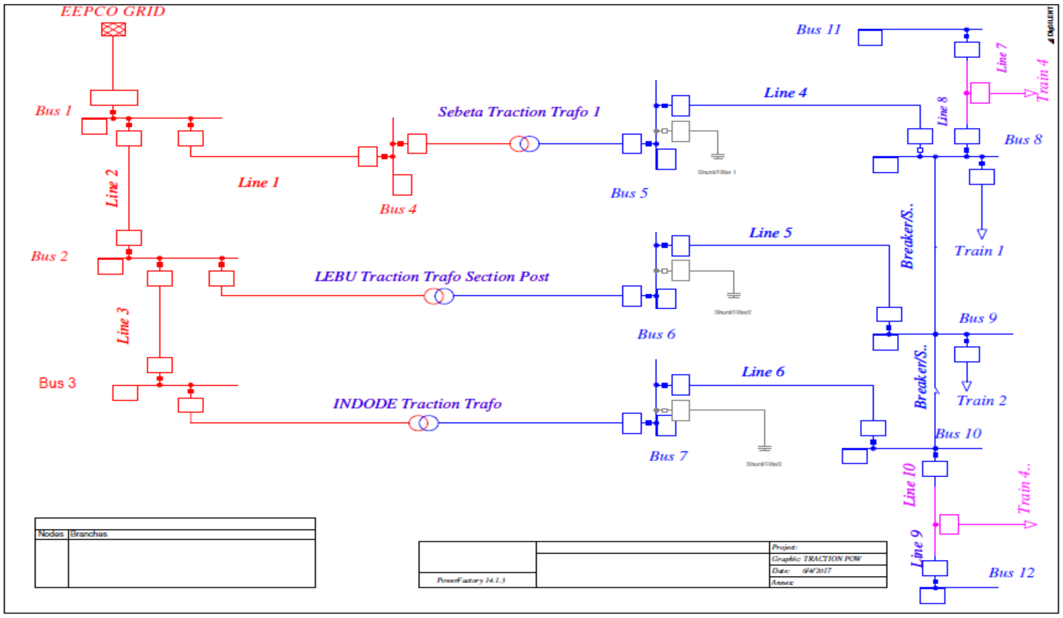


Figure 6.8 Single Line Diagram Representation of Load Flow with opened Shunt Capacitor

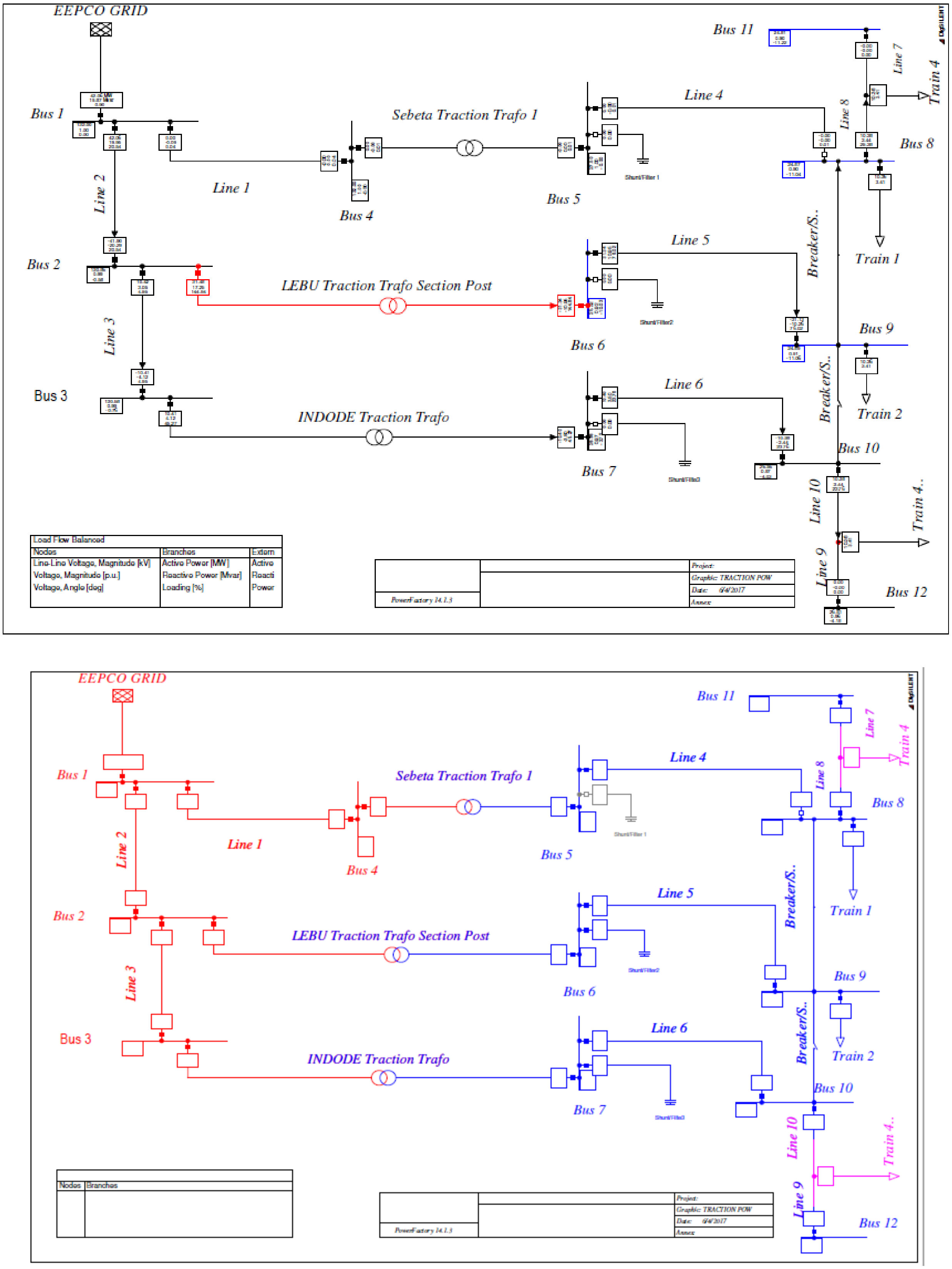


Figure 6.9 Single Line Diagram Representation of Load Flow with Shunt Capacitor

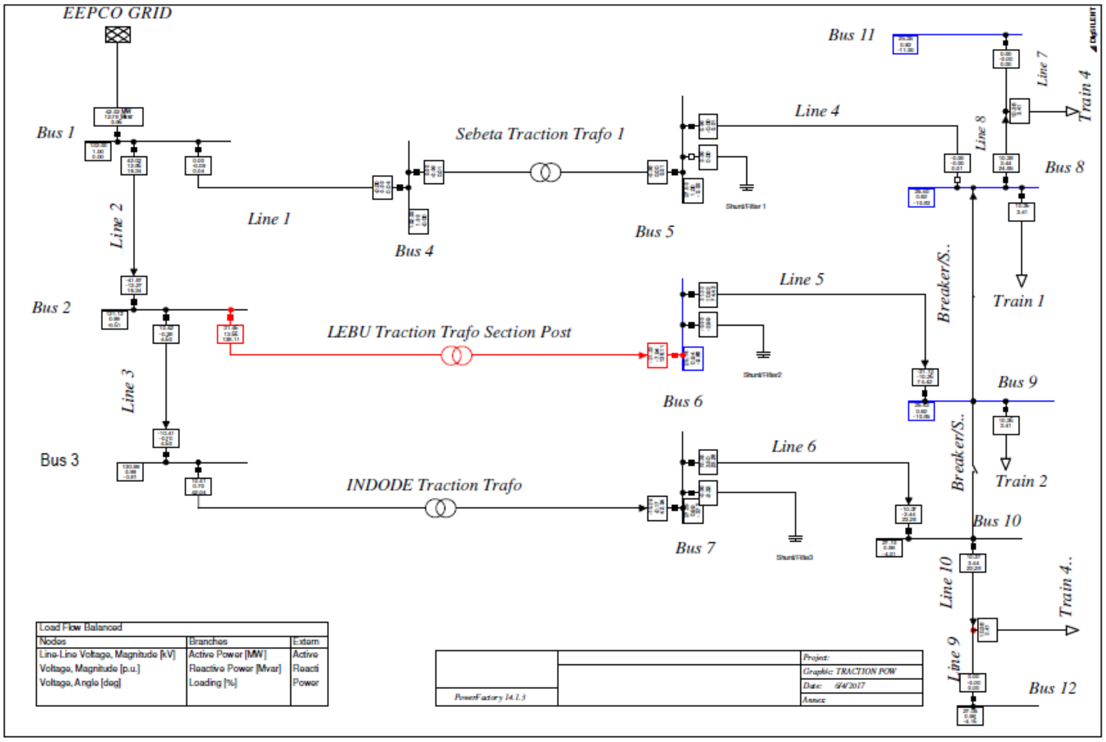


Figure 6.10 Single Line Diagram Representation of Load Flow result with Shunt Capacitor

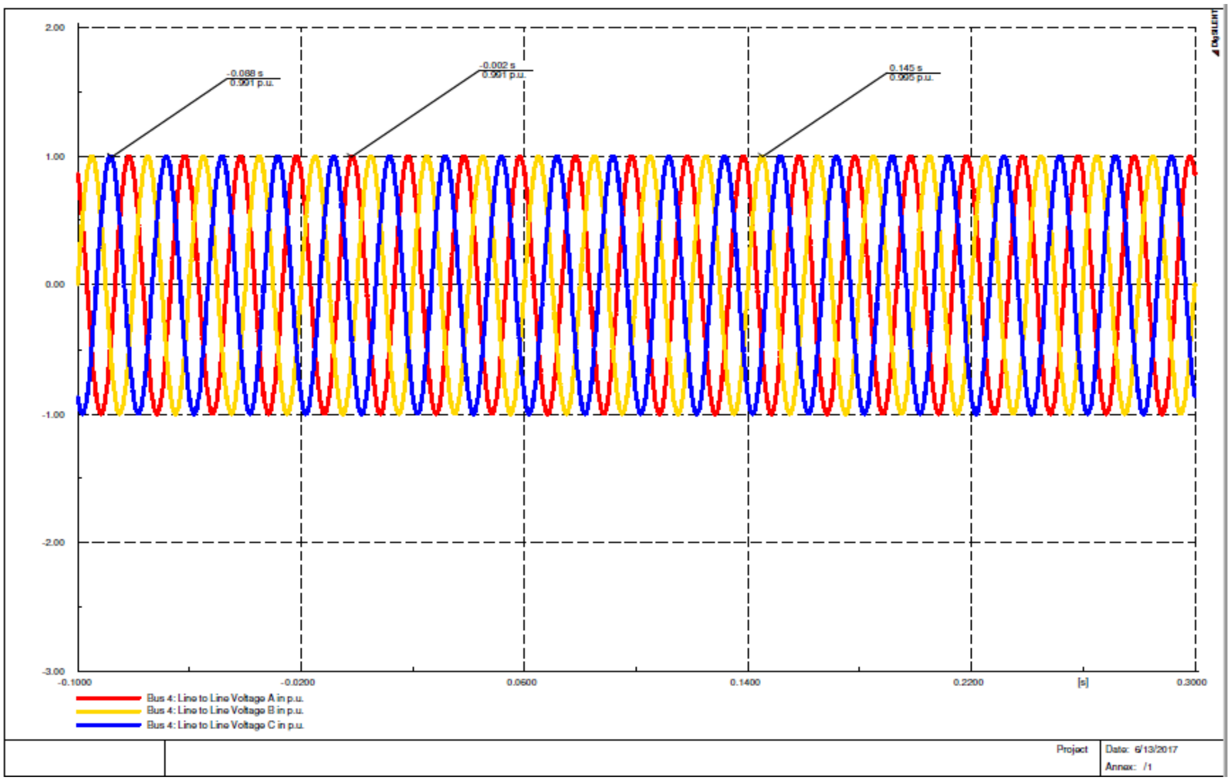


Figure 6.11 Line to Line voltage waveform representation with No fault plot

Short Circuit Analysis Result, Fault occurred Near to the grid

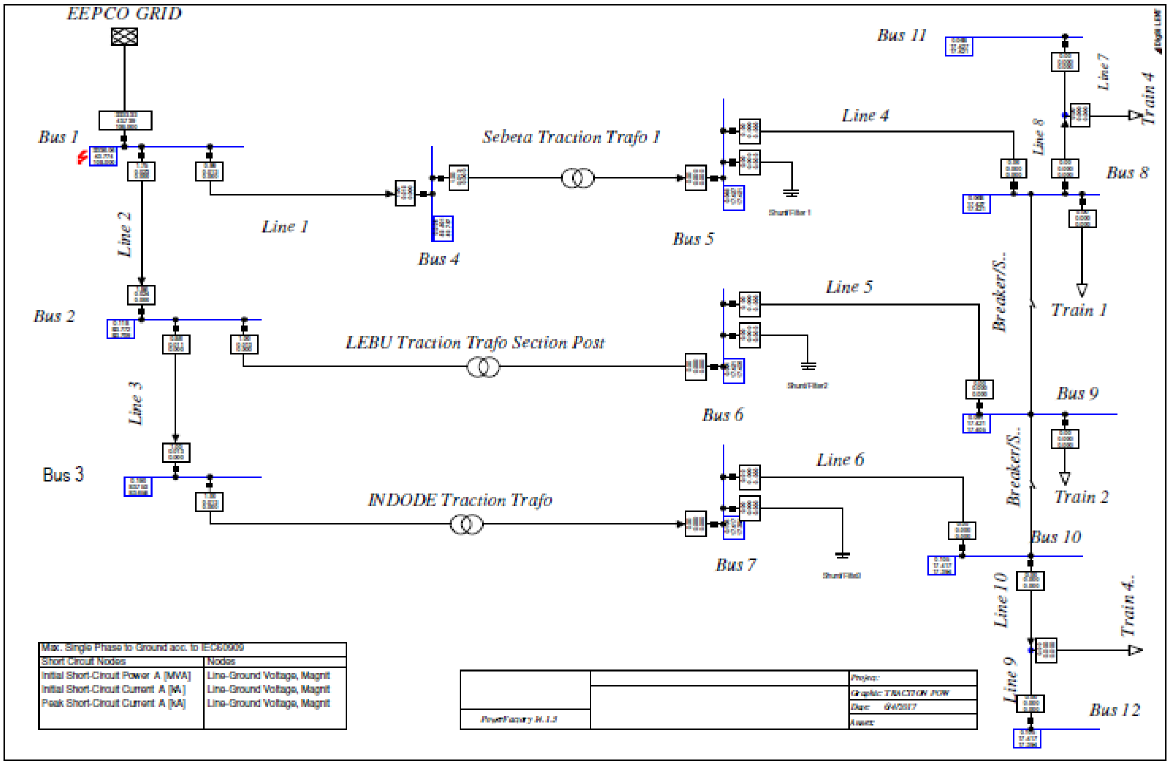
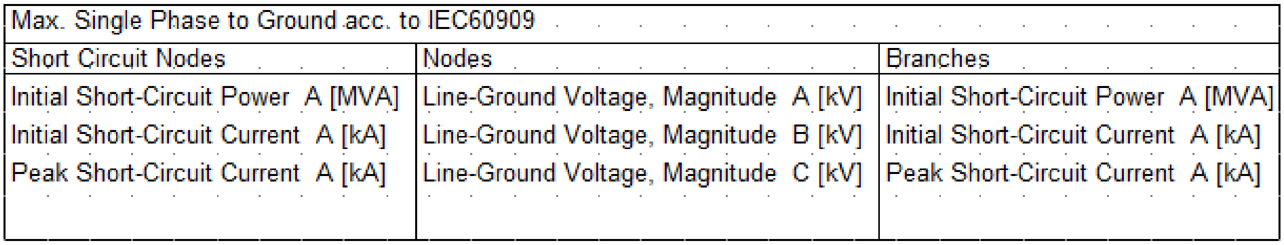


Figure 6.12 Fault Occurred Near to the Grid Short circuit analysis result

Table 6.1 summarize the result representation shown in figure 6.12



Max. Single Phase to Ground acc. to IEC60909		
Short Circuit Nodes	Nodes	Branches
Initial Short-Circuit Power A [MVA]	Line-Ground Voltage, Magnitude A [kV]	Initial Short-Circuit Power A [MVA]
Initial Short-Circuit Current A [kA]	Line-Ground Voltage, Magnitude B [kV]	Initial Short-Circuit Current A [kA]
Peak Short-Circuit Current A [kA]	Line-Ground Voltage, Magnitude C [kV]	Peak Short-Circuit Current A [kA]

In Table 6.1 summarize the result representation shown in Figure 6.12 i.e. the maximum single phase to ground fault result, that occurred near to the grid it represent the initial short circuit power in MVA, initial and peak short circuit current in kA at each short circuit nodes, the line ground voltage magnitude at each nodes in kV and also it shows the initial short–circuit power, current and peak short-circuit current at each branches of the modeled system according to IEC60909 standards.

In appendix D, the short circuit analysis result report shows:-I_P - Peak short circuit current in [kA],I_b - The short circuit breaking current in kA, I_k'' - Initial symmetrical short circuit current in kA, and S_k''- Initial symmetrical short circuit apparent power in MVA.

Single line to ground fault short circuit fault at high voltage side

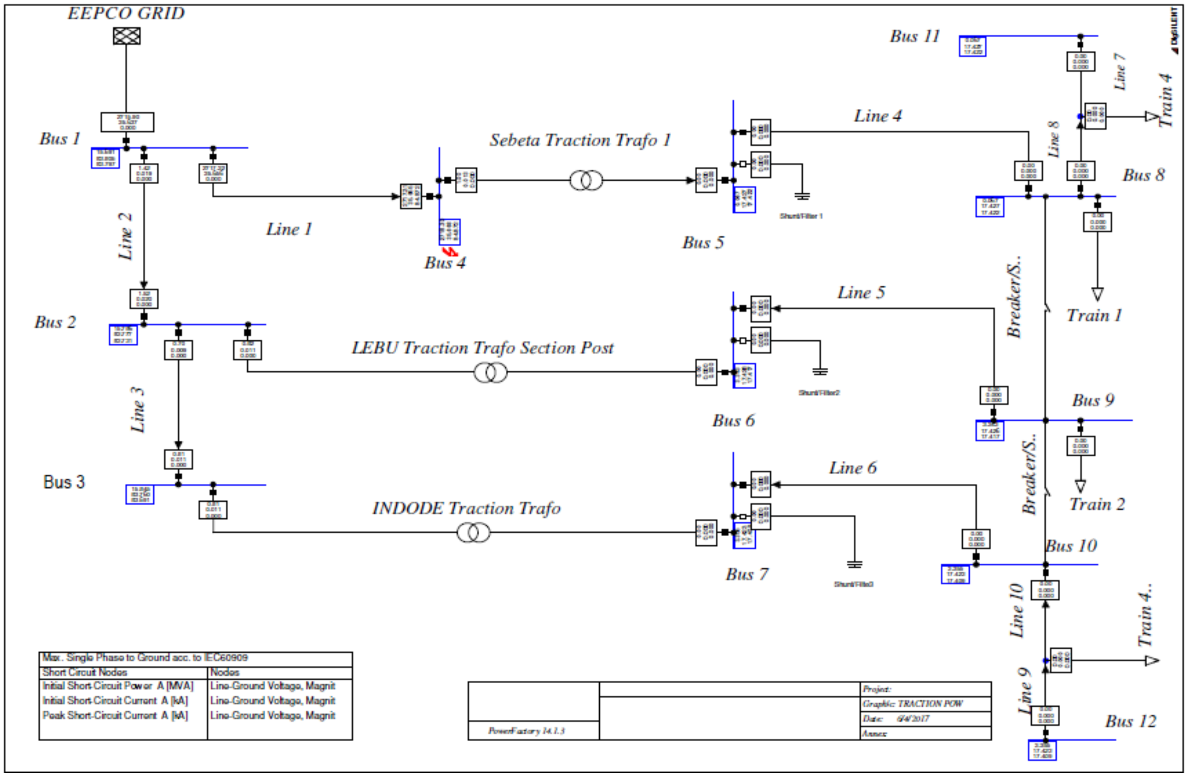


Figure 6.13 Single Line to Ground Short Circuit Fault occurred at High Voltage Side

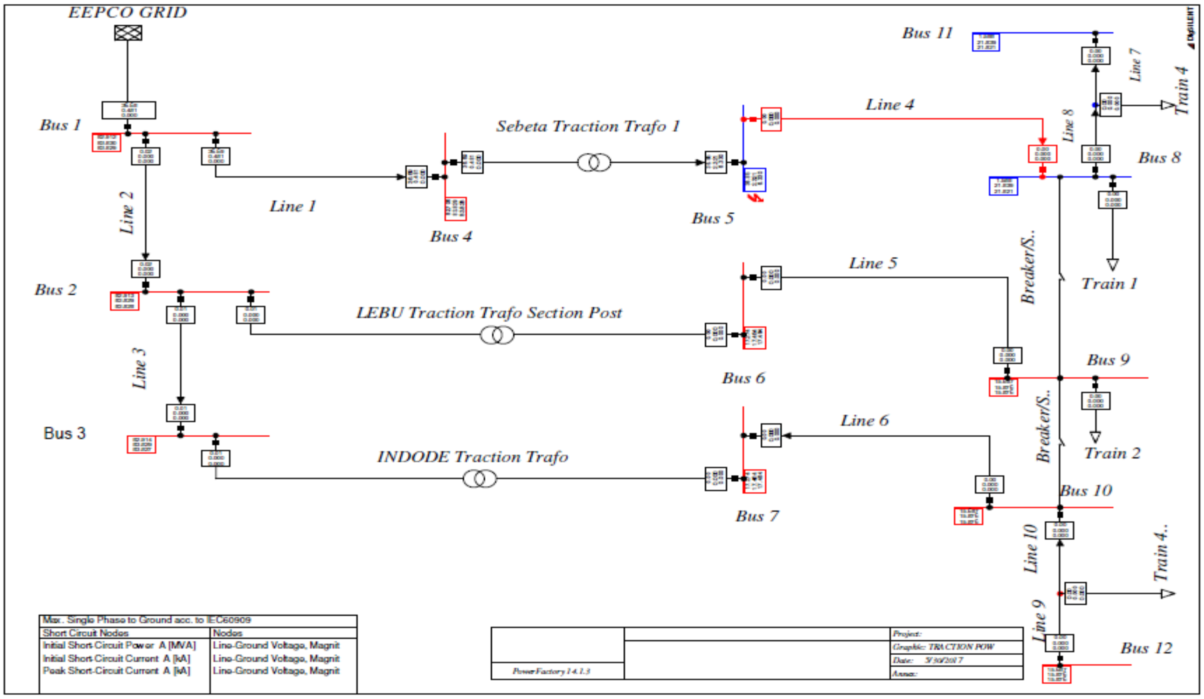


Figure 6.14 Single Line to Ground Short Circuit Fault occurred at Low Voltage Side

Short circuit fault occurred at load side

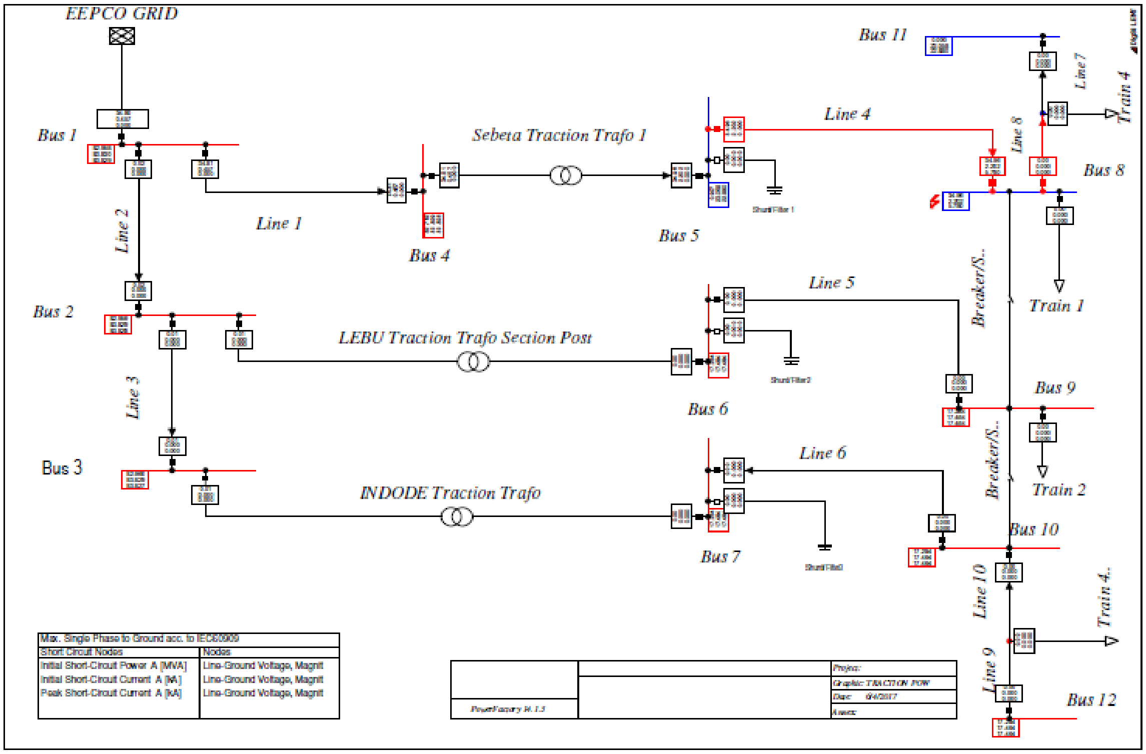


Figure 6.14 Single Line to Ground Short Circuit Fault occurred at Load Side

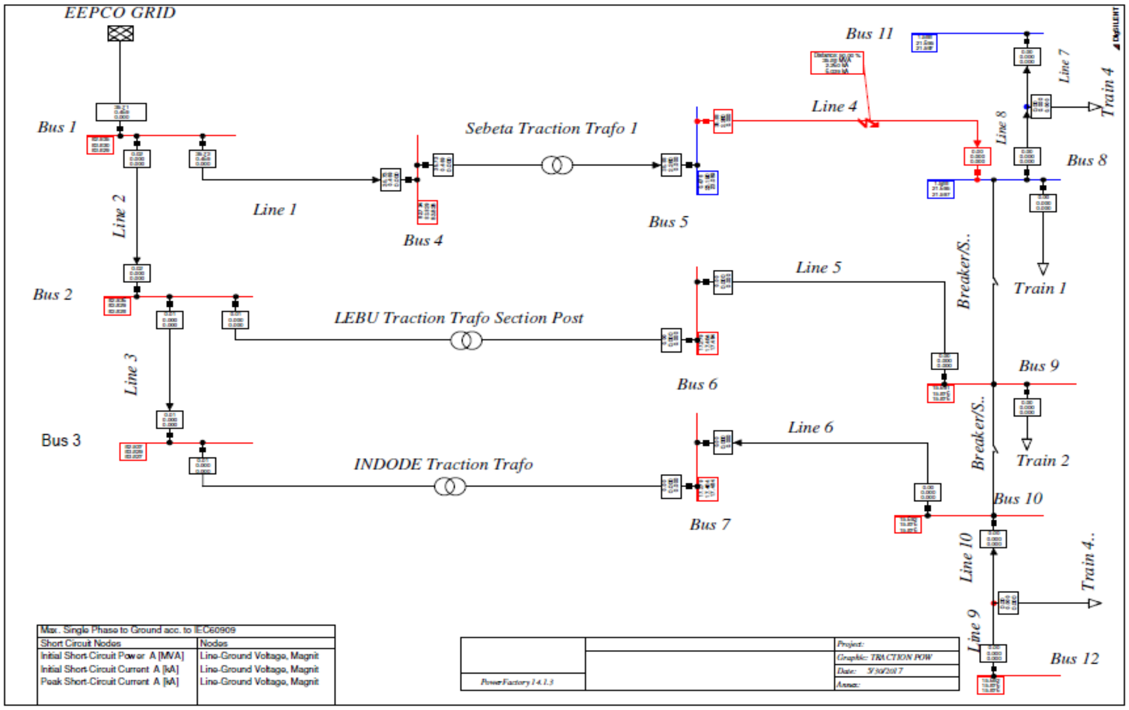


Figure 6.15 Single Line to Ground Short Circuit Fault occurred at Line Side

Three phase and single line to ground short circuit fault Voltage and current plot at grid side and/or at high voltage side,

Now, this thesis consider some conditions of creating fault at various scenarios to validate three phase short circuit and single line ground fault, Thus, now staring from 0 to 0.1 sec no fault occurred this lead as voltage is developed and there is no short current is build up in the plot, exactly at 0.1001sec there is three phase short circuit fault is created here voltage is goes down and three phase current is developed and 4.146KA its value, at 0.2 sec fault is cleared and the fault current is zero then the system try to build up the voltage. Exactly at 0.20001 sec single line to ground fault build up at phase A then,

- ✓ Phase A voltage goes down
- ✓ other phase voltage the same
- ✓ phase A current buildup 2.556KA its values
- ✓ starting from 0.3 to 0.4 sec the fault totally cleared and the total simulation time covered 0.5 sec

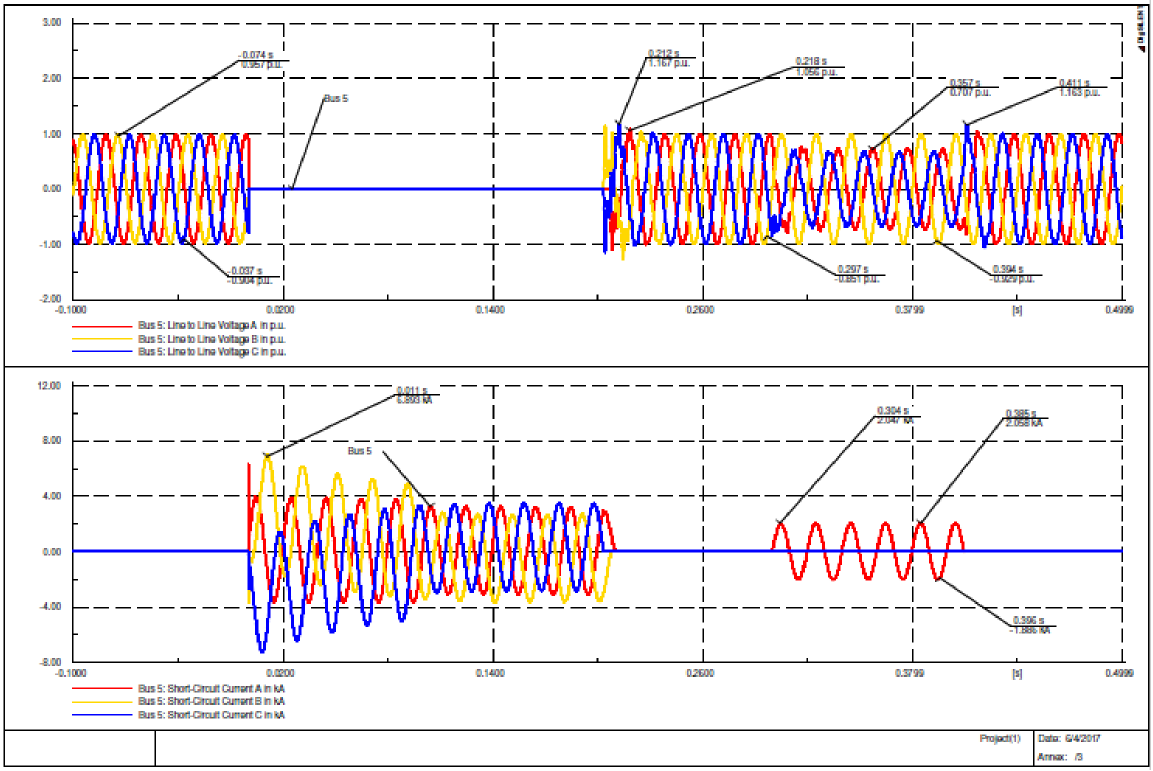


Figure *6.16 Three phase voltage and single line to ground short circuit voltage and current wave form at bus 5*

Two phase and single line to ground short circuit fault Voltage and current plot at Bus 5

Now, this thesis consider some conditions of creating fault at various scenarios to validate two phase short circuit fault and single line ground fault, Thus, now staring from 0 to 0.1 sec no fault occurred this lead as voltage is developed and there is no short current is build up in the plot, exactly at 0.1001sec there is two phase short circuit fault is created here voltage is goes down and three phase current is developed and 6.973KA its value, at 0.2 sec fault is cleared and the fault current is zero then the system try to build up the voltage. Exactly at 0.20001 sec single line to ground fault build up at phase A then,

- ✓ Phase A voltage goes down
- ✓ other phase voltage the same
- ✓ phase A current buildup 2.747KA its values
- ✓ starting from 0.3 to 0.4 sec the fault totally cleared and the total simulation time covered 0.5 sec

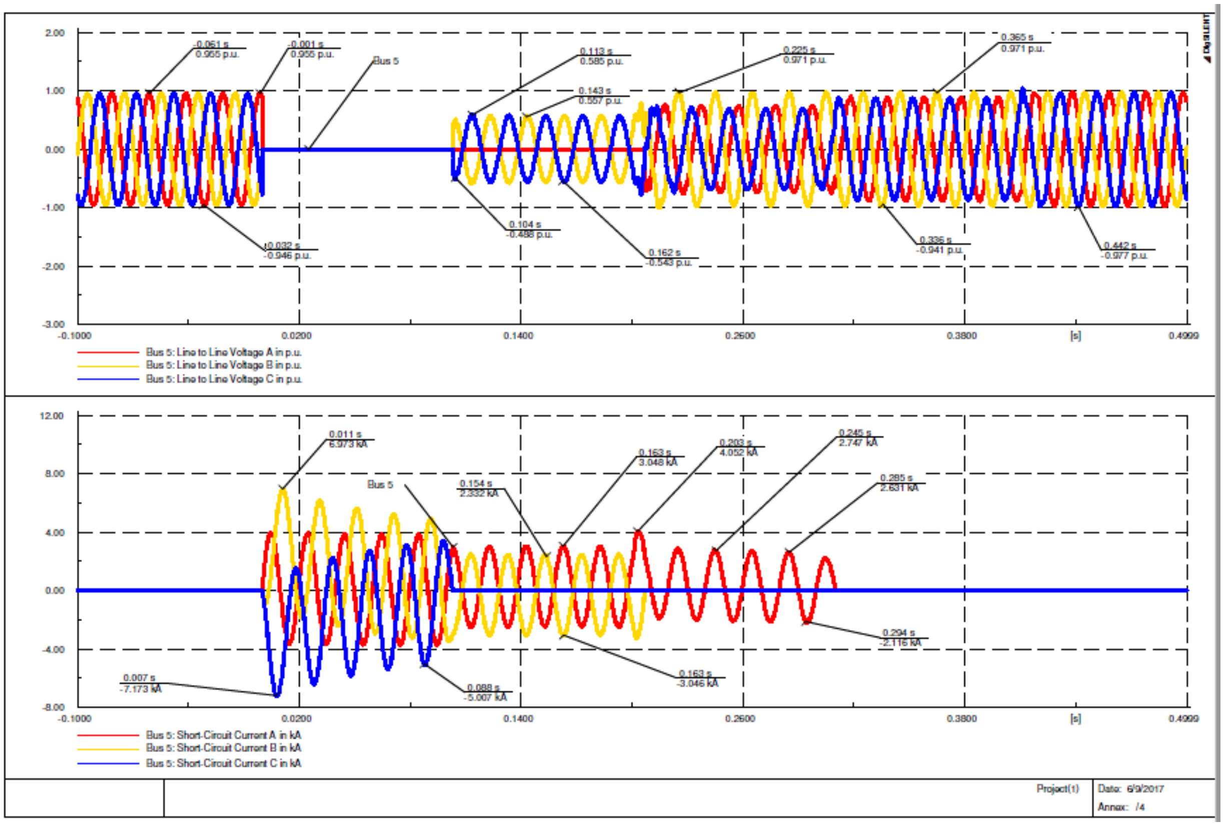


Figure 6.17 Two phase voltage and single line to ground short circuit voltage and current wave form at bus 5

Two phase and single line to ground short circuit fault Voltage and current plot at bus 6

Now, this thesis consider some conditions of creating fault at various scenarios to validate two phase short circuit fault and single line ground fault, Thus, now staring from 0 to 0.1 sec no fault occurred this lead as voltage is developed and there is no short current is build up in the plot, exactly at 0.1001sec there is two phase short circuit fault is created here voltage is goes down and three phase current is developed and 5.803KA its value, at 0.2 sec fault is cleared and the fault current is zero then the system try to build up the voltage. Exactly at 0.20001 sec single line to ground fault build up at phase A then,

- ✓ Phase A voltage goes down
- ✓ other phase voltage the same
- ✓ phase A current buildup 2.224KA its values
- ✓ starting from 0.3 to 0.4 sec the fault totally cleared and the total simulation time covered 0.5 sec

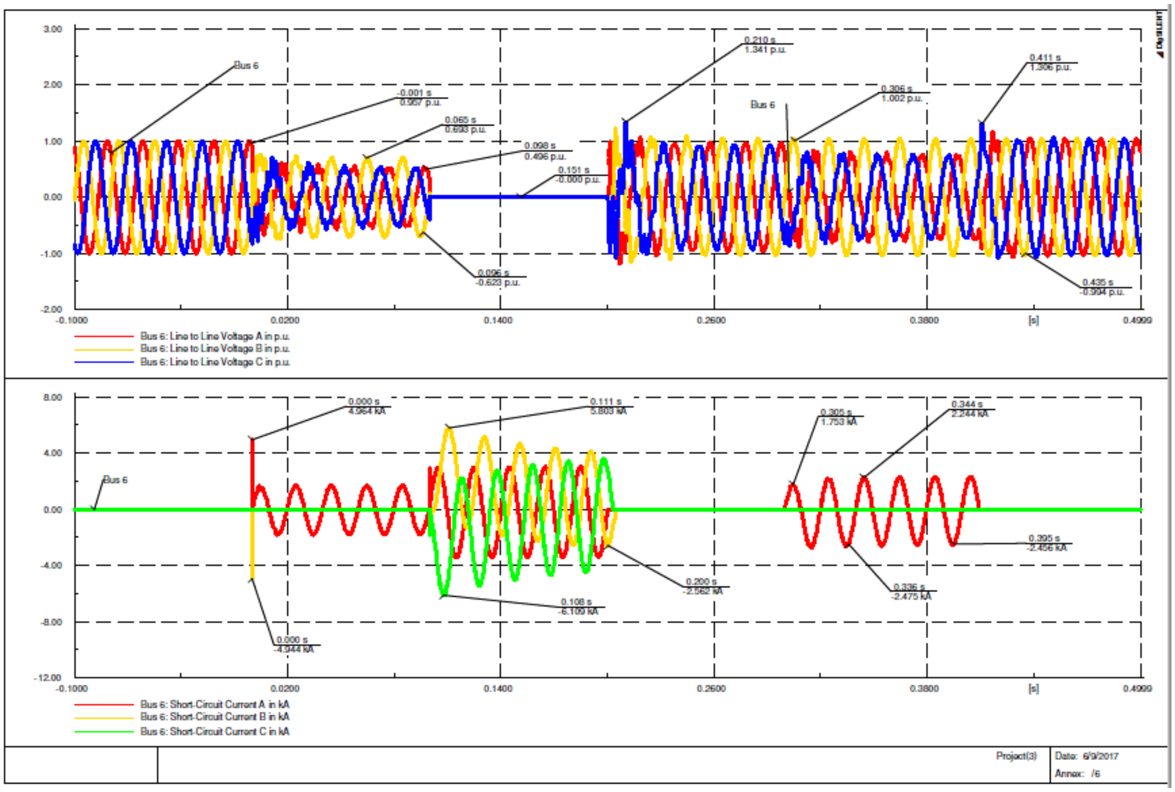


Figure 6.18 Two phase voltage and single line to ground short circuit voltage and current wave form at bus 6

Active power variations of a traction substation at the presence of a fault in the feeding line of the traction substation.

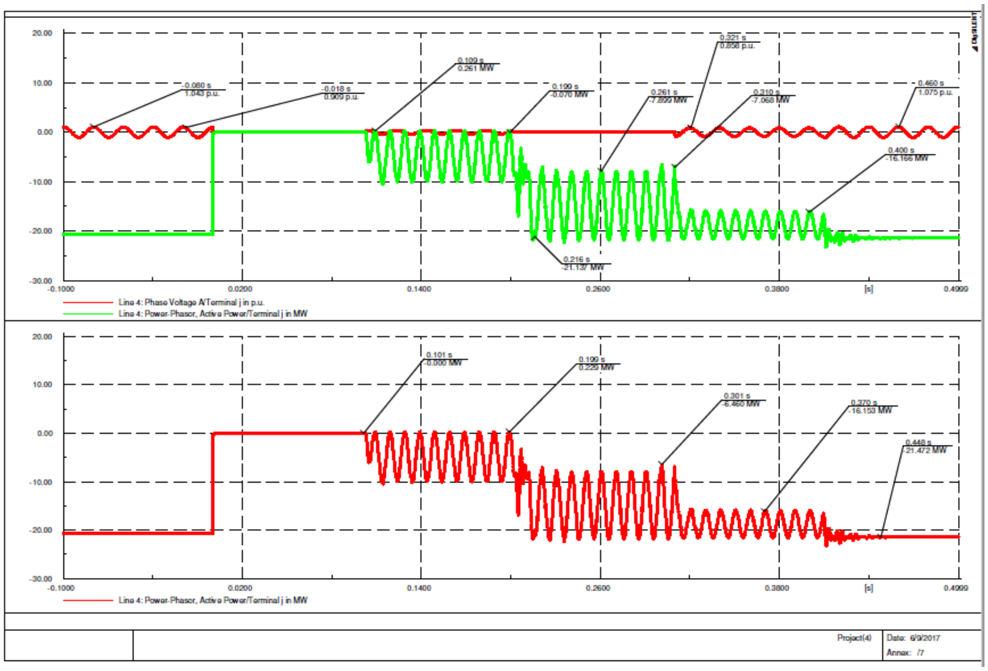


Figure 6.19 Active power in MW and phase voltage in Pu

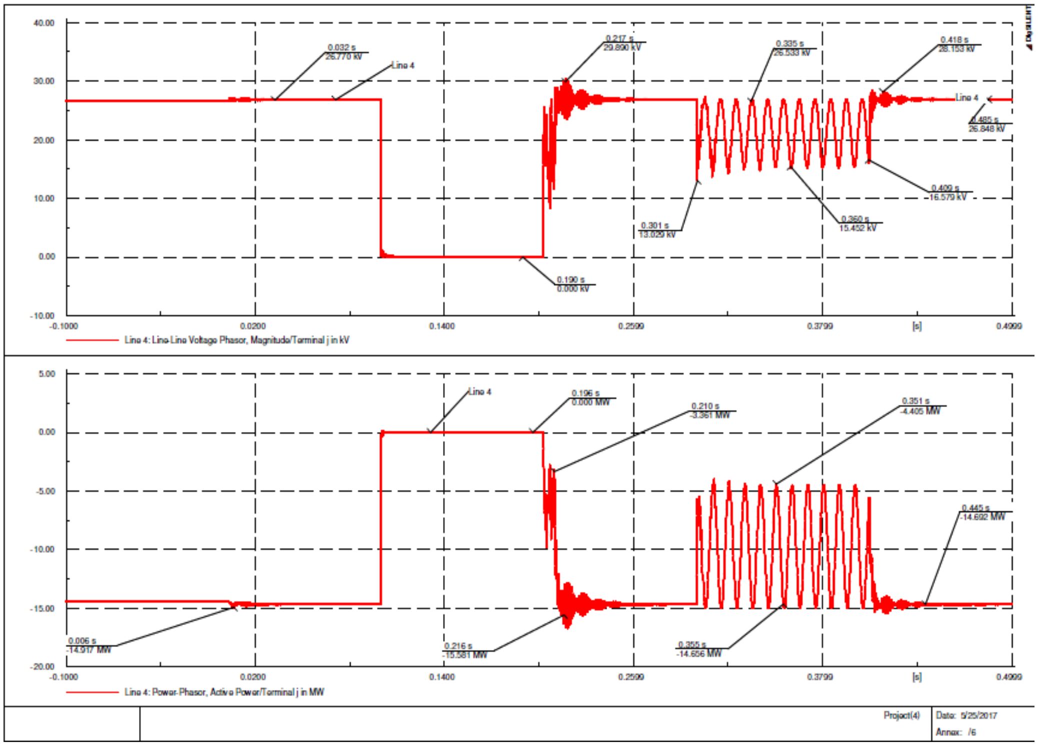


Figure 6.20 Power, voltage and Distance at fault location in km wave form at bus 5

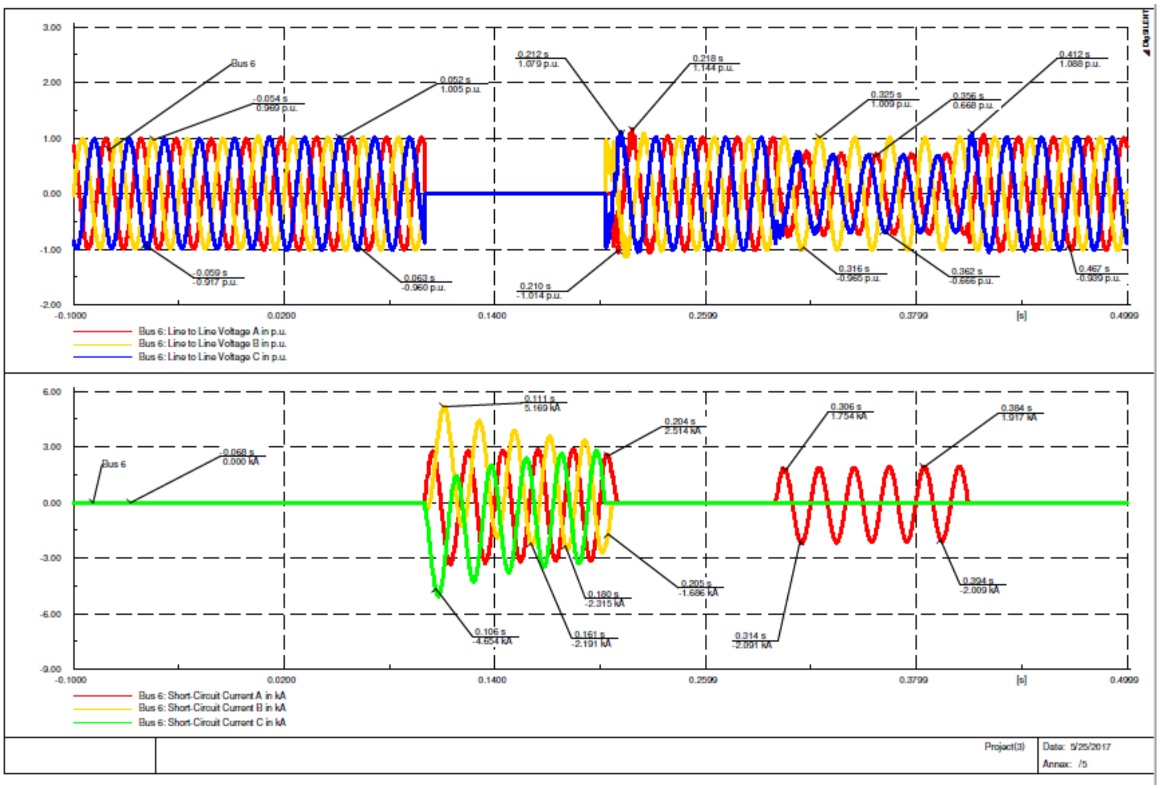


Figure 6.21 Three phase voltage and single line to ground short circuit voltage and current wave

Voltage profile plot before compensator

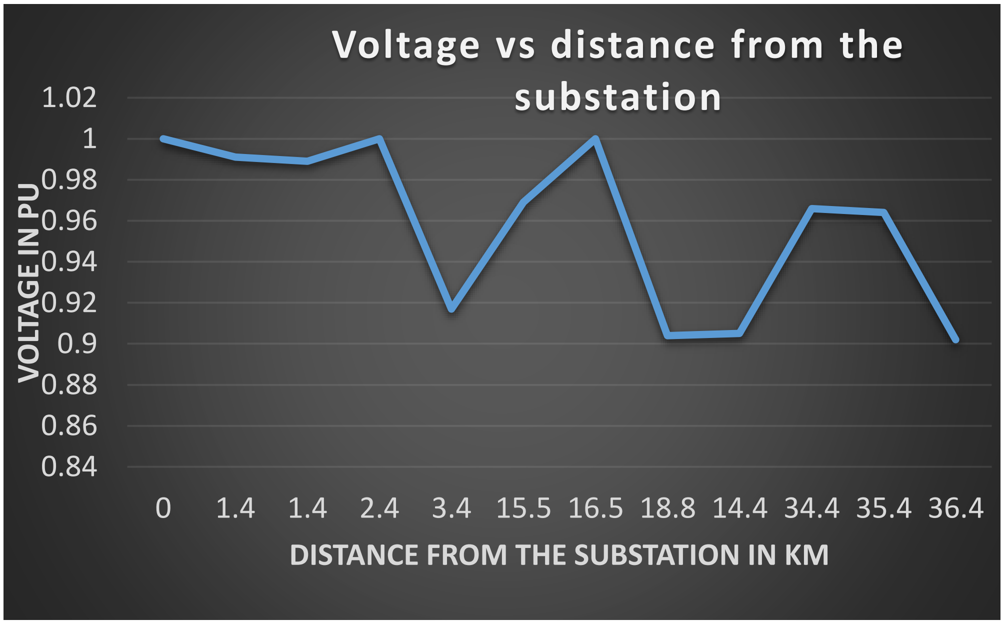


Figure 7.1 Bus voltage profile vs Distance from the substation

Designing compensator (Capacitor in MVar)

In case two this thesis consider P=10.365MW and with power factor of 0.95, thus now determine the reactive power at the load side is Q in MVar,

i.e.$Q_{\text{load}} = P_{\text{load}} * \tan(\cos^{-1}(\emptyset))$

$$= 10.365 * \tan(\cos^{-1}(0.95)) = 10.365 * \tan 0.3175))$$

$Q_{\text{load}} = 3.407 MVar$, This is the compensator, shunt capacitor designed value at the load side.

Maximum Percentage voltage level increment is:-

$$\%voltage\ level\ increment$$

$$= \frac{voltage\ level\ in\ orginal\ System\ in\ pu - voltage\ with\ shunt\ capacitor\ in\ pu}{voltage\ level\ in\ original\ system\ in\ pu} * 100$$

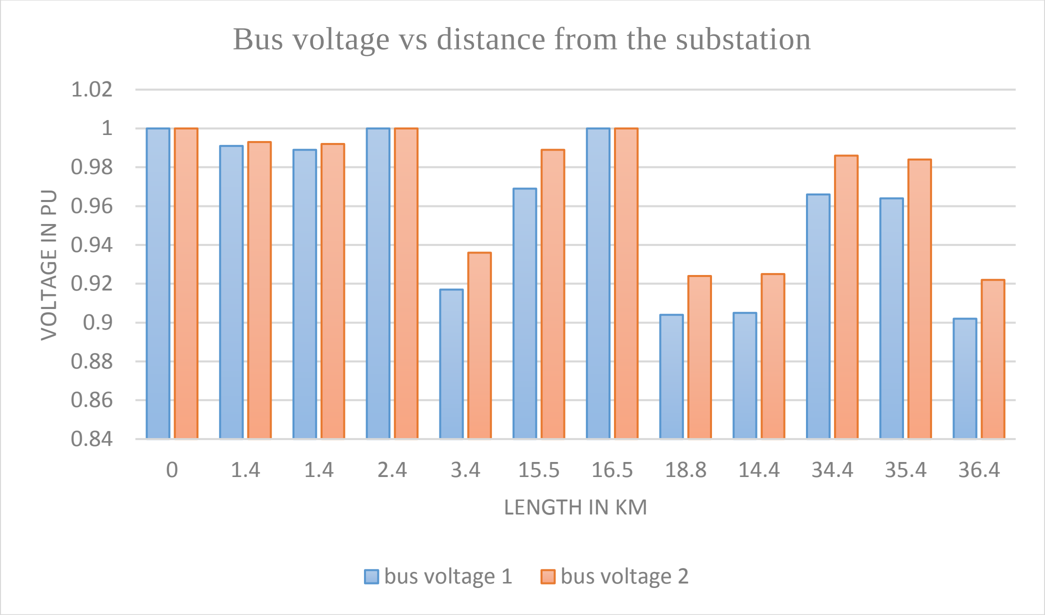
For Bus 11,

$$\%voltage\ level\ increment = \frac{0.902 - 0.922}{0.902} * 100$$

$$= 2.22\%\ this\ is\ the\ maximum\ bus\ voltage\ increment\ by\ this\ perecent\ after\ compensation$$

Table 7.1 Tabulated Data of Bus Voltage Before and After compenstion

Bus voltage 1	Bus voltage 2	Bus type	Length of the substation
1	1	1	0
0.991	0.993	2	15.5
0.989	0.992	3	18.81
1	1	4	1.41
0.917	0.936	6	1.4
0.969	0.989	7	15.5
1	1	5	34.4
0.904	0.924	8	2.4
0.905	0.925	9	16.5
0.966	0.986	10	35.4
0.964	0.984	12	3.4
0.902	0.922	11	36.4



Voltage profile after compensation

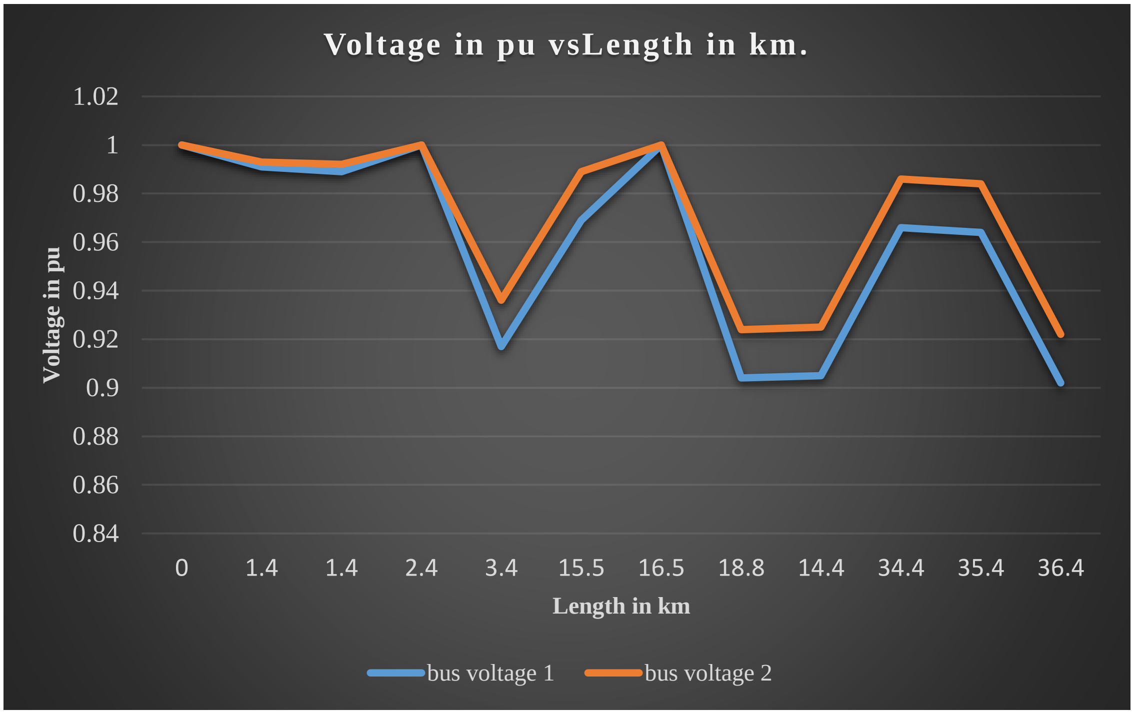
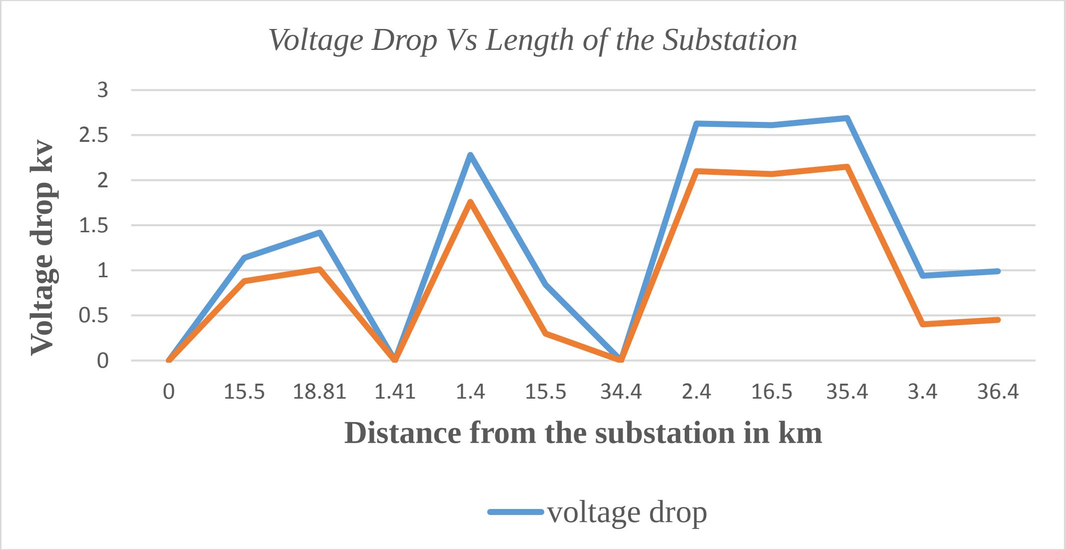


Figure 7.3 After Compensated Voltage Profile in pu vs Length in km

Table 7.2 Tabulated Data of Voltage Drop Before and After compenstion result

Bus no	Voltage drop in kV	% Voltage drop	Voltage drop after shunt capacitor in kV	% Voltage drop	Length from the Substation in km
1	0	0	0	0	0
2	1.14	0.871	0.88	0.671	1.4
3	1.42	1.09	1.01	0.771	1.4
4	0	0	0	0	2.4
6	2.28	9.04	1.76	6.84	3.4
7	0.84	3.15	0.3	1.101	15.5
5	0	0	0	0	15.5
8	2.63	10.58	2.1	8.27	16.5
9	2.61	10.49	2.07	8.14	18.81
10	2.69	10.84	2.15	8.48	34.4
12	0.94	3.34	0.4	1.48	35.4
11	0.99	3.734	0.45	1.66	36.4

Figure 7.4 Voltage drop before compensation and after compestion



Maximum Percentage voltage drop improvement determination is:-

$$\%voltage\ drop\ improvment$$
$$= \frac{voltage\ level\ in\ orginal\ System\ in\ kV - voltage\ with\ shunt\ capacitor\ in\ kV}{voltage\ level\ in\ original\ system\ in\ kV} * 100$$

For Bus 10,

$$\%voltage\ level\ increment = \frac{2.69 - 2.15}{2.69} * 100$$
$$= 20.1\%\ thus, after\ compensation\ the\ voltage\ drop\ improved\ by\ this\ \ percent$$

Chapter Seven

Conclusion and Recommendation

7.1. Conclusion

In this thesis, an AC 25 kV, 50 Hz electrified railway traction power supply system is simulated with DIgSILENT/PowerFactory software. The simulated system consisting of two traction substation (i.e. Sebeta and Indode) with one Lebu traction post. Sebeta have two single phase transformers one is working the other becomes hot backup and two Vv type transformer for other traction substation.

The model of Sebeta to Indode traction power supply system and its general parameter model such as catenary or the feeding line model, substation model, transmission line model and the load model of the system is modeled,

- ✓ The energy consumption from Sebeta to Indode substation is determined
- ✓ The power flow of the modeled system investigated.
- ✓ Substation voltage drop, catenary voltage drop, power consumption and power loss in the sebeta substation and also their fault location is investigated.

In this thesis work, the power flow analysis is done using Newton Raphson method and the result convergence after 8th iteration. In this thesis two cases are considered, in case one two passenger trains are considered in a section and a power consumption of 3.22 MW is calculated at load side. The voltage deviation analyzed from the load flow result is within the standard. In case two one passenger train and one freight train is considered, load flow result shows that the voltage deviation is between the standard at normal condition. But when a fault occurred at Sebeta substation at the load side, the train at Sebeta substation couldn’t get power and switch/load breaker, should automatically deliver power from Lebu section post. In this case the length becomes increased to supply power to the load, then the voltage deviation becomes high, to minimize this voltage drop a compensator (shunt capacitor) at load voltage side with a 3.41Mvar is designed. The voltage drop for buses 8, 9 and 10 is improved from 2.63, 2.61 and 2.69kV to 2.1, 2.07 and 2.15kV respectively. After compensation the voltage at buses 6, 8, 9, 10 and 11 are improved from 0.917, 0.904, 0.905, 0.902 and 0.969 p.u to 0.936, 0.924, 0.925, 0.922 and 0.989 p.u, respectively.i.e. with maximum percentage bus voltage increment of 2.22% after compensation. Also the total power loss for the modeled system is decreased from 0.6MW to 0.56 MW. Furthermore, short circuit fault analysis and transient simulations of an AC traction power supply system in electrified railway were presented in this thesis. The simulation is conducted with DIgSILENT/*PowerFactory software.* Thus, From the transient simulation result at bus 5 the maximum peak short circuit current for single line to ground fault is 2.747kA and for two phase short circuit fault current is 6.973kA.Therefore, this thesis deduce that the worst type of fault is the short circuit fault in the overhead contact system of the trains.

Generally, the Faults in AC electrified railway are divided into two categories. The first is the faults in the power network feeding the traction substations that depending on the fault type and duration can cause poor performance of the traction system. Three phase faults in the transmission lines feeding the traction substations have the worst effect resulting in the traction transformers to be outaged. Whereas considering a single phase or two phase faults, in the transmission line lower power can be fed to the traction substations and the rest power demand can be gained from adjacent traction substations, therefore the trains along the track would not suffer unless the high tractive force is needed by the trains.

The second and worst type of the faults is the short circuit fault in the overhead contact system of the trains. Considering this fault in the overhead contact systems can cause great troubles for the train sets along that track. Such faults can result in the stopping of the trains along the track or the power equipment can be damaged severely.

Findings from this research are presented as following;

1. At the location of train from substation increases; the traction network voltage decreases: whereas, the traction voltage loss increases.
2. The traction network maximum voltage loss heavily depends on; the distance of traction network, obtain at the end of the line around section post.

Generally, it is also necessary to study power dispatch in the system under faulty conditions. For increasing the reliability of the traction electrical system, it is necessary to design the structure of traction power supply system in a way that it would be able to still be fed from other feeders when a disconnection occurs in a feeder. For this reason, the electrical distribution system is designed to be able to feed all of the traction substations without any problems such as overloading.

7.2 Recommendation

Based on the result of this thesis work, it is strongly recommended that the Ethiopian Railway Corporation has to consider compensator at Sebeta substation to enhance overall system power transfer capability, improving the network voltage and reduce voltage and power losses across the line in the system.

7.3 Future work

There are always new systems or set-ups: which require, different modeling and simulation of single and Vv connection transformer is one among the many approaches. Further development on employing: auto-transformer modeling often enhances the level of details in the output or targets. On the other hand, computational demand is certainly going up; with more complicated models. By considering auto-transformer; the effect of voltage level could be: studied in order to have a deeper knowledge, about AC traction power supply system voltage level: which is, still needs further study to get reliable result.

Furthermore,

- ✓ Working on distance and other protection schemes
- ✓ Making and breaking load switch breaker automatically in DIgSILENT power factory simulator software
- ✓ Simulation of the whole traction line from SEBETA to Djibouti Railway traction power line in order to investigate the voltage drop and power loss of the system.

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Appendix A

IEC voltage factor

As per IEC 60909 the equivalent voltage source (rms) is given by the relations IEC voltage factor

$$\mathrm{U_{es}} = \frac{\mathrm{C} * \mathrm{U_n}}{\sqrt{3}}\mathrm{V}$$

Nominal voltage $\mathrm{U_{n,V}}$	Minimum short circuit currents,$\mathrm{C_{min}}$	Maximum short circuit currents,$\mathrm{C_{max}}$	Tolerance %
Low voltage $\mathrm{U_n} \in (100{,}1000)\mathrm{Kv}$	0.95	1.05	6
Medium voltage $\mathrm{U_n} \in (1{,}35)\mathrm{Kv}$		1.10	10
High voltage $\mathrm{U_n} > 35\mathrm{Kv}$	1.00	1.10	

Appendix B

Number of trains passenger/freight trains (unit:$^{\mathbf{pair}}/_{\mathbf{day}}$)

Research year	Interval	The number of trains (pair/day)			
		Passenger train	Freight train	Set out	Subtotal
Preliminary Stage	Sebeta-Adama	4	4	1	9
	Adama-awash	1	4	1	6
	Awash-Mieso	1	4	1	6
Short term	Sebeta-Adama	6	7	1	14
	Adama-awash	1	8	1	10
	Awash-Mieso	1	9	1	11
Long term	Sebeta-Adama	10	16	1	27
	Adama-awash	2	17	1	20
	Awash-Mieso	2	19	1	22

Appendix C

Table and Figure below describes the locomotive tractive effort versus speed and the electrical braking effort versus speed graphs

Speed in km/h	Tractive force at wheel rim(KN)	Electrical braking force at wheel rim (KN)
0	570	0
2	570	0
5	570	400
10	555.833	400
30	499.167	400
50	442.5	400
65	400	400
70	371.429	371.429
75	346.667	346.667
80	325.000	325.000
85	305.882	305.882
90	288.889	288.889
95	273.684	273.684
100	260.000	260.000
105	247.619	247.619
110	236.364	236.364
115	226.087	226.087
120	216.667	216.667

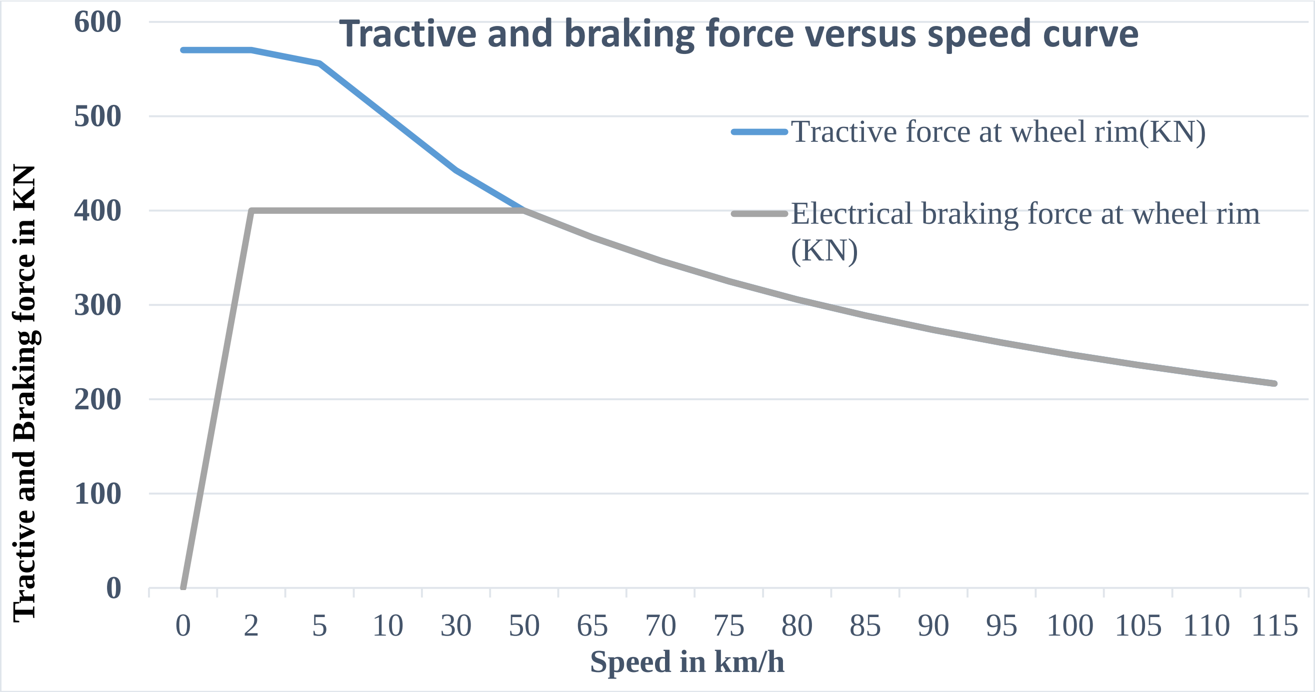


Figure: Tractive and braking force versus speed curve

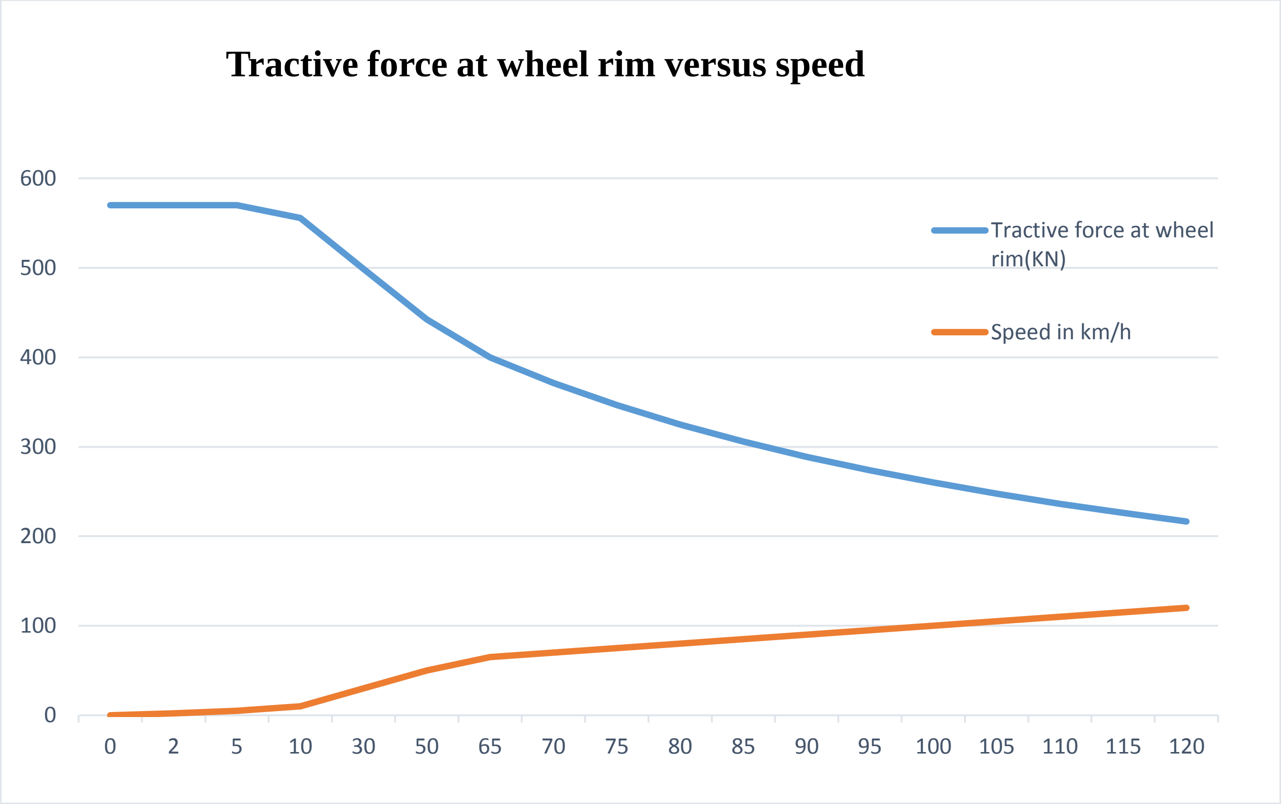
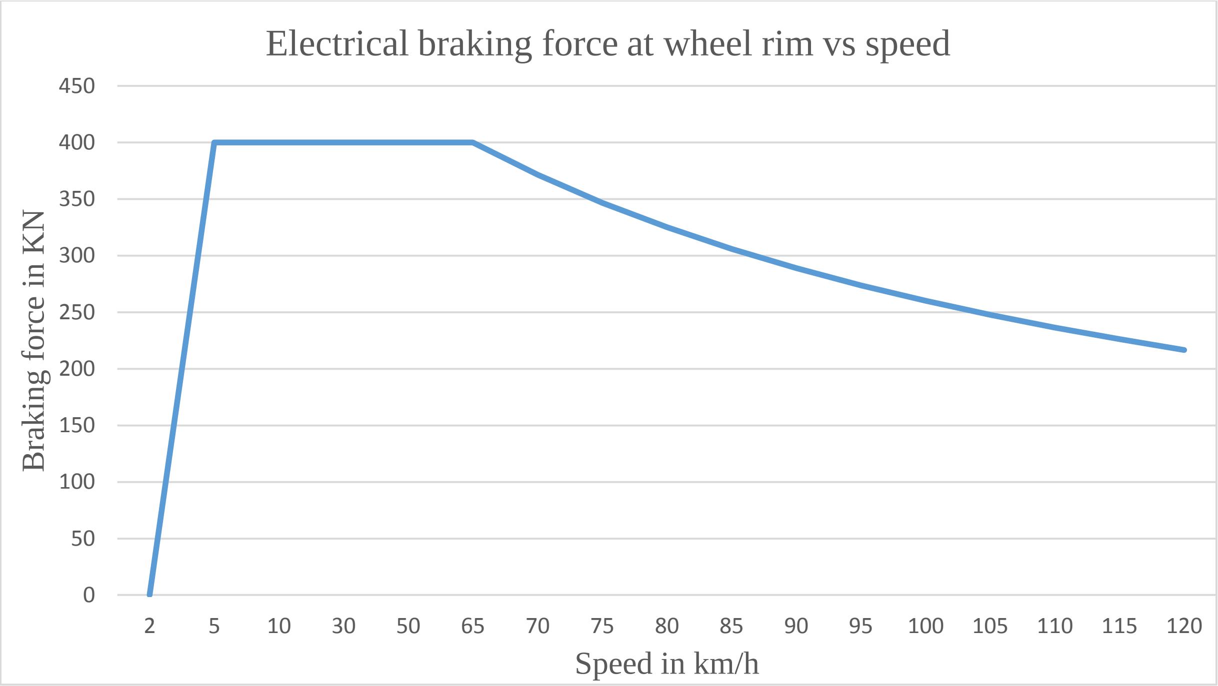
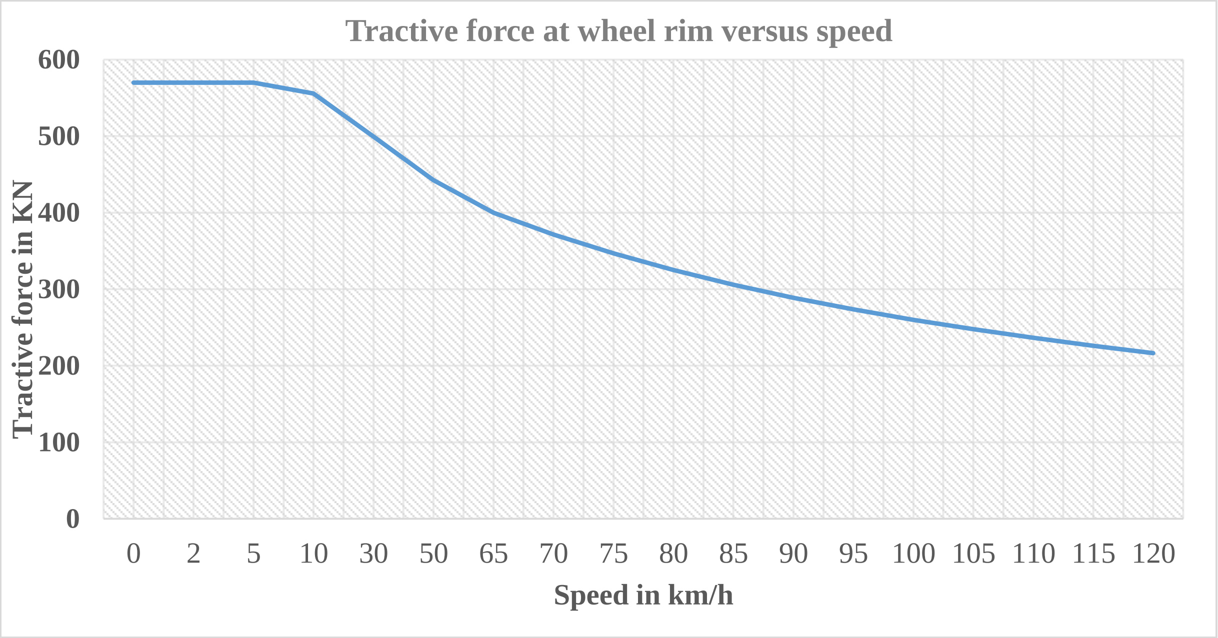


Figure: Tractive force at wheel rim vs speed

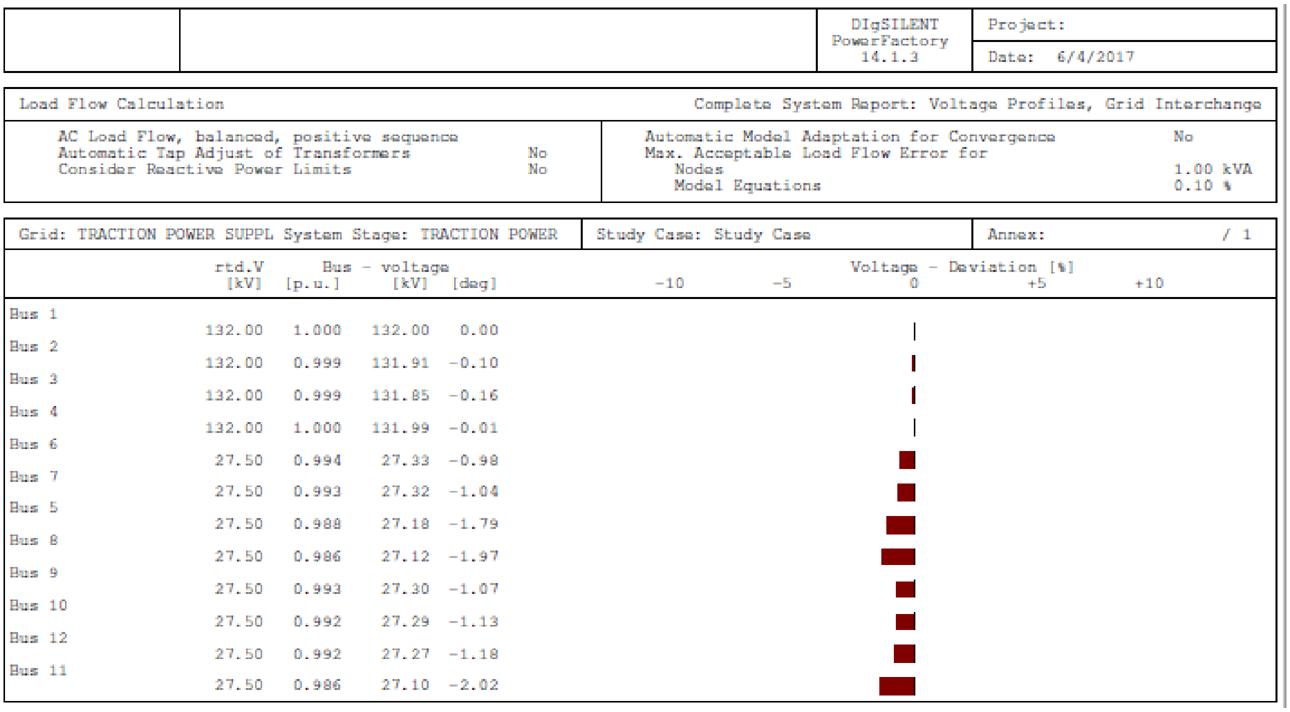

Electrical braking force at wheel rim vs speed
Braking force in KN
450
400
350
300
250
200
150
100
50
0
2
5
10
30
50
65
70
75
80
85
90
95
100
105
110
115
120
Speed in km/h


Tractive force at wheel rim versus speed
Tractive force in KN
600
500
400
300
200
100
0
0
2
5
10
30
50
65
70
75
80
85
90
95
100
105
110
115
120
Speed in km/h

Appendix D

Load flow and short circuit result report

Case1: Two passenger train occupied the track section load flow report



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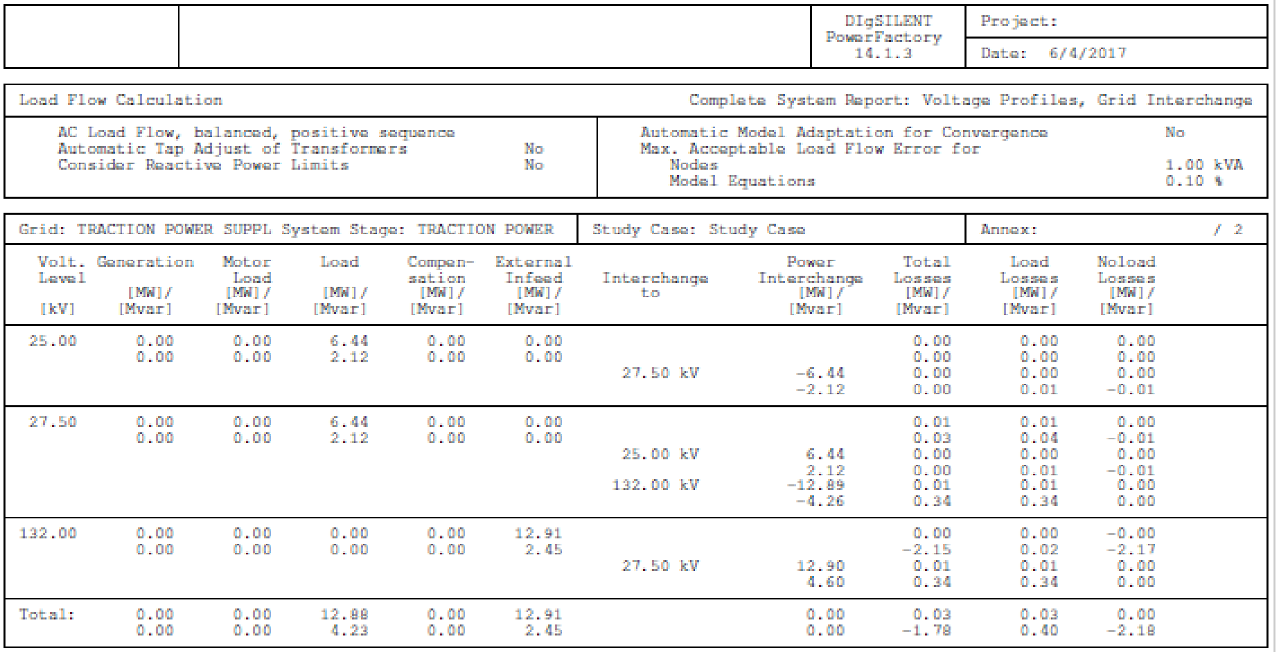
                                                                DIgSILENT       Project:
                                                                PowerFactory
                                                                  14.1.3        Date:   6/4/2017

Load Flow Calculation                                    Complete System Report: Voltage Profiles, Grid Interchange

    AC Load Flow, balanced, positive sequence               Automatic Model Adaptation for Convergence          No
    Automatic Tap Adjust of Transformers      No            Max. Acceptable Load Flow Error for
    Consider Reactive Power Limits            No               Nodes                                       1.00 kVA
                                                               Model Equations                             0.10 %

Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER | Study Case: Study Case         | Annex:            / 1

                      rtd.V     Bus - voltage                                 Voltage - Deviation [%]
                      [kV]  [p.u.]    [kV]  [deg]           -10         -5           0          +5         +10
Bus 1
                    132.00   1.000  132.00   0.00
Bus 2
                    132.00   0.999  131.91  -0.10
Bus 3
                    132.00   0.999  131.85  -0.16
Bus 4
                    132.00   1.000  131.99  -0.01
Bus 6
                     27.50   0.994   27.33  -0.98
Bus 7
                     27.50   0.993   27.32  -1.04
Bus 5
                     27.50   0.988   27.18  -1.79
Bus 8
                     27.50   0.986   27.12  -1.97
Bus 9
                     27.50   0.993   27.30  -1.07
Bus 10
                     27.50   0.992   27.29  -1.13
Bus 12
                     27.50   0.992   27.27  -1.18
Bus 11
                     27.50   0.986   27.10  -2.02
```



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                                                                DIgSILENT       Project:
                                                                PowerFactory
                                                                  14.1.3        Date:   6/4/2017

Load Flow Calculation                                    Complete System Report: Voltage Profiles, Grid Interchange

    AC Load Flow, balanced, positive sequence               Automatic Model Adaptation for Convergence          No
    Automatic Tap Adjust of Transformers      No            Max. Acceptable Load Flow Error for
    Consider Reactive Power Limits            No               Nodes                                       1.00 kVA
                                                               Model Equations                             0.10 %

Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER | Study Case: Study Case         | Annex:            / 2

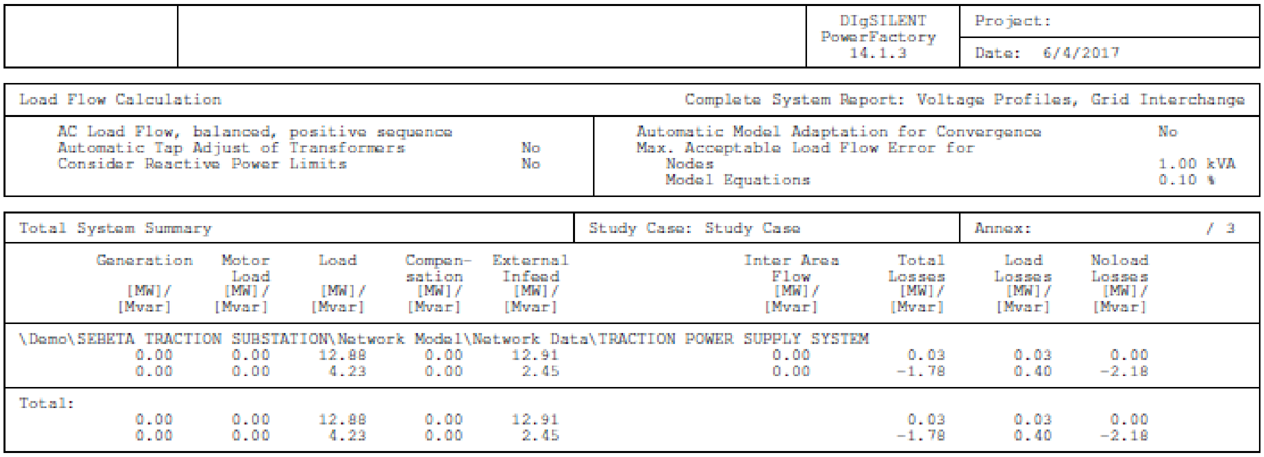
  Volt. Generation  Motor     Load    Compen-  External                  Power      Total     Load    Noload
  Level              Load             sation   Infeed   Interchange  Interchange   Losses    Losses   Losses
          [MW]/     [MW]/    [MW]/    [MW]/    [MW]/        to          [MW]/      [MW]/     [MW]/    [MW]/
  [kV]    [Mvar]    [Mvar]   [Mvar]   [Mvar]   [Mvar]                   [Mvar]     [Mvar]    [Mvar]   [Mvar]

 25.00     0.00      0.00     6.44     0.00     0.00                                0.00      0.00     0.00
           0.00      0.00     2.12     0.00     0.00                                0.00      0.00     0.00
                                                       27.50 kV         -6.44       0.00      0.00     0.00
                                                                        -2.12       0.00      0.01    -0.01

 27.50     0.00      0.00     6.44     0.00     0.00                                0.01      0.01     0.00
           0.00      0.00     2.12     0.00     0.00                                0.03      0.04    -0.01
                                                       25.00 kV          6.44       0.00      0.00     0.00
                                                                         2.12       0.00      0.01    -0.01
                                                      132.00 kV        -12.89       0.01      0.01     0.00
                                                                        -4.26       0.34      0.34     0.00

132.00     0.00      0.00     0.00     0.00    12.91                                0.00      0.00    -0.00
           0.00      0.00     0.00     0.00     2.45                               -2.15      0.02    -2.17
                                                       27.50 kV         12.90       0.01      0.01     0.00
                                                                         4.60       0.34      0.34     0.00

Total:     0.00      0.00    12.88     0.00    12.91                     0.00       0.03      0.03     0.00
           0.00      0.00     4.23     0.00     2.45                     0.00      -1.78      0.40    -2.18
```



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                                                          DIgSILENT       Project:
                                                          PowerFactory
                                                           14.1.3         Date:  6/4/2017

Load Flow Calculation                                   Complete System Report: Voltage Profiles, Grid Interchange

    AC Load Flow, balanced, positive sequence              Automatic Model Adaptation for Convergence        No
    Automatic Tap Adjust of Transformers          No       Max. Acceptable Load Flow Error for
    Consider Reactive Power Limits                No          Nodes                                          1.00 kVA
                                                              Model Equations                                0.10 %

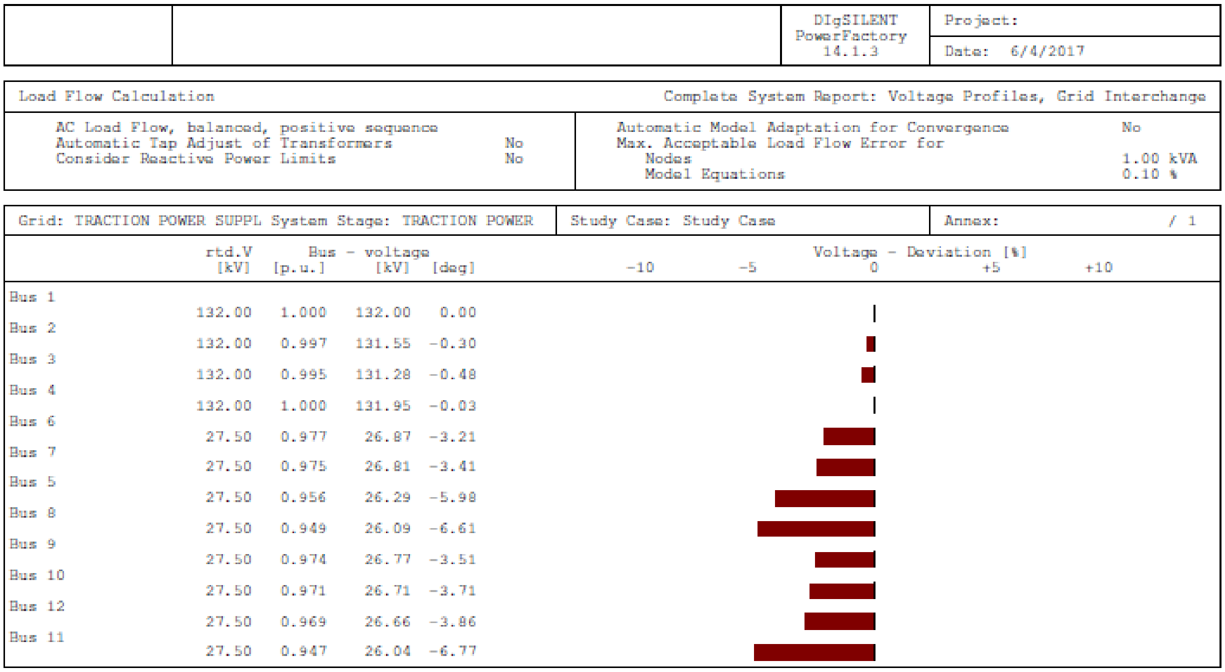
Total System Summary                                    Study Case: Study Case                   Annex:            / 3

         Generation  Motor     Load     Compen-  External                  Inter Area   Total     Load     Noload
                      Load              sation    Infeed                      Flow      Losses    Losses    Losses
           [MW]/     [MW]/     [MW]/    [MW]/     [MW]/                      [MW]/      [MW]/     [MW]/     [MW]/
          [Mvar]    [Mvar]    [Mvar]   [Mvar]    [Mvar]                     [Mvar]     [Mvar]    [Mvar]    [Mvar]

\Demo\SEBETA TRACTION SUBSTATION\Network Model\Network Data\TRACTION POWER SUPPLY SYSTEM
            0.00      0.00     12.88     0.00     12.91                       0.00       0.03      0.03      0.00
            0.00      0.00      4.23     0.00      2.45                       0.00      -1.78      0.40     -2.18

Total:
            0.00      0.00     12.88     0.00     12.91                                  0.03      0.03      0.00
            0.00      0.00      4.23     0.00      2.45                                 -1.78      0.40     -2.18
```

Case two when one passenger train and one freight train occupied the track section



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                                                      DIgSILENT       Project:
                                                      PowerFactory
                                                       14.1.3         Date:  6/4/2017

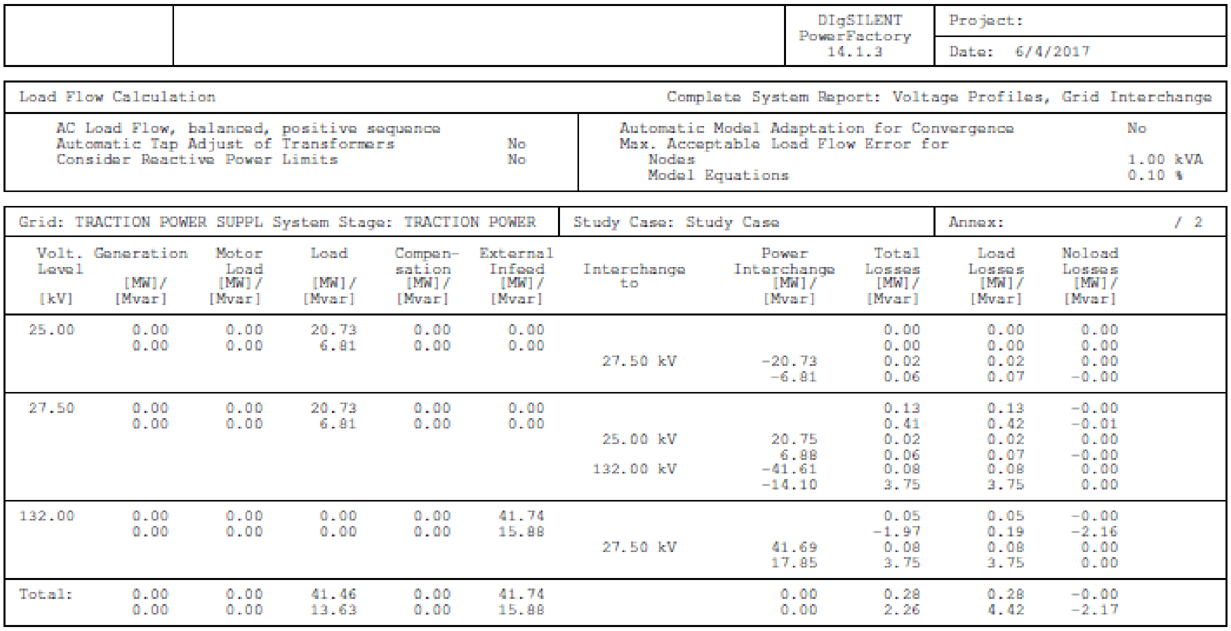
Load Flow Calculation                                Complete System Report: Voltage Profiles, Grid Interchange

    AC Load Flow, balanced, positive sequence           Automatic Model Adaptation for Convergence       No
    Automatic Tap Adjust of Transformers        No      Max. Acceptable Load Flow Error for
    Consider Reactive Power Limits              No         Nodes                                         1.00 kVA
                                                           Model Equations                               0.10 %

Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER  Study Case: Study Case            Annex:            / 1

                     rtd.V      Bus - voltage                        Voltage - Deviation [%]
                     [kV]   [p.u.]    [kV]   [deg]          -10          -5           0           +5          +10

Bus 1
                    132.00   1.000   132.00   0.00
Bus 2
                    132.00   0.997   131.55  -0.30
Bus 3
                    132.00   0.995   131.28  -0.48
Bus 4
                    132.00   1.000   131.95  -0.03
Bus 6
                     27.50   0.977    26.87  -3.21
Bus 7
                     27.50   0.975    26.81  -3.41
Bus 5
                     27.50   0.956    26.29  -5.98
Bus 8
                     27.50   0.949    26.09  -6.61
Bus 9
                     27.50   0.974    26.77  -3.51
Bus 10
                     27.50   0.971    26.71  -3.71
Bus 12
                     27.50   0.969    26.66  -3.86
Bus 11
                     27.50   0.947    26.04  -6.77
```



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                                                    DIgSILENT   | Project:
                                                  PowerFactory  |
                                                     14.1.3     | Date:  6/4/2017

Load Flow Calculation                        Complete System Report: Voltage Profiles, Grid Interchange

   AC Load Flow, balanced, positive sequence          Automatic Model Adaptation for Convergence     No
   Automatic Tap Adjust of Transformers      No       Max. Acceptable Load Flow Error for
   Consider Reactive Power Limits            No          Nodes                                    1.00 kVA
                                                         Model Equations                          0.10 %

Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER | Study Case: Study Case    | Annex:           / 2

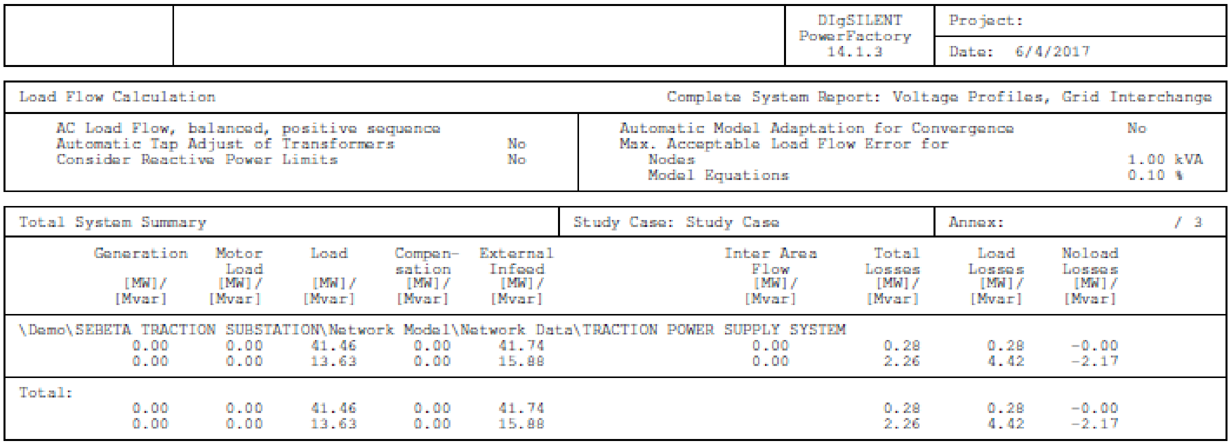
  Volt. Generation  Motor    Load    Compen-  External                  Power    Total    Load    Noload
  Level              Load            sation   Infeed   Interchange  Interchange Losses   Losses   Losses
           [MW]/    [MW]/    [MW]/    [MW]/    [MW]/        to         [MW]/    [MW]/    [MW]/    [MW]/
  [kV]    [Mvar]   [Mvar]   [Mvar]   [Mvar]   [Mvar]                    [Mvar]   [Mvar]   [Mvar]   [Mvar]

 25.00      0.00     0.00    20.73     0.00     0.00                              0.00     0.00     0.00
            0.00     0.00     6.81     0.00     0.00                              0.00     0.00     0.00
                                                       27.50 kV      -20.73      0.02     0.02     0.00
                                                                      -6.81      0.06     0.07    -0.00

 27.50      0.00     0.00    20.73     0.00     0.00                              0.13     0.13    -0.00
            0.00     0.00     6.81     0.00     0.00                              0.41     0.42    -0.01
                                                       25.00 kV       20.75      0.02     0.02     0.00
                                                                       6.88      0.06     0.07    -0.00
                                                      132.00 kV      -41.61      0.08     0.08     0.00
                                                                     -14.10      3.75     3.75     0.00

132.00      0.00     0.00     0.00     0.00    41.74                              0.05     0.05    -0.00
            0.00     0.00     0.00     0.00    15.88                             -1.97     0.19    -2.16
                                                       27.50 kV       41.69      0.08     0.08     0.00
                                                                      17.85      3.75     3.75     0.00

Total:      0.00     0.00    41.46     0.00    41.74                  0.00      0.28     0.28    -0.00
            0.00     0.00    13.63     0.00    15.88                  0.00      2.26     4.42    -2.17
```



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                                                    DIgSILENT   | Project:
                                                  PowerFactory  |
                                                     14.1.3     | Date:  6/4/2017

Load Flow Calculation                        Complete System Report: Voltage Profiles, Grid Interchange

   AC Load Flow, balanced, positive sequence          Automatic Model Adaptation for Convergence     No
   Automatic Tap Adjust of Transformers      No       Max. Acceptable Load Flow Error for
   Consider Reactive Power Limits            No          Nodes                                    1.00 kVA
                                                         Model Equations                          0.10 %

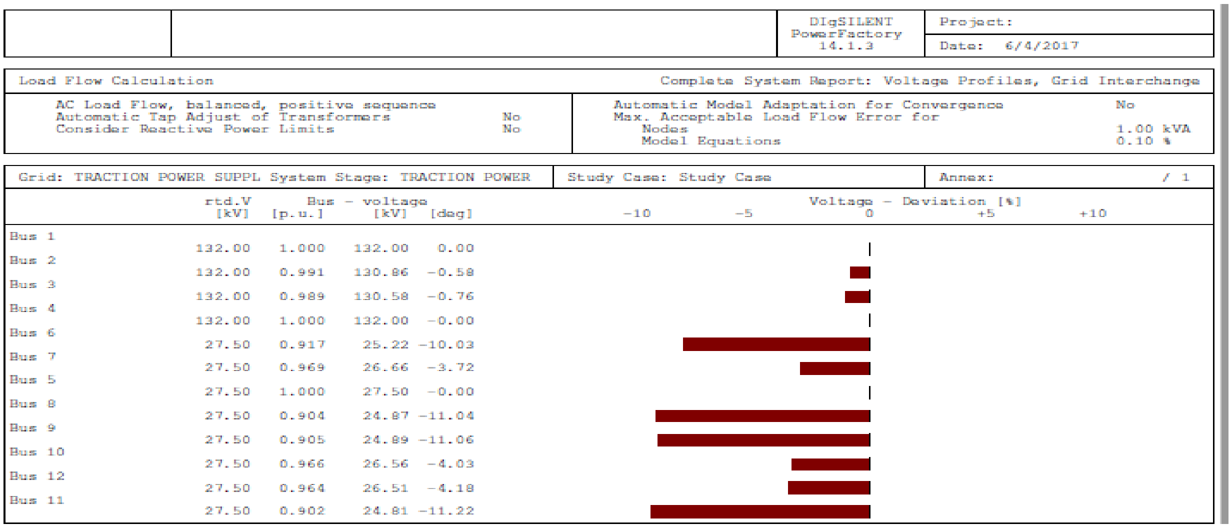
Total System Summary                                    | Study Case: Study Case    | Annex:           / 3

        Generation  Motor    Load    Compen-  External              Inter Area   Total    Load    Noload
                     Load            sation   Infeed                   Flow     Losses   Losses   Losses
           [MW]/    [MW]/    [MW]/    [MW]/    [MW]/                  [MW]/    [MW]/    [MW]/    [MW]/
          [Mvar]   [Mvar]   [Mvar]   [Mvar]   [Mvar]                 [Mvar]   [Mvar]   [Mvar]   [Mvar]

\Demo\SEBETA TRACTION SUBSTATION\Network Model\Network Data\TRACTION POWER SUPPLY SYSTEM
            0.00     0.00    41.46     0.00    41.74                  0.00      0.28     0.28    -0.00
            0.00     0.00    13.63     0.00    15.88                  0.00      2.26     4.42    -2.17

Total:
            0.00     0.00    41.46     0.00    41.74                            0.28     0.28    -0.00
            0.00     0.00    13.63     0.00    15.88                            2.26     4.42    -2.17
```

Section post power feed load flow result report



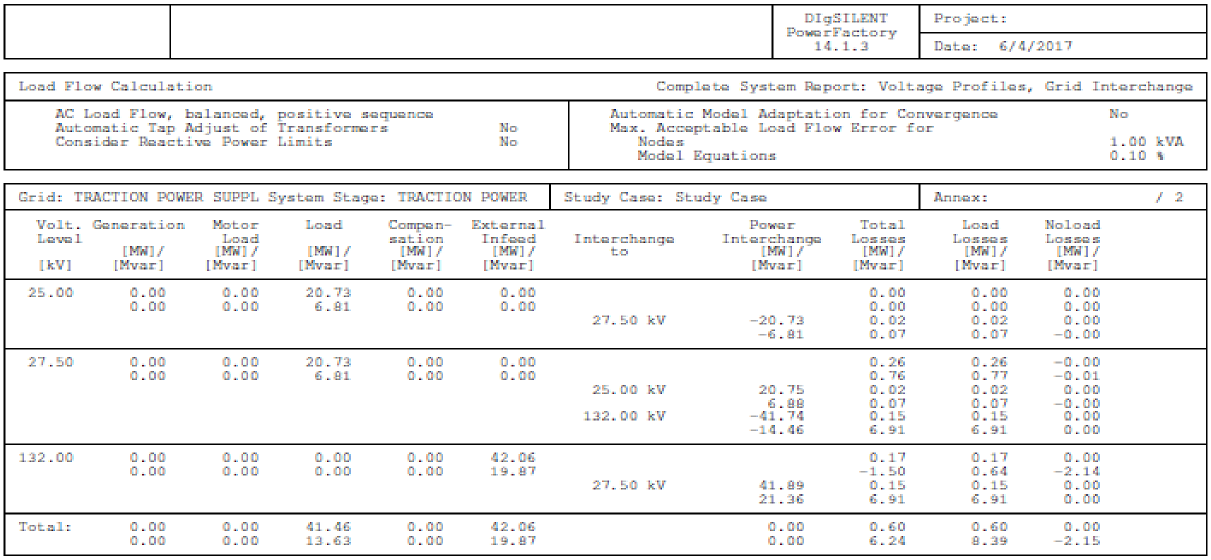
```
                                                    DIgSILENT   | Project:
                                                  PowerFactory  |
                                                     14.1.3     | Date:  6/4/2017

Load Flow Calculation                        Complete System Report: Voltage Profiles, Grid Interchange

   AC Load Flow, balanced, positive sequence          Automatic Model Adaptation for Convergence     No
   Automatic Tap Adjust of Transformers      No       Max. Acceptable Load Flow Error for
   Consider Reactive Power Limits            No          Nodes                                    1.00 kVA
                                                         Model Equations                          0.10 %

Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER | Study Case: Study Case    | Annex:           / 1

                   rtd.V      Bus - voltage                           Voltage - Deviation [%]
                   [kV]   [p.u.]     [kV]   [deg]       -10       -5         0        +5        +10
Bus 1
                  132.00   1.000   132.00    0.00
Bus 2
                  132.00   0.991   130.86   -0.58
Bus 3
                  132.00   0.989   130.58   -0.76
Bus 4
                  132.00   1.000   132.00   -0.00
Bus 6
                   27.50   0.917    25.22  -10.03
Bus 7
                   27.50   0.969    26.66   -3.72
Bus 5
                   27.50   1.000    27.50   -0.00
Bus 8
                   27.50   0.904    24.87  -11.04
Bus 9
                   27.50   0.905    24.89  -11.06
Bus 10
                   27.50   0.966    26.56   -4.03
Bus 12
                   27.50   0.964    26.51   -4.18
Bus 11
                   27.50   0.902    24.81  -11.22
```



```
                                                       DIgSILENT          Project:
                                                       PowerFactory
                                                       14.1.3             Date:  6/4/2017

Load Flow Calculation                                Complete System Report: Voltage Profiles, Grid Interchange

    AC Load Flow, balanced, positive sequence           Automatic Model Adaptation for Convergence       No
    Automatic Tap Adjust of Transformers        No      Max. Acceptable Load Flow Error for
    Consider Reactive Power Limits              No         Nodes                                         1.00 kVA
                                                           Model Equations                               0.10 %

Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER | Study Case: Study Case              | Annex:          / 2

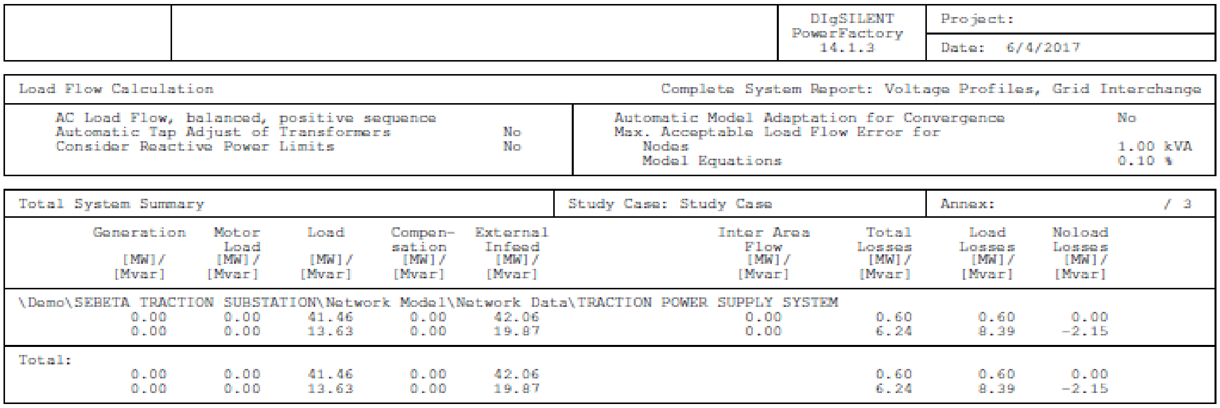
  Volt. Generation   Motor     Load    Compen-  External                   Power       Total     Load     Noload
  Level              Load              sation   Infeed    Interchange   Interchange    Losses    Losses   Losses
          [MW]/     [MW]/     [MW]/    [MW]/    [MW]/        to           [MW]/       [MW]/     [MW]/    [MW]/
  [kV]   [Mvar]    [Mvar]    [Mvar]   [Mvar]   [Mvar]                    [Mvar]      [Mvar]    [Mvar]   [Mvar]

 25.00     0.00      0.00    20.73     0.00     0.00                                  0.00      0.00     0.00
           0.00      0.00     6.81     0.00     0.00                                  0.00      0.00     0.00
                                                          27.50 kV      -20.73        0.02      0.02     0.00
                                                                         -6.81        0.07      0.07    -0.00

 27.50     0.00      0.00    20.73     0.00     0.00                                  0.26      0.26    -0.00
           0.00      0.00     6.81     0.00     0.00                                  0.76      0.77    -0.01
                                                          25.00 kV       20.75        0.02      0.02     0.00
                                                                          6.88        0.07      0.07    -0.00
                                                         132.00 kV      -41.74        0.15      0.15     0.00
                                                                        -14.46        6.91      6.91     0.00

132.00     0.00      0.00     0.00     0.00    42.06                                  0.17      0.17     0.00
           0.00      0.00     0.00     0.00    19.87                                 -1.50      0.64    -2.14
                                                          27.50 kV       41.89        0.15      0.15     0.00
                                                                         21.36        6.91      6.91     0.00

Total:     0.00      0.00    41.46     0.00    42.06                      0.00        0.60      0.60     0.00
           0.00      0.00    13.63     0.00    19.87                      0.00        6.24      8.39    -2.15
```



```
                                                       DIgSILENT          Project:
                                                       PowerFactory
                                                       14.1.3             Date:  6/4/2017

Load Flow Calculation                                Complete System Report: Voltage Profiles, Grid Interchange

    AC Load Flow, balanced, positive sequence           Automatic Model Adaptation for Convergence       No
    Automatic Tap Adjust of Transformers        No      Max. Acceptable Load Flow Error for
    Consider Reactive Power Limits              No         Nodes                                         1.00 kVA
                                                           Model Equations                               0.10 %

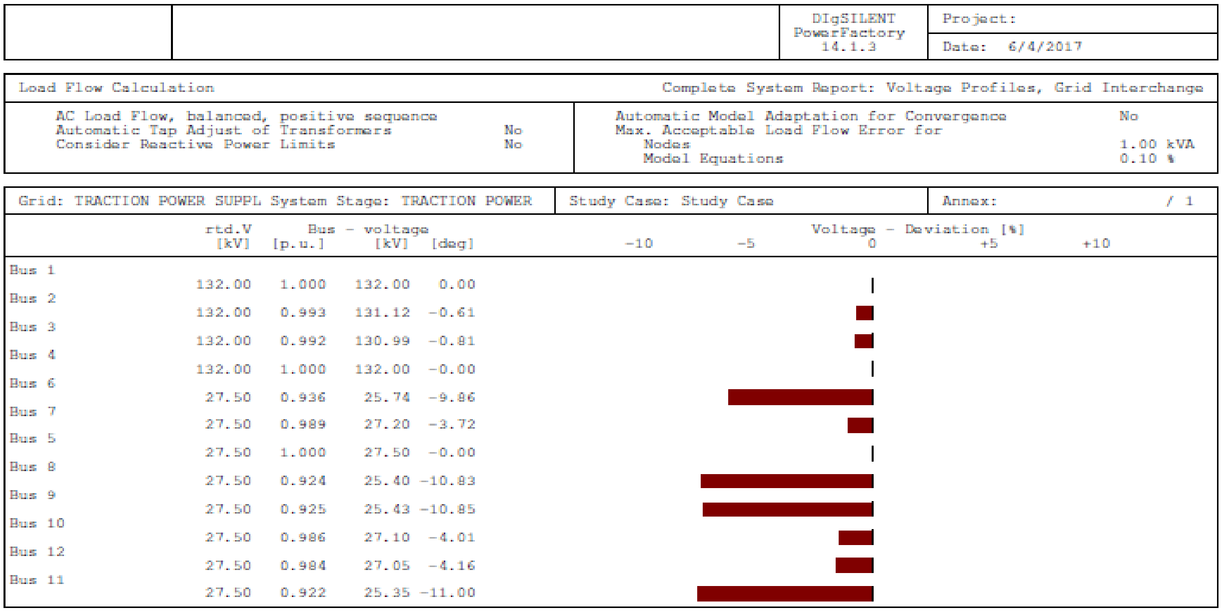
Total System Summary                                  | Study Case: Study Case              | Annex:          / 3

        Generation   Motor     Load    Compen-  External                 Inter Area   Total     Load     Noload
                     Load              sation   Infeed                     Flow       Losses    Losses   Losses
          [MW]/     [MW]/     [MW]/    [MW]/    [MW]/                      [MW]/      [MW]/     [MW]/    [MW]/
         [Mvar]    [Mvar]    [Mvar]   [Mvar]   [Mvar]                     [Mvar]     [Mvar]    [Mvar]   [Mvar]

\Demo\SEBETA TRACTION SUBSTATION\Network Model\Network Data\TRACTION POWER SUPPLY SYSTEM
           0.00      0.00    41.46     0.00    42.06                       0.00       0.60      0.60     0.00
           0.00      0.00    13.63     0.00    19.87                       0.00       6.24      8.39    -2.15

Total:
           0.00      0.00    41.46     0.00    42.06                                  0.60      0.60     0.00
           0.00      0.00    13.63     0.00    19.87                                  6.24      8.39    -2.15
```

Section post power feed load flow result report after compensation



```
                                                       DIgSILENT          Project:
                                                       PowerFactory
                                                       14.1.3             Date:  6/4/2017

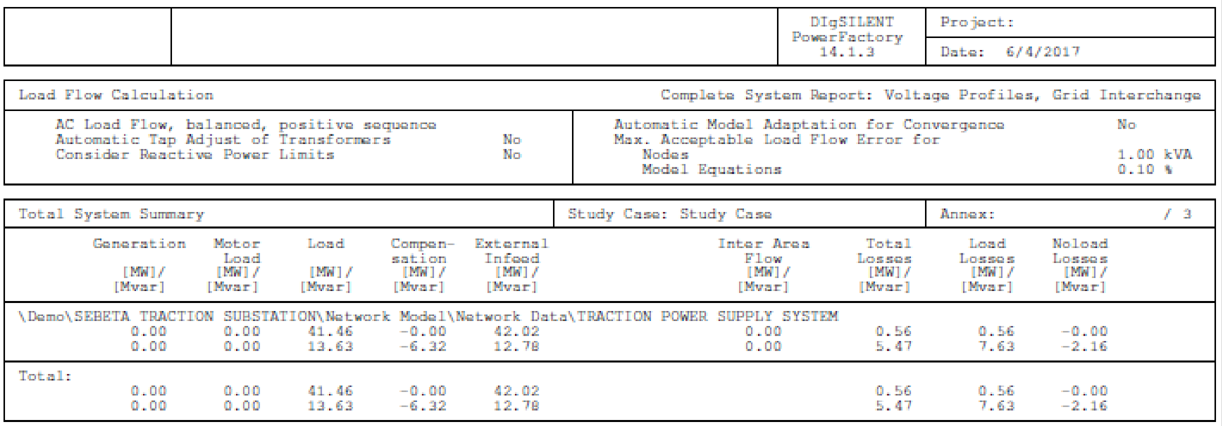
Load Flow Calculation                                Complete System Report: Voltage Profiles, Grid Interchange

    AC Load Flow, balanced, positive sequence           Automatic Model Adaptation for Convergence       No
    Automatic Tap Adjust of Transformers        No      Max. Acceptable Load Flow Error for
    Consider Reactive Power Limits              No         Nodes                                         1.00 kVA
                                                           Model Equations                               0.10 %

Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER | Study Case: Study Case              | Annex:          / 1

                   rtd.V       Bus - voltage                       Voltage - Deviation [%]
                   [kV]   [p.u.]     [kV]   [deg]          -10        -5         0         +5        +10

Bus 1
                  132.00   1.000   132.00    0.00
Bus 2
                  132.00   0.993   131.12   -0.61
Bus 3
                  132.00   0.992   130.99   -0.81
Bus 4
                  132.00   1.000   132.00   -0.00
Bus 6
                   27.50   0.936    25.74   -9.86
Bus 7
                   27.50   0.989    27.20   -3.72
Bus 5
                   27.50   1.000    27.50   -0.00
Bus 8
                   27.50   0.924    25.40  -10.83
Bus 9
                   27.50   0.925    25.43  -10.85
Bus 10
                   27.50   0.986    27.10   -4.01
Bus 12
                   27.50   0.984    27.05   -4.16
Bus 11
                   27.50   0.922    25.35  -11.00
```



```
                                                            DIgSILENT       Project:
                                                            PowerFactory
                                                             14.1.3         Date:   6/4/2017

Load Flow Calculation                              Complete System Report: Voltage Profiles, Grid Interchange

   AC Load Flow, balanced, positive sequence             Automatic Model Adaptation for Convergence          No
   Automatic Tap Adjust of Transformers        No        Max. Acceptable Load Flow Error for
   Consider Reactive Power Limits              No           Nodes                                            1.00 kVA
                                                            Model Equations                                  0.10 %

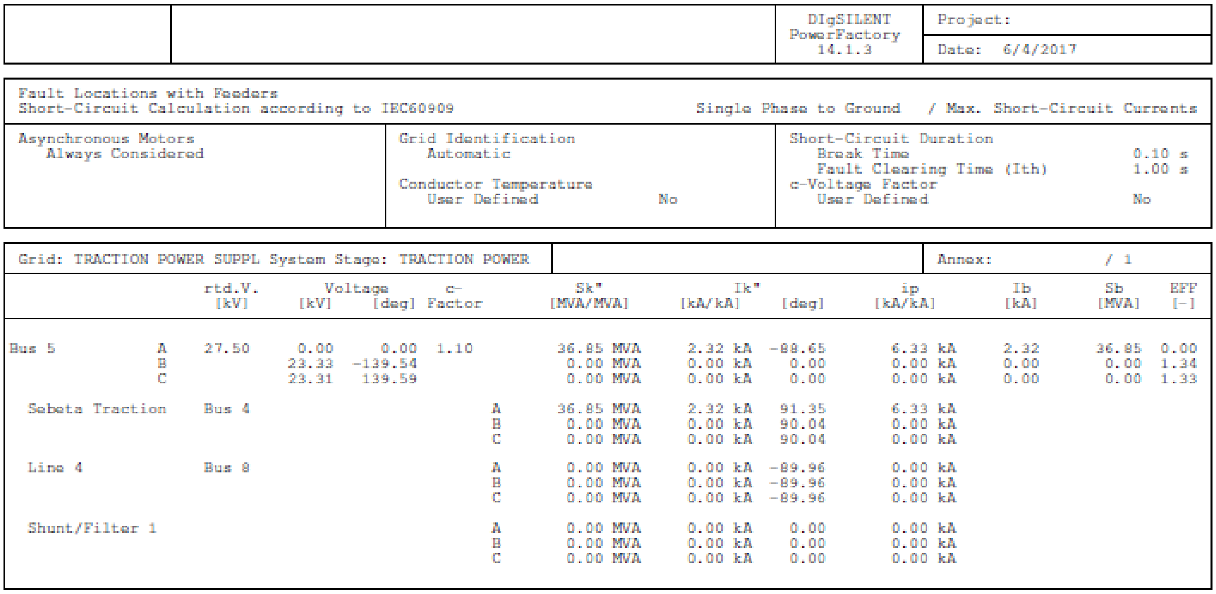
Total System Summary                          Study Case: Study Case             Annex:                   / 3

         Generation   Motor     Load     Compen-  External                  Inter Area    Total     Load     Noload
                       Load               sation   Infeed                      Flow       Losses    Losses   Losses
           [MW]/      [MW]/     [MW]/     [MW]/    [MW]/                      [MW]/       [MW]/     [MW]/    [MW]/
          [Mvar]     [Mvar]    [Mvar]    [Mvar]   [Mvar]                     [Mvar]      [Mvar]    [Mvar]   [Mvar]

\Demo\SEBETA TRACTION SUBSTATION\Network Model\Network Data\TRACTION POWER SUPPLY SYSTEM
            0.00       0.00     41.46     -0.00    42.02                       0.00        0.56      0.56     -0.00
            0.00       0.00     13.63     -6.32    12.78                       0.00        5.47      7.63     -2.16

Total:
            0.00       0.00     41.46     -0.00    42.02                                   0.56      0.56     -0.00
            0.00       0.00     13.63     -6.32    12.78                                   5.47      7.63     -2.16
```

LV side short circuit report



```
                                                            DIgSILENT       Project:
                                                            PowerFactory
                                                             14.1.3         Date:   6/4/2017

Fault Locations with Feeders
Short-Circuit Calculation according to IEC60909                  Single Phase to Ground   / Max. Short-Circuit Currents

Asynchronous Motors             Grid Identification                Short-Circuit Duration
   Always Considered               Automatic                          Break Time                       0.10 s
                                                                      Fault Clearing Time (Ith)        1.00 s
                                Conductor Temperature              c-Voltage Factor
                                   User Defined          No           User Defined                     No

Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER                            Annex:             / 1

                     rtd.V.     Voltage      c-          Sk"            Ik"              ip         Ib       Sb    EFF
                      [kV]    [kV]   [deg] Factor     [MVA/MVA]    [kA/kA]   [deg]    [kA/kA]      [kA]     [MVA]  [-]

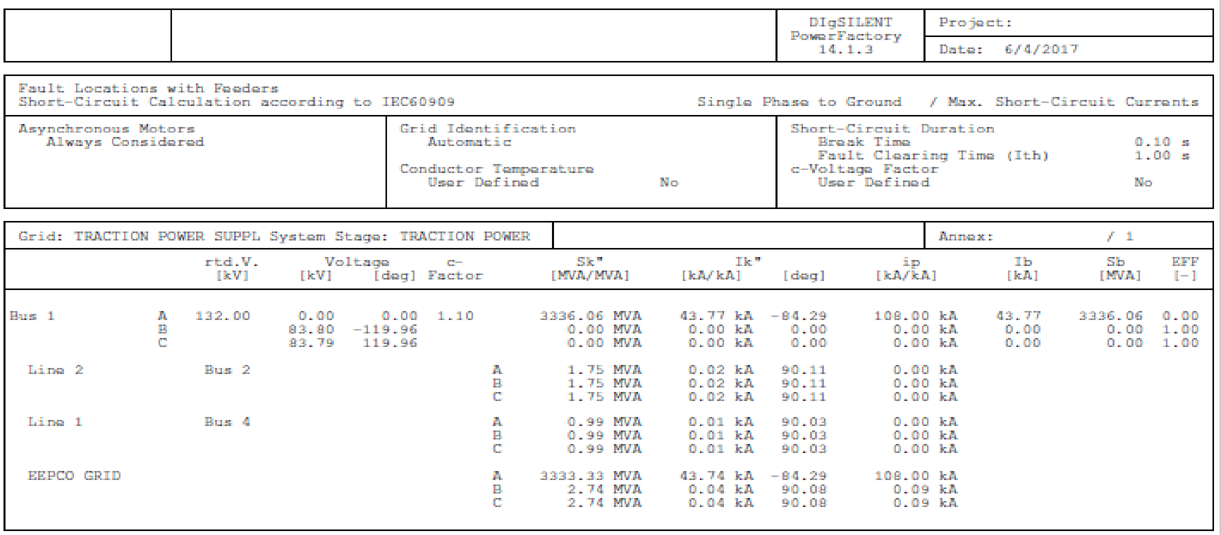
Bus 5           A     27.50    0.00    0.00  1.10       36.85 MVA    2.32 kA -88.65     6.33 kA    2.32     36.85 0.00
                B             23.33 -139.54              0.00 MVA    0.00 kA   0.00     0.00 kA    0.00      0.00 1.34
                C             23.31  139.59              0.00 MVA    0.00 kA   0.00     0.00 kA    0.00      0.00 1.33

  Sebeta Traction     Bus 4                     A       36.85 MVA    2.32 kA  91.35     6.33 kA
                                                B        0.00 MVA    0.00 kA  90.04     0.00 kA
                                                C        0.00 MVA    0.00 kA  90.04     0.00 kA

  Line 4              Bus 8                     A        0.00 MVA    0.00 kA -89.96     0.00 kA
                                                B        0.00 MVA    0.00 kA -89.96     0.00 kA
                                                C        0.00 MVA    0.00 kA -89.96     0.00 kA

  Shunt/Filter 1                                A        0.00 MVA    0.00 kA   0.00     0.00 kA
                                                B        0.00 MVA    0.00 kA   0.00     0.00 kA
                                                C        0.00 MVA    0.00 kA   0.00     0.00 kA
```

HV side short circuit report



```
                                                            DIgSILENT       Project:
                                                            PowerFactory
                                                             14.1.3         Date:   6/4/2017

Fault Locations with Feeders
Short-Circuit Calculation according to IEC60909                  Single Phase to Ground   / Max. Short-Circuit Currents

Asynchronous Motors             Grid Identification                Short-Circuit Duration
   Always Considered               Automatic                          Break Time                       0.10 s
                                                                      Fault Clearing Time (Ith)        1.00 s
                                Conductor Temperature              c-Voltage Factor
                                   User Defined          No           User Defined                     No

Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER                            Annex:             / 1

                     rtd.V.     Voltage      c-          Sk"            Ik"              ip         Ib       Sb    EFF
                      [kV]    [kV]   [deg] Factor     [MVA/MVA]    [kA/kA]   [deg]    [kA/kA]      [kA]     [MVA]  [-]

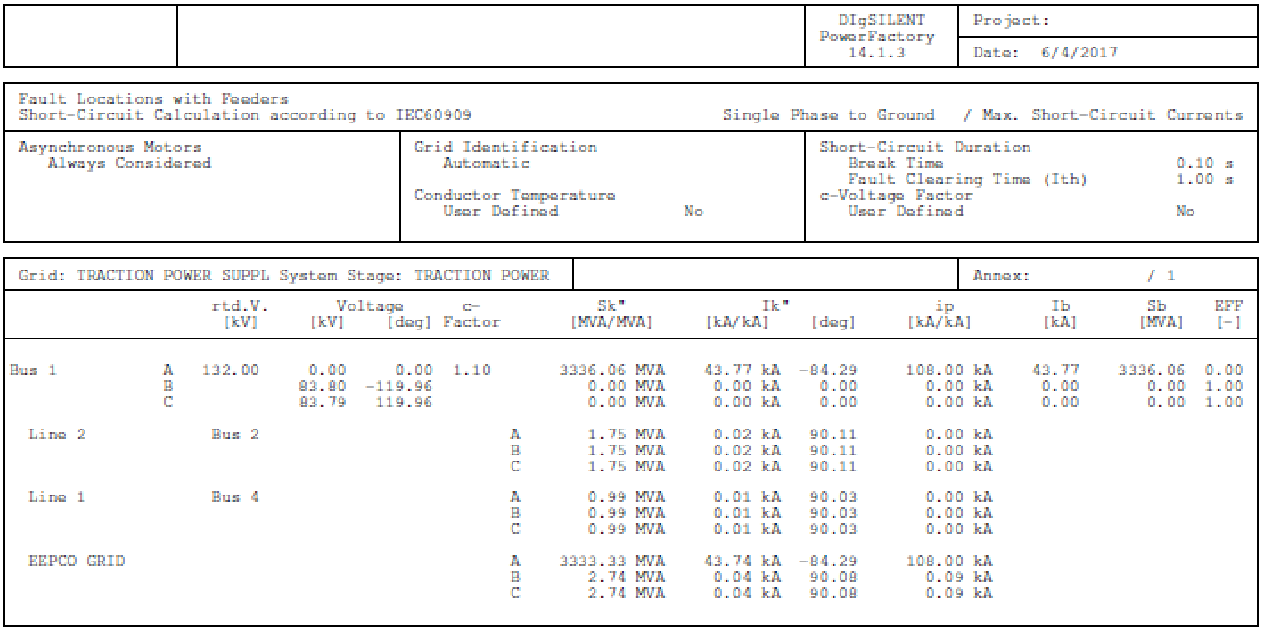
Bus 1           A    132.00    0.00    0.00  1.10     3336.06 MVA   43.77 kA -84.29   108.00 kA   43.77   3336.06 0.00
                B             83.80 -119.96              0.00 MVA    0.00 kA   0.00     0.00 kA    0.00      0.00 1.00
                C             83.79  119.96              0.00 MVA    0.00 kA   0.00     0.00 kA    0.00      0.00 1.00

  Line 2              Bus 2                     A        1.75 MVA    0.02 kA  90.11     0.00 kA
                                                B        1.75 MVA    0.02 kA  90.11     0.00 kA
                                                C        1.75 MVA    0.02 kA  90.11     0.00 kA

  Line 1              Bus 4                     A        0.99 MVA    0.01 kA  90.03     0.00 kA
                                                B        0.99 MVA    0.01 kA  90.03     0.00 kA
                                                C        0.99 MVA    0.01 kA  90.03     0.00 kA

  EEPCO GRID                                    A     3333.33 MVA   43.74 kA -84.29   108.00 kA
                                                B        2.74 MVA    0.04 kA  90.08     0.09 kA
                                                C        2.74 MVA    0.04 kA  90.08     0.09 kA
```

Short circuit fault Near to Grid side



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                                                     DIgSILENT        Project:
                                                    PowerFactory
                                                       14.1.3         Date:   6/4/2017

Fault Locations with Feeders
Short-Circuit Calculation according to IEC60909                      Single Phase to Ground   / Max. Short-Circuit Currents

Asynchronous Motors                       Grid Identification                       Short-Circuit Duration
   Always Considered                         Automatic                                 Break Time                        0.10 s
                                                                                        Fault Clearing Time (Ith)         1.00 s
                                          Conductor Temperature                     c-Voltage Factor
                                             User Defined            No                User Defined                      No

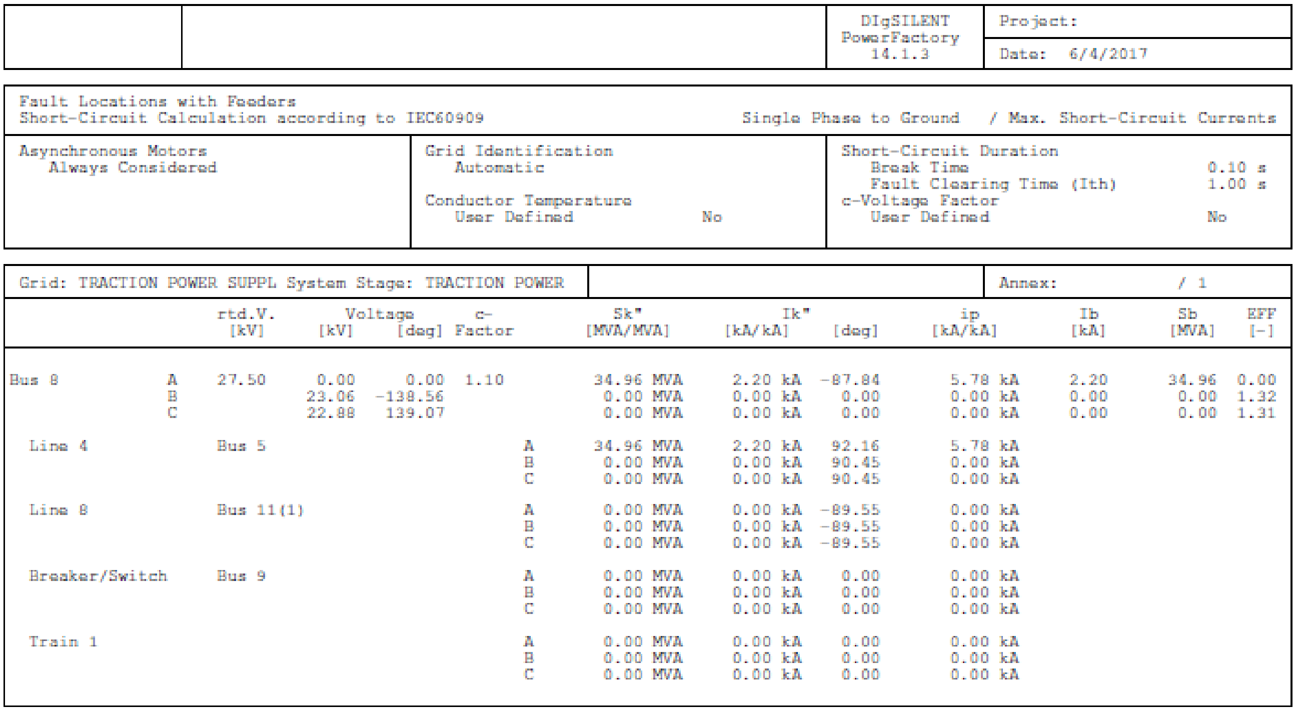
Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER                             Annex:             / 1

                         rtd.V.     Voltage     c-          Sk"          Ik"                 ip          Ib        Sb     EFF
                          [kV]    [kV]    [deg] Factor    [MVA/MVA]    [kA/kA]    [deg]    [kA/kA]      [kA]      [MVA]    [-]

Bus 1               A   132.00     0.00     0.00  1.10     3336.06 MVA   43.77 kA  -84.29   108.00 kA   43.77   3336.06  0.00
                    B             83.80  -119.96              0.00 MVA    0.00 kA    0.00     0.00 kA    0.00      0.00  1.00
                    C             83.79   119.96              0.00 MVA    0.00 kA    0.00     0.00 kA    0.00      0.00  1.00
  Line 2                Bus 2                         A       1.75 MVA    0.02 kA   90.11     0.00 kA
                                                      B       1.75 MVA    0.02 kA   90.11     0.00 kA
                                                      C       1.75 MVA    0.02 kA   90.11     0.00 kA

  Line 1                Bus 4                         A       0.99 MVA    0.01 kA   90.03     0.00 kA
                                                      B       0.99 MVA    0.01 kA   90.03     0.00 kA
                                                      C       0.99 MVA    0.01 kA   90.03     0.00 kA

  EEPCO GRID                                          A    3333.33 MVA   43.74 kA  -84.29   108.00 kA
                                                      B       2.74 MVA    0.04 kA   90.08     0.09 kA
                                                      C       2.74 MVA    0.04 kA   90.08     0.09 kA
```



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                                                     DIgSILENT        Project:
                                                    PowerFactory
                                                       14.1.3         Date:   6/4/2017

Fault Locations with Feeders
Short-Circuit Calculation according to IEC60909                      Single Phase to Ground   / Max. Short-Circuit Currents

Asynchronous Motors                       Grid Identification                       Short-Circuit Duration
   Always Considered                         Automatic                                 Break Time                        0.10 s
                                                                                        Fault Clearing Time (Ith)         1.00 s
                                          Conductor Temperature                     c-Voltage Factor
                                             User Defined            No                User Defined                      No

Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER                             Annex:             / 1

                         rtd.V.     Voltage     c-          Sk"          Ik"                 ip          Ib        Sb     EFF
                          [kV]    [kV]    [deg] Factor    [MVA/MVA]    [kA/kA]    [deg]    [kA/kA]      [kA]      [MVA]    [-]

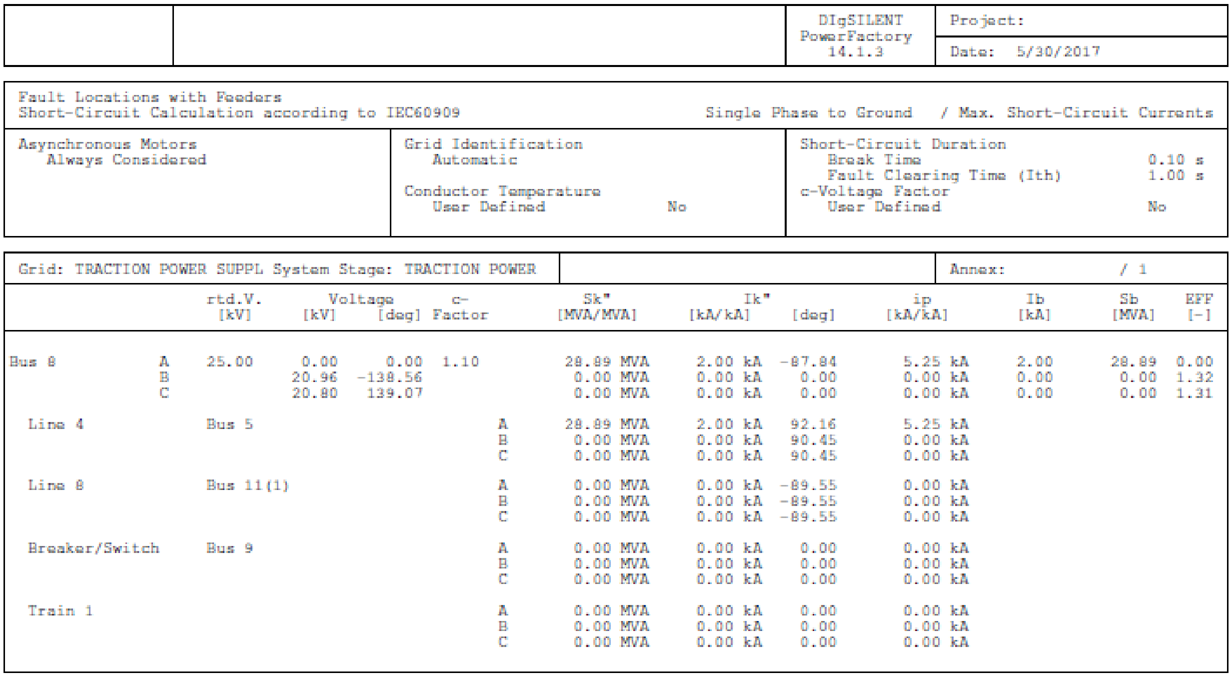
Bus 8               A    27.50     0.00     0.00  1.10       34.96 MVA    2.20 kA  -87.84     5.78 kA    2.20     34.96  0.00
                    B             23.06  -138.56              0.00 MVA    0.00 kA    0.00     0.00 kA    0.00      0.00  1.32
                    C             22.88   139.07              0.00 MVA    0.00 kA    0.00     0.00 kA    0.00      0.00  1.31
  Line 4                Bus 5                         A      34.96 MVA    2.20 kA   92.16     5.78 kA
                                                      B       0.00 MVA    0.00 kA   90.45     0.00 kA
                                                      C       0.00 MVA    0.00 kA   90.45     0.00 kA

  Line 8                Bus 11(1)                     A       0.00 MVA    0.00 kA  -89.55     0.00 kA
                                                      B       0.00 MVA    0.00 kA  -89.55     0.00 kA
                                                      C       0.00 MVA    0.00 kA  -89.55     0.00 kA

  Breaker/Switch        Bus 9                         A       0.00 MVA    0.00 kA    0.00     0.00 kA
                                                      B       0.00 MVA    0.00 kA    0.00     0.00 kA
                                                      C       0.00 MVA    0.00 kA    0.00     0.00 kA

  Train 1                                             A       0.00 MVA    0.00 kA    0.00     0.00 kA
                                                      B       0.00 MVA    0.00 kA    0.00     0.00 kA
                                                      C       0.00 MVA    0.00 kA    0.00     0.00 kA
```

Single line to ground fault report at load side



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                                                         DIgSILENT       Project:
                                                         PowerFactory
                                                           14.1.3        Date:   5/30/2017

Fault Locations with Feeders
Short-Circuit Calculation according to IEC60909                        Single Phase to Ground    / Max. Short-Circuit Currents

Asynchronous Motors                  Grid Identification                 Short-Circuit Duration
   Always Considered                    Automatic                           Break Time                        0.10 s
                                                                            Fault Clearing Time (Ith)         1.00 s
                                     Conductor Temperature               c-Voltage Factor
                                        User Defined           No           User Defined                      No

Grid: TRACTION POWER SUPPL System Stage: TRACTION POWER                                Annex:              / 1

                       rtd.V.      Voltage       c-          Sk"           Ik"                 ip          Ib        Sb     EFF
                        [kV]     [kV]     [deg]  Factor    [MVA/MVA]    [kA/kA]   [deg]      [kA/kA]       [kA]      [MVA]   [-]

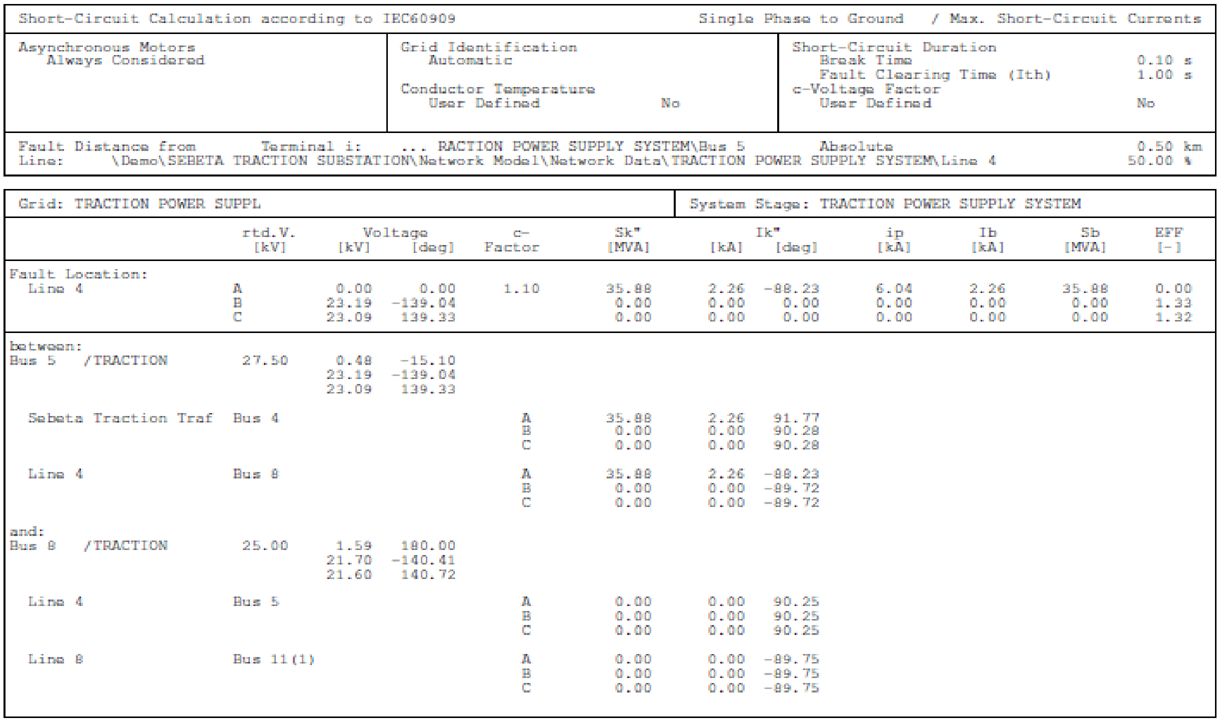
Bus 8              A    25.00     0.00     0.00  1.10        28.89 MVA    2.00 kA  -87.84      5.25 kA     2.00      28.89  0.00
                   B             20.96  -138.56               0.00 MVA    0.00 kA    0.00      0.00 kA     0.00       0.00  1.32
                   C             20.80   139.07               0.00 MVA    0.00 kA    0.00      0.00 kA     0.00       0.00  1.31

  Line 4                Bus 5                      A         28.89 MVA    2.00 kA   92.16      5.25 kA
                                                   B          0.00 MVA    0.00 kA   90.45      0.00 kA
                                                   C          0.00 MVA    0.00 kA   90.45      0.00 kA

  Line 8                Bus 11(1)                  A          0.00 MVA    0.00 kA  -89.55      0.00 kA
                                                   B          0.00 MVA    0.00 kA  -89.55      0.00 kA
                                                   C          0.00 MVA    0.00 kA  -89.55      0.00 kA

  Breaker/Switch        Bus 9                      A          0.00 MVA    0.00 kA    0.00      0.00 kA
                                                   B          0.00 MVA    0.00 kA    0.00      0.00 kA
                                                   C          0.00 MVA    0.00 kA    0.00      0.00 kA

  Train 1                                          A          0.00 MVA    0.00 kA    0.00      0.00 kA
                                                   B          0.00 MVA    0.00 kA    0.00      0.00 kA
                                                   C          0.00 MVA    0.00 kA    0.00      0.00 kA
```



```
Short-Circuit Calculation according to IEC60909                        Single Phase to Ground    / Max. Short-Circuit Currents

Asynchronous Motors                  Grid Identification                 Short-Circuit Duration
   Always Considered                    Automatic                           Break Time                        0.10 s
                                                                            Fault Clearing Time (Ith)         1.00 s
                                     Conductor Temperature               c-Voltage Factor
                                        User Defined           No           User Defined                      No

Fault Distance from       Terminal i:     ... RACTION POWER SUPPLY SYSTEM\Bus 5        Absolute                  0.50 km
Line:      \Demo\SEBETA TRACTION SUBSTATION\Network Model\Network Data\TRACTION POWER SUPPLY SYSTEM\Line 4       50.00 %

Grid: TRACTION POWER SUPPL                                    System Stage: TRACTION POWER SUPPLY SYSTEM

                        rtd.V.      Voltage         c-          Sk"           Ik"             ip        Ib         Sb       EFF
                         [kV]     [kV]    [deg]   Factor       [MVA]      [kA]   [deg]       [kA]      [kA]       [MVA]     [-]
Fault Location:
  Line 4                A          0.00     0.00    1.10        35.88      2.26  -88.23       6.04      2.26       35.88     0.00
                        B         23.19  -139.04                 0.00      0.00    0.00       0.00      0.00        0.00     1.33
                        C         23.09   139.33                 0.00      0.00    0.00       0.00      0.00        0.00     1.32

between:
Bus 5    /TRACTION       27.50     0.48   -15.10
                                  23.19  -139.04
                                  23.09   139.33

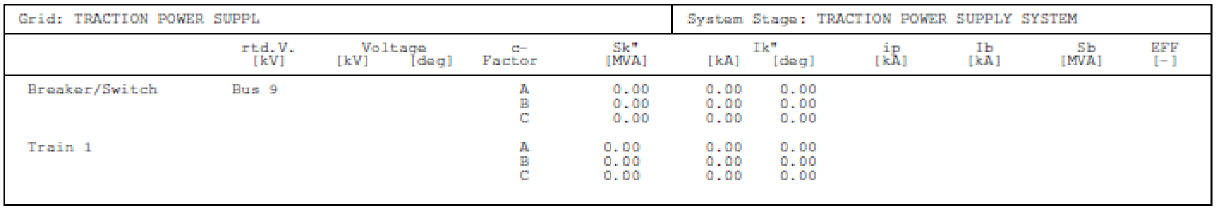
  Sebeta Traction Traf  Bus 4                     A             35.88      2.26   91.77
                                                  B              0.00      0.00   90.28
                                                  C              0.00      0.00   90.28

  Line 4                Bus 8                     A             35.88      2.26  -88.23
                                                  B              0.00      0.00  -89.72
                                                  C              0.00      0.00  -89.72

and:
Bus 8    /TRACTION       25.00     1.59   180.00
                                  21.70  -140.41
                                  21.60   140.72

  Line 4                Bus 5                     A              0.00      0.00   90.25
                                                  B              0.00      0.00   90.25
                                                  C              0.00      0.00   90.25

  Line 8                Bus 11(1)                 A              0.00      0.00  -89.75
                                                  B              0.00      0.00  -89.75
                                                  C              0.00      0.00  -89.75
```



```
Grid: TRACTION POWER SUPPL                                    System Stage: TRACTION POWER SUPPLY SYSTEM

                        rtd.V.      Voltage         c-          Sk"           Ik"             ip        Ib         Sb       EFF
                         [kV]     [kV]    [deg]   Factor       [MVA]      [kA]   [deg]       [kA]      [kA]       [MVA]     [-]

  Breaker/Switch        Bus 9                     A              0.00      0.00    0.00
                                                  B              0.00      0.00    0.00
                                                  C              0.00      0.00    0.00

  Train 1                                         A             0.00       0.00    0.00
                                                  B             0.00       0.00    0.00
                                                  C             0.00       0.00    0.00
```