ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY (AAiT)

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

TCSC DESIGN IN AC TRACTION NETWORK: CASE STUDY OF SEBETA-ADAMA RAILWAY

BY

YOSEF TSEGAYE

ADVISOR

ATO KIROS TESFAY

A THESIS SUBMITTED TO ADDIS ABABA UNIVERSITY, INSTITUTE OF TECHNOLOGY, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE IN ELECTRICAL ENGINEERING (RAILWAY)

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____________________	___________	___________
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Advisor	Signature	Date
__________________	____________	___________
Internal Examiner	Signature	Date
__________________	____________	___________
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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.

Yosef Tsegaye ________________

Name Signature

Addis Ababa, Ethiopia October ,2014

Place Date of Submission

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

Ato Kiros Tesfay ____________

Advisor's Name Signature

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ABSRACT

An electric transmission in an electrified railway system must provide power transmission within the voltage limit at safe and quality conditions. Therefore, system analysis within the traction power system is vital to the design and operation of an electrified railway. Loads in traction power system are often characterized by their mobility, wide range of power variations, regeneration and service dependence. Voltage drop in electrified railway have an influence on the location of traction substation (reduces distance between traction transformer and section post length) and operating railway transport in a such condition disturbs transportation system, as a result the reactive power compensator should be installed to have a better voltage at receiving end.

Ethiopian railway cooperation is constructing national railway transport from Sebeta to Meiso with seven feeding traction substation from Sebeta to Adama. In this thesis traction network voltage drop analysis is undertaken for various feeding condition. Taking sample section from Sebeta substation to Indode substation to analyse traction network voltage drop at traction subsatation and a feeder network for normal section operation and overzone feeding condtion during fault. After analysis the propper compensation is achieved but for 0.95 power factor, no need to design the reactive power compensator because the reactive compensator is done with assumption that supply voltage is being constant. In general if supply voltage varies, the reactive power will not vary separately with the load and compensator error will be there, therefore in such condition it is better to design Voltage regulator. Therefore, in this thesis TCSC(thyrestor controlled series compensator) is used for compensation and the output is simulated with MATLAB/SIMPOWER system

From analysis and simulation result,the voltage drop for normal and overzone feeding operation is 3.56kV,6.952kV but after proper compensation the voltage drop become 0.84kV,1.75kV with 3.48% ,7.52% percentage regulation respectively.When this result is comppared with standard of worst senario which is 25% of regulation, it is good enough for reliable and safe operation of railway trasporation of case studied section from Sebeta to Adama.

Keywords: -TCSC(Thyrestor controlled series compensator),Normal section operation, Overzonefeeding,energy consumption,V-V connection transforme

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LIST OF ABBREVIATIONS AND SYMBOLS

a_{ik}	The mutual distance of conductors in loops
d	the diameter (m) of the round steel bar used as the earthling body
CBPS	circuit breaker paralleling section
CBS	section circuit breaker
'e'	is axle load in tone.
E_a	To accelerate the train
Eg	Energy output of driving axle to overcome the gradient
Er	Energy output of deriving axle to overcome friction
Eout	Energy output of deriving axles to accelerate the train
Espo	Specific energy output
Econ	Energy consumption
Espc	Specific energy consumption
Eov–con	Over all energy consumption
f	power supply frequency
F*a*	Tractive effort for acceleration
F*g*	Tractive effort required to balance the gravitational pull
Fr	Tractive effort to overcome train resistance
FC	Tractive effort to overcome curve resistance
Ft	Total tractive effort
I_{avg}	Train average current
I_F	Feeder daily average current
I_{FE}	Feeder daily effective current of a double track of unilateral power supply

I_{II} Feeder current for down track

I_{I} Feeder current for up track

I_{rT} is the rated current of the transformer on the high-voltage or low-voltage side

l the length of the upright earthling body

$L^{\bullet}_{ex}$ Is external inductance

MPSS Midpoint sub sectioning

P_{krT} is the total loss of the transformer in the windings at rated current.

P Power of a traction motor

P_{max} Power output required from the deriving axle to propel the train is maximum

OCS Over head contact system.

$R^{\bullet}$ Resistance in Ω/km

$R_{E}^{\bullet}$ Resistance of the earth returns path and the resistance per unit length are49.3mΩ/km for 50Hz.

r conductor radius

'r' the resistance in kg per tone

R_{grid} Resistance of transmission line from national grid to sebeta substation

R is the radius of curvature in meters

S_{rT} is the rated apparent power of the transformer.

TCSC Thyrestor Control Series Compensator

U_{rT} is the rated voltage of the transformer, on the high-voltage or low-voltage side.

U_{kr} is the short-circuit voltage at rated current in percent

ΔV Voltage drop is given by

W weight of train (hauling capacity of a train)

W_{e} effective weight of a train

$X^{\bullet}_{ex}$ External reactance and

$X^{\bullet}_{in}$ Inner reactance of the conductor

X_{T} The positive-sequence short-circuits reactance of a two-winding transformer

X_{grid} Reactance transmission line from national grid to sebeta substation

Z_{m} mutual impedance between feeders

Z_{grid}	Impedance transmission line from national grid to sebeta substation
δ_E	Penetration depth of the current in the earth and
ρ_E	Resistivity of soil in Ωm
α	Acceleration of a train
β	Retardetion of a train
η	The efficiency of a transmission gear
η_{gear}	Efficiency of the gear
η_{motor}	Motor efficiency

.

1 INTRODUCTION

1.1 Motivation and Background

Traction power supply system obtains energy from power grid and transits it to electric locomotive after voltage step down. A traction power supply system is composed of traction substation and traction network .Composition of traction power supply system is indicated in figure1.1. The single phase 50 Hz power for the electric traction is obtained from 220/132/110/66 kV extra high Voltage 3 phase grid system through step down single phase transformers. For this purpose duplicate feeders comprising of only 2 phases are run from the nearest sub-station of the supply authority to the traction substation. In general traction power supply begin at power of state grid and then voltage and frequency conversion at AC traction substation, supply railway train with required electrification,

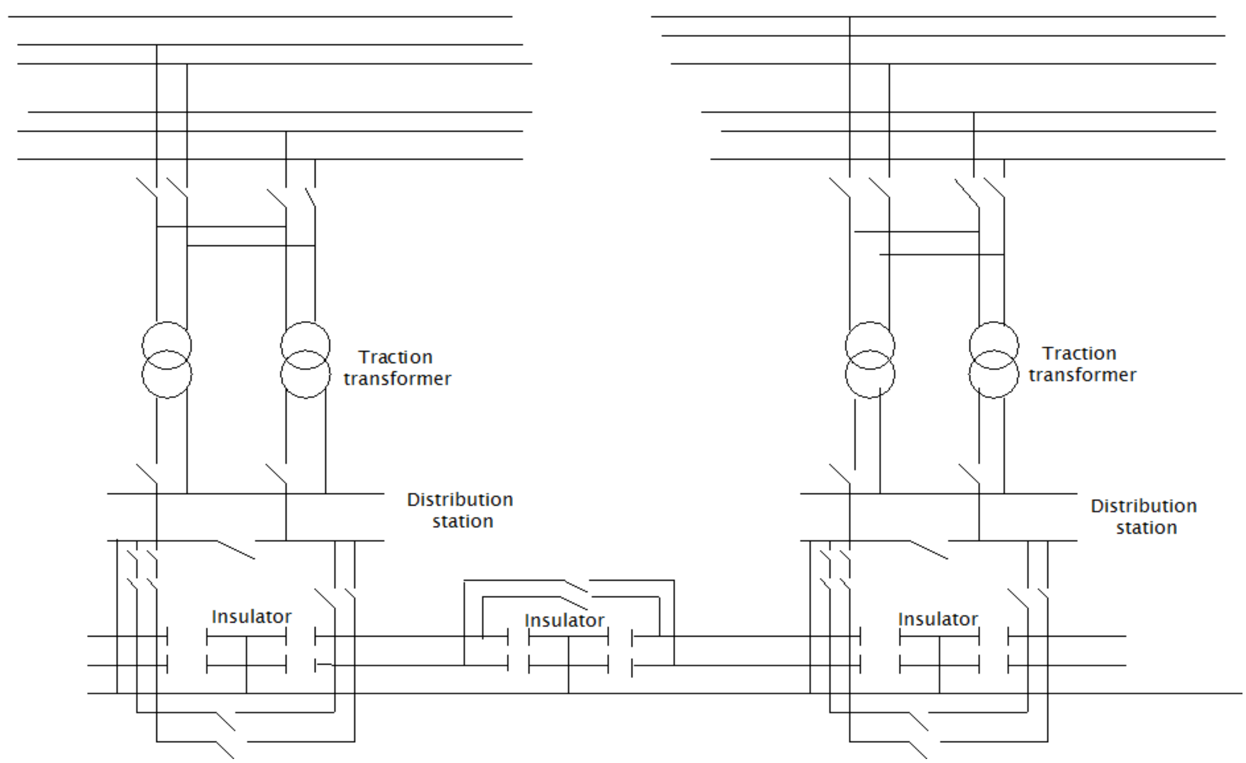

Figure 1.1 power supply arrangement for 50HZ catenaries arrangement

Line are electrified today 25kV, 50HZ is normally used ,in such case, the connection of two power supply stations close to each other is completely in dependant of their connection to the main as shown in figure 1.1. The single phase catenaries is fed from two phases of the supplying three phase grid ,this naturally causes asymmetries in the three phase voltage since the railway supply is a single phase load.

1.2Traction feeder network

Traction feeder network or traction power network is an electricity grid for the supply of electrified rail networks, a traction network include the following, feeder, OCS and return line.

Feeder is a wire which connects between traction substation bus and OCS. Feeding section at normal power supply mode is from traction substation feeder to the end of the OCS .If these sections are directly powered by adjacent traction substation, it will increase not only the complexity but also the length of the feeder [3].

1.3 Power supply mode

(TBl0009-2005) this version, as one of China's railway engineering construction standards in English series, which in compliance with relevant procedures and regulations, is translated by economic and planning institute of ministry of railways authorized by construction management department of ministry of railways.

Power supply mode for primary system is the connection mode between power grid and traction power supply system. It depends on voltage level of the traction load and power grid distribution. TB 10009-2005, “Design Instruction for Railway Traction Power Supply System”: electrified traction load is level 1st load. Traction substation shall have dual power source. When any power supply fails, other can resume normal power supply. Dual power source can input from different regional substation or different power bus at same substation or different bus split section .Power supply mode for traction power system are the following, Direct supply mode for traction system ,Booster transformer power supply ,Direct power with return power mode [3].

1.4 Voltage Regulation

Voltage regulation**:** When a transmission line is carrying current, there is a voltage drop in the line due to resistance and inductance of the line. The result is that receiving end voltage (VR) of the line is generally less than the sending end voltage (VS). In many applications this voltage itself may not be good enough for obtaining the best operating condition for the loads. This voltage drop (VS − VR) in the line is expressed as a percentage of receiving end voltage VR and is called voltage regulation. Traction network voltage demanding no less than 19kV in traction power supply system design. The minimum short circuit capacity shall be considered that under larger system short circuit impedance, train traction requirement shall be met. Traction network voltage is limited by three factors: power grid voltage loss, traction transformer voltage loss and traction network voltage loss.

1.5 Statement of the problem

One of the national railway line starts from Sebeta southwest to Addis Ababa and go east through Akaka, Bishoftu. Mojo. Adama, Metehara, Awash to Mieso, length of which is 328.959km. The line from Sebeta to Adama is double track and the line from Adama to Mieso is single line. The line will build_7 traction substations that include Sebeta, Indode, Mojo, D1k153, Metehara, Dk290, Mieso,and 3 section posts including Labu,D1k6, Adama.[6].

This system considered under study for voltage regulation is proposed Ethiopian single-phase 25kV AC electrified system. In this system, the traction transformers are supplied from state grid, normally at 132kV, this voltage further step down to 25kV, nominal voltage at traction substation of using 132/27.5kV transformer. Each traction substation has two 132kV independent power lines. Branch connection is used at 132kVside and single bus bar section supplied at 27.5kV bus bar. Power supply mode for traction system is direct power with return line mode.

Eventhough, traction tranformer is designed by forcasting future railway trasportation demand , traction substation are not equipped with reactive power compensation device temporarily and installation spaces for high order harmonic filter devices are remained. Catenary power supply mode and operation mode adopts unilateral power supply mode. In the double track section, section post is set between two adjacent traction substation to parallel connect up and down catenary and remain over zone feeding at fault or repair situation. Neutral section and over zone switch are set between two adjacent traction substations to realize over zone feeding [6].

When overzone feeding scenario taken in to consideration ,there will be load variation per traction feeder section which results huge voltage drop problem at traction substation and at traction feeder section. Such problem can be solved through this thesis by the taking into considration a number of scenarios of load in the traction network.

1.5.1 Feeder section voltage drop due to section and over zone feeding scenario

For two reasons section between Sebeta to Indode has taken to realize voltage drop (1) As a station distance is less, and then high current is drawn by the train .Section between Sebeta to Indode is taken as a sample, because this section has the smallest distance between stations among other and results high voltage drop, and section between Sebeta to Lebu section post has no alternative to get power during this tip substation is under fault and maintenance except from Indode substation which feeds train from long distance. (2)Section between indode to Lebu exposed for highest gradient which is 18.3% - line gradient is the main factor influencing traction power, and energy consumption and varies the load current, at normal operation traction transformer installed capacity, traction network current-carrying capacity and minimum voltage of traction network need to achieve the requirement of annual transportation. During fault operation, over zone feeding mode is carried out. Under this situation, traction power supply system shall be designed to meet the requirements of one train running. I have used sample section between Sebeta traction substation and Indode traction substation has been used to realize voltage drop along the catenary line and at substation, as shown in figure (1.2)

1.5.1.1 Feeder section voltage drop

Maximum voltage drop in the feeder section in double rail track of 4 section four segment operation scenarios, due to over zone feeding because of the adjacent traction substation under maintenance or one of the section under fault condition .This voltage drop have an influence on the location of traction substation (reduces distance between traction transformer) and section post length, operating railway transport in scenario disturbs transportation system [3]

Catenary power supply mode and operation mode adopts unilateral power supply mode. In the double track section, section post is set between two adjacent traction substation to parallel connect up and down catenary and remain over zone feeding at fault or repair situation. Neutral section and over zone switch are set between two adjacent traction substations to realize over zone feeding [6].

In general there are two possibilities to undertake over zone feeding at section post, (1) Motor operating disconnector is installed between supply sections to implement over zone power supply. (2) Circuit breaker is installed between up direction feeder and down direction feeder to implement parallel connected power supply and independent power supply [6].

1.5.1.2 Traction transformer voltage drop

Transformer impedance parameters and system impedance parameters viewed at secondary Winding side (pay attention impedance transformer from V_V connection). Winding voltage drop transformer impedance and system impendence can be viewed as secondary side

$$Z=Zs+Zt=(r_s+r_t)+j(x_s+x_t) \quad (1.1)$$

Based on winding port voltage and winding current $I\angle\phi$,Φ- is angle between port voltage And winding current,therefore the voltage drop at traction substation depends on or varies acording to the feeder current[6].

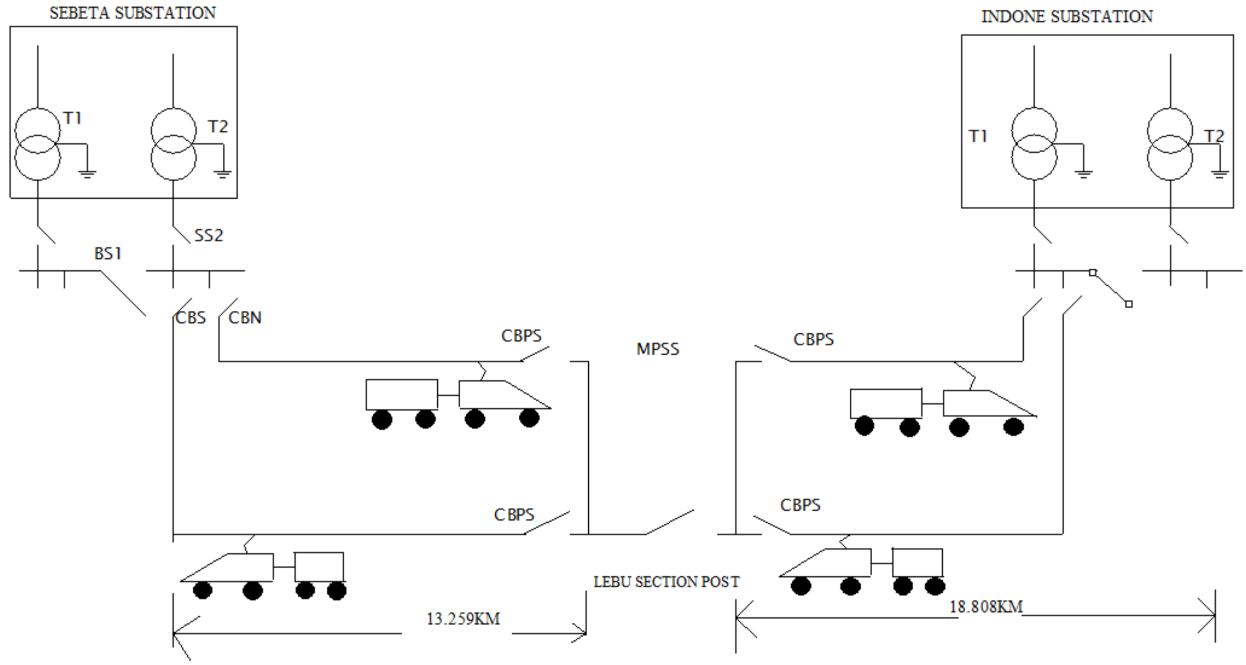

Figure 1.2 traction feeder network section between Sebeta to Indode

1.5.1.3 Voltage drop for various gradient conditions through the feeding network.

Trains running needs to overcome gravity when climbing. At low speed, air resistance is small. Line gradient is the main factor influencing traction power, and energy consumption. Traction load of a single train fluctuates rapidly because of complexity in railway line condition (speed, line gradient, etc.). The count of trains in the same feeding section is variable [3].

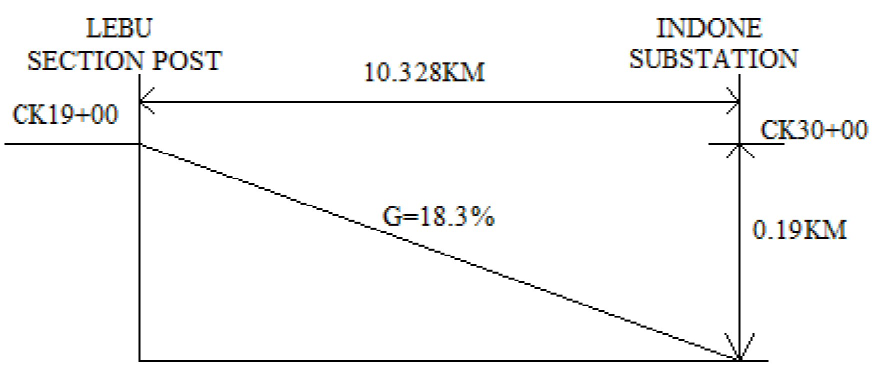

Figure1.3 for track profile between Lebu section post to indode power station as well as passenger station.

1.6 General Objective

To design voltage regulation for AC traction network in section between Sebeta to Indode, therefore by compensating the voltage drop of specified section by taking the rated voltage of the electric locomotive and pantograph centenary is 25kV and maintaining the maximum voltage 28kV and the minimum operating voltage at 20kV, under abnormal condition the operated voltage not less than 19kV as per standard of TB10009-2005 railway traction power supply design specification, eventually maintaining the power reliability of a traction network and the rail transportation become safe and efficient.

Even though, the reactive compensator designed, to improve source power factor to unity. This reduces the rating of the power conductor and Losses due to the feeder impedance, here voltage of supply is being assumed to be constant. In general if supply voltage varies, the reactive power (Q) will not vary separately with the load and compensator error will be there. The question is: whether it is possible to make, in order to achieve zero voltage regulation irrespective of change in the load. The answer is yes, if the compensator consisting of purely reactive components, has enough capacity to supply to required amount of the reactive power.

1.6.1 Specific objective

- ✓ Mathematical modeling traction transformer voltage drop.
- ✓ Realizing the relation of V-V connectivity transformer and sections load
- ✓ Mathematical modeling normal section operation voltage drop.
- ✓ Mathematical modeling over zone feeding operation voltage drop.
- ✓ Reliazing section paralling and voltage drop.
- ✓ Evaluating voltage drop without compensator using MATLAB SIMULATOR.
- ✓ To Desigh series compensator.
- ✓ Evaluating voltage drop with compensator using MATLAB SIMULATOR.
- ✓ Identifying place where compensator are placed in a traction network.

1.7 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 literatures where all the theoretical information regarding traction network voltage drop. 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 system components. Once the model is developed using MATLAB/ SIMULINK, the analysis of the system is performed. Then based on the analysis result proper compensator is designed. Finally, the performance of the compensator is analyzed in different position feeding network and a comparison is made. The general block diagram of the methodology is given below.

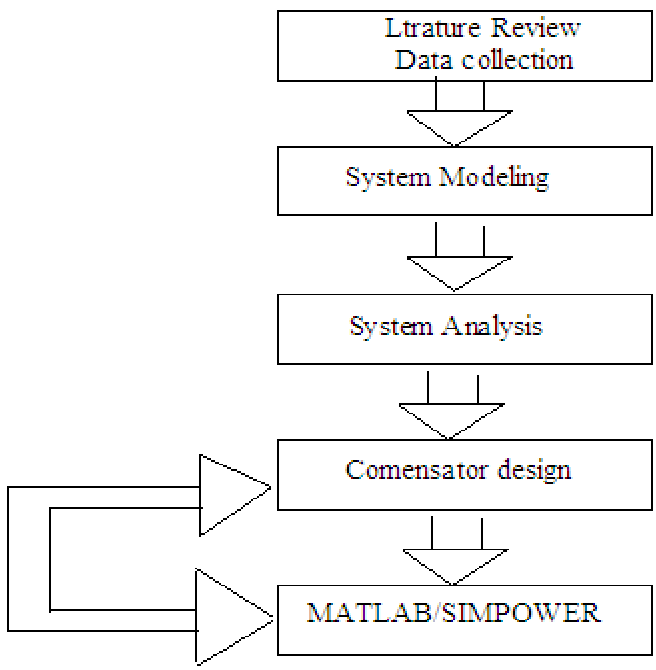

Figure 1.4 Block summery of methodology

1.8 Related work

POWER QUALITY ISSUES IN RAILWAY TRACTION SYSTEM

Demeke Kebede Hailu

Electrical Power Engineering Dept., College of Engineering, Defense University, Bishoftu, Ethiopia

This paper presents the traction system various power quality issues and methods for improvement mainly to *voltage unbalance* and *harmonic distortion*. An external balancing method with booster transformer arrangement is proposed on the existing traction system to improve the voltage unbalance and telecommunication disturbance. A multisession harmonic filter is also designed to reduce higher order harmonics wave. Modeling and simulation of the traction system is performed using MATLAB/SIMULINK. The electrical parameters are taken from the double-track Sebeta to Adama Section of Ethiopia Railway Corporation. The results are compared with IEEE and other standards. The voltage unbalance factor and the total harmonic distortion simulated violate the standard. By applying a range of remedies, power quality improvements have been achieved [1].

After numerous simulations, results depict that, the voltage unbalance and harmonics are above the standard limits. After applying the designed multisession filter the harmonics distortion is reduced highly .The voltage unbalance is improved using capacitor and inductor arrangement with further shunt compensation. The high order harmonics waves are safely reduced with the use of multi section filter designed [31].

In the investigation for literature, that will support my work on devising a model that will enhance the power efficiency and achievable rate of transmission voltage levels during operation of various load condition. Voltage regulation can be defined as the proportional change in voltage magnitude at the load bus due to change in load current (say from no load to full load). And the voltage drop is caused due to feeder impedance carrying the load current.

Revising the above paper on power quality; I have proposed to implement voltage regulation at a traction network by taking in to consideration voltage drop at a traction network and voltage drop at traction transformer for various operation scenarios mentioned at section of statement of the problem.

- Regulation of Voltage Quality by Bart Franken, Virendra Ajodhia, Konstantin Petrov, Katja Keller and Christine Müller.

This paper provides an appraisal of what regulators need to consider in establishing an effective voltage quality regulatory framework for distribution networks. In particular, the paper considers the regulation of five voltage quality dimensions: short interruptions, voltage dips, flicker, supply voltage variation, and harmonic distortions. The paper assesses the most appropriate regulatory control method and presents practical experiences through a number of case studies.

Voltage quality is an important aspect of the electricity service and customers are becoming increasingly sensitive to disturbances in voltage quality. This issue is particularly important to take into account in new regulatory frameworks which put strong emphasis on cost reduction thereby potentially jeopardizing quality. Against this background the aim of this paper was to explore the issues that regulators need to consider when establishing a voltage quality regulatory framework for distribution networks. The outcome of this paper is a set of guidelines with respect to the development of a voltage quality regulatory framework.

In order to bridge the gap between the perceived and the target quality level regulators could employ different control methods to achieve their objectives, viz performance monitoring, minimum standards and incentive schemes. In theory, an incentive scheme is the most effective control as it imposes a direct link between performance and financial incentives.

Although often limited by practical concerns, it still may be an interesting option for regulating especially short interruptions and voltage dips and to a lower degree flicker, supply voltage variations and harmonic distortion. In contrast, performance monitoring is practically simple to implement but lacks true incentives for increasing voltage quality. Therefore minimum standards seem to strike a good balance between performance monitoring and incentive schemes since the degree of measurement data is more restricted than under incentive schemes. At the same time, minimum standards also provide financial incentives for good voltage quality. They dictate a minimum performance and set a clear boundary of what is acceptable quality and what is not.

This paper deals about voltage regulation for the sake of power quality issue taking different cases like: short interruptions, voltage dips, flicker, supply voltage variation, and harmonic distortions. On this paper different country experience was touched like progress made in Norway, Italy and the Netherlands with regard to voltage quality regulation in order to obtain more practical insights into how this issue is dealt with in Europe [35].

- Modelling, Simulation and Performance Analysis of FACTS Controller in Transmission line.

The main objective of this paper is to implement FACTS devices in a transmission line for dynamic reactive power compensation to increase the line capacity .This paper shows the results that show the performance of the system for each of the FACTS devices in improving the power flow in the transmission line. All the simulations are carried out by using MATLAB/SIMULINK software. The simulation result shows the performance of FACTS devices in transmission line.

A basic transmission (11kV) model has been employed in MATLAB/SIMULINK program to study about the FACTS devices in detail. 11kV voltage is supplied from the ac voltage source to the system. The transmission line is considered to be a short transmission line hence capacitance of the line is neglected. The resistance of the line is 5Ω and the inductance is 0.06mH. The source impedance is (0.01+0.001) Ω and the load is kept constant at 25MW and 50MVAR .The current and voltage measurement blocks are used to measure the voltage and current at source. By the use of active and reactive power measurement block, the real and reactive power in the load is measured. This paper concludes using TCSC increases power flow through the system increases capacitance that both active and reactive power increases with the increase in capacitance value up to 30μF. Beyond this value both real and reactive power starts decreasing. So the better compensation is obtained at a capacitor value of 30μF [36].

- Shunt versus Series compensation in the improvement of Power system Performance

This paper study about VAR compensation which involves the management of reactive power for the improvement of electric power system performances. Adequate reactive power control solves power quality problems like flat voltage profile maintenance at all power transmission levels, and improvement of power factor, transmission efficiency and system stability.

Series and shunt VAR compensation techniques are used to modify the natural electrical characteristics of electric power system. Series compensation modifies the reactance parameter of the transmission or distribution system, while shunt compensation changes the equivalent load impedance. In both cases, the line reactive power can be effectively controlled thereby improving the performance of the overall electric power system. This paper presents an overview of the reactive power and static VAR compensation technologies. In case study, an application example is illustrated. The results obtained by applying both series and shunt VAR compensation techniques individually to the case study illustrated are tabulated for comparison.

This paper concludes that constant load voltage, sending end voltage to be maintained is low with Series– capacitive arrangement than with Shunt capacitive arrangement but Shunt capacitive arrangement reduces the total active power loss while Series– capacitive arrangement does not affect it. Series capacitive arrangement reduces the total reactive power loss by a large margin as compared to Shunt capacitive arrangement. Shunt capacitive arrangement improves the system power factor by a large margin as compared to Series capacitive arrangement. Load power factor remains always constant with and without any compensation technique [37].

1.9 Thesis Organization

This thesis is organized into seven chapters with each chapter explains in detail about the research. The first chapter provides an introduction of the project and defines the subject of the thesis.

The second chapter generally covers about data analysis on train energy consumption used to find train average current, train effective RMS current when is moving a section.

The third chapter deals about concept and methods computation of voltage drops in a traction network including type of transmission line used for in the system.

In the fourth chapter, system component modeling expressed and shown their physical representation to analyze the effect of voltage drop. In chapter five, mathematical model for traction substation and feeder network voltage drop is well defined, Analysis for system impedance from its short circuit characteristics, Voltage drop of normal section operation, and over zone feeding condition is analysis is done.

In chapter six, covers about voltage drop and mitigation techniques in generally is defined including type of compensator used in railway system.

In chapter seven, based on the selected data the system is simulated and result analysis is performed. This includes the interpretation of the result obtained with respect to the standards.

In the final part, the concluding remarks that summarize the research results and gives future work recommendations on subjects related to the thesis are presented.

2 DATA ANALYSIS

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].

2.2 Tractive effort for acceleration:

Force is required to give linear acceleration to the train and is given by

$$\mathrm{F}a = 1000W\frac{\alpha * 1000}{3600} \rightarrow \quad \mathrm{F}a = 277.8W\alpha \ Newton \qquad (2.1)$$

Where W, is weight in tone, α is train acceleration

When the speed of the train is being changed it behaves as a mass greater than its dead weight, this is due to angular speed

$$\mathrm{Fa} = 277.8\mathrm{We}\alpha \text{ Newton} \quad \text{Assuming } W_e = 1.1*W$$

$$\mathrm{Fa} = \frac{277.8}{9.81}\mathrm{We}\alpha \text{ kg} \qquad (2.2)$$

Tractive effort to give acceleration of 1kmphps to 1 ton is given as

Fa =28.3*(1.1W)*1kg =31.1W kg

2.3 Tractive effort required to balance the gravitational pull

When train is on an up gradient, gravity component of dead weight of a train parallel to the track (W sin Θ) 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 (2.3)

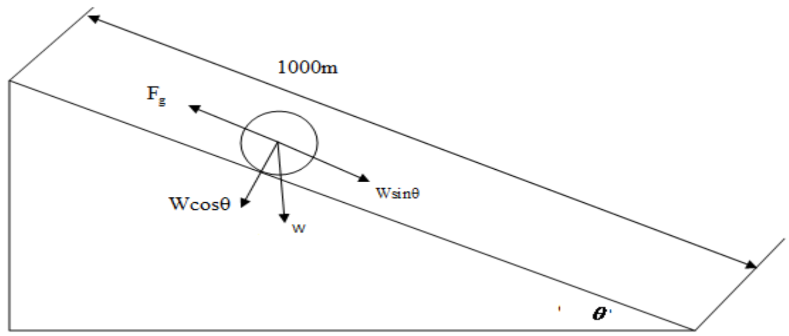

Figure 2.1 Train on up gradient [33]

$$F_g = 1000W \sin\theta * 9.81 Newton \quad (2.3)$$

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

$$G = \sin\theta * 1000 \quad (2.4)$$

Substitutes (2.4) in (2.3)

$$G = 1000W * \frac{G}{1000} * 9.81$$

$$= 9.81WG \quad Newton \quad (2.5)$$

Location of gradient has important effect on the over loading that can be permitted on the traction motors. For instance if the short ruling gradient happens to be after a down gradient, it does not create any problem as momentum of the train takes it up the steep gradient. On the other hand if ruling happen to be in the middle of raising gradient, the length of gradient becomes very important in determining the temperatures rise of the motor, another factor which affects the overloading of motor is the location of signal with respect to the gradient to the gradient. If stopping signal is at the foot of rising gradient, speed pick up will be low and motors are likely to be overloaded

2.4 Tractive effort to overcome train resistance

Train resistance consists of all the force which opposes the motion the train on level track. Those forces which are internal to the rolling stock such as friction at journals, axle guide bogie pivot buffer etc. and those forces which are external to the rolling stock such as friction between wheels and rails, flange friction resistance as a result of temporary deflection of track and aerodynamic drag. Flange friction increase with oscillation of the coach and affected by side wind pressure. Track resistance depends upon the strength of the track and the nature of the track and the nature of the ballast.

Aerodynamic drag consists of pressure drag and friction drag. Former may be due to end and the latter due to the length of the train. End resistance comprises of head resistance and tail resistance due to suction of air at the rear. Both of the ends depend upon the area perpendicular to the motion. The shape of front and rear and wind velocity, since head resistance is about ten times the suction resistance. Shape of the front carriage is very important in reducing the wind resistance. Wind resistance due to the length of the train is due to air friction on side top and under side of the train. This sometimes termed as skin friction. The pressure drag is found to be far less than the frictional drag for long train. It is also found that endeavor to diminish the pressure drag is not so effective for reduction of total drag.

All the internal and external resistance, excluding wind resistance, is termed as mechanical resistance. Although different component of mechanical resistance behave in a different way with the increase in speed, it is reasonably correct assumption to consider mechanical resistance as a whole to remain constant specially at high speeds and is proportional to the weight of the train .wind resistance on the other hand is considered to vary with the square of the speed of the train. Total train resistance F_r in the case of electric train hauled by electric locomotive is represented by equation, formula used by S.N.C.F (society national des chemin de France) based on axle loading is given below for comparison sake

$$r = (1.5\sqrt{\frac{10}{e}} + \frac{Vm^2}{120e})\ kg/tonne \qquad (2.6)$$

Where 'e' is axle load in tone and 'r' the resistance in kg per tone .this form gives lower value in low speed range and higher value in high speed range than the value obtained by the use of formula adapted by Indian railway ,now total train resistance is given as follows,

$$F_r = 9.81 * r * W \ \text{Newton} \qquad (2.7)$$

Where W is the weight of train including locomotive and r is the train resistance in $kg/tonne$.

Starting friction, which is also called "striction "is more than the running friction. This very much depends upon the starting condition of the train. For example starting resistance of the train will be more if inter- vehicle coupler are in tension which happens in the case of up gradient. On the hand inter vehicle coupler will be in compression and starting resistance will be low for train standing on down gradient .it is due to this reason that the signal should be ,as possible ,not be placed on up gradient. Even on level tracks it is a better practice to move back locomotive by few meters so as to release inter-vehicle tension. This makes the starting friction low as it has been observed that the starting resistance is due to the first few vehicles. Once train starts moving, resistance drops and remaining of vehicle are easily hauled by locomotive. Formulas adopted by S.N.C.F are given below [33].

(i) For gradient up to 7%

r= (gradient per thousand +4.5) kg. Up to 10 tone axle load.

= (gradient per thousand +4.2) kg above 10 tone axle load.

(ii) For gradient above 7%

r= (1.25*gradient per thousand +2.75) kg up to 10 tone axle load

= (1.25*gradient per thousand +2.45) kg above 10 tone axle load

2.5 Tractive effort to overcome curve resistance

Curve resistance is due to the friction at a wheel flanges more the radius of the curvatures less will be the curve resistance .Curve resistance is given by the following empirical formula and usually added to the track resistance.

$$FC = \frac{700}{R} W \ \ Kg \qquad (2.8)$$

Where R is the radius of curvature in meters, in railway practice sharpness of the curve is expressed more conveniently in degree of curvature than by radius of curvature.1^0Curve is defined as that which in 100ft. (or $100 / 327$ meters) turns the $1/360^0$ of a complete circle or in a track of 100 meters it turns through 3.27^0curvature will have $5730 / 327c$ meters of radius of curvature substituting this for value of R in equation.

$$FC = \frac{700*327}{5730} C*W \ \ Kg$$

$$=0.4CW \text{ kg} \qquad (2.9)$$

Curve resistance is usually taken to be the part of train resistance and is combined with it .Total tractive effort in that case is given as

$$Ft = Fa + Fg + Fc + Fr \qquad (2.10)$$

$$=28.3W_e\ \alpha \pm WG + W(r+0.4C)\ kg$$

$$=277.8W_e\ \alpha\ \pm 9.81WG+9.81W(r+0.4C)\ Newton$$

$$=277.8W_e\ \alpha\ \pm 9.81WG+9.81*\frac{700}{R}W+9.81WrNewton.$$

Sometimes in traction mechanics, it is convenient to express curve resistance in equivalent gradient resistance given by equation (2.3) and (2.3) above and added to the actual per thousand gradients

$$F_t=277.8W_e\ \alpha + (0.4C \pm G)\ W + W*r\ kg$$

$$=277.8W_e\ \alpha +9.81(0.4C \pm G)\ W\ \pm 9.81W*r\ Newton \qquad (2.11)$$

Positive sign is to be taken for train movement up gradient and negative sign for train movement down gradient [33].

Table 2-0-1 Train Specification Parameters HXD1C Freight Electric Locomotive [31]

Start up traction effort	570KN
Continuous traction effort	400KN
Traction power at wheel rim	7200KW
The maximum speed of locomotive	V_m=120kmph
Continuous speed of the locomotive	65kmph
Radius of curvature	800m
Axle load	25 ton

Table 2-0-2 Train Acceleration and Retardation for Various Train Transportation service [33]

Sr.No.	Parameter of comparision	Urban service	Sub-urban service	Mainline service
1	Acceleration	1.5 to4kmphps	1.5 to4kmphps	0.6 to0.8kmphps
2	Retardetion	3 to 4kmphps	3 to 4 kmphps	1.5kmphps
3	Maximum speed	120kmph	120kmph	100kmph
4	Distance between station	1km	2.5-3.5km	Morethan 10km
5	Special remark if any	Free running period is absent coasting period is small	Free running period is absent coasting period is long	Long free running and coasting period.acceleration and breaking period is small

α =2.16kmphps

$R=\frac{5370}{327C} \Rightarrow$ 800meter , $C=\frac{5370}{327R}=$,

$r=(1.5\sqrt{\frac{10}{25}}+\frac{Vm^2}{120*25})$ =5.748683298

W_e =1.1

$$F_t = W\,[1.1*277.8*\alpha+9.81G+\frac{700}{R}+9.81r\,]$$

$$W=\frac{Ft}{1.1*277.8*\alpha+9.81G+\frac{700}{R}+9.81r}\text{ ton}$$

$$W=\frac{570000N}{1.1*277.8*0.8+9.81*.0183+9.81*\frac{700}{800}+9.81*5.748683298}=1840.955309\text{ton}$$

Tractive effort that required per weight a train (hauling capacity of locomotive) is given below

$$\frac{\text{tractiveeffort}}{\text{weight}}=\frac{570000}{1088.767287}=523.527\frac{N}{ton}$$

2.6 Power of a traction motor, power is the rate of doing work and is given by

$$P=F_t*V*\frac{1000}{3600}\text{ watt} \qquad (2.12)$$

Now consider an instant at point D in fig 2.2 just after D speed remain constant but tractive effort required is less as no acceleration of train take place .just before D, tractive effort required is maximum and 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].

$$P_{max}=F_t*V_{max}*\frac{1000}{3600}\text{ watt} \qquad (2.12)$$

$=0.278*Ft*V_{max}$

=570KN*120km/hr*0.2778 =19MW

If we the continuous speed (65km/hr) of the train, it is possible to get continuous power consumption of a train =10.292MW

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

$$P_{max} = \frac{0.278 * F_t * V_{max}}{\eta} \text{ watt} \quad (2.13)$$

Output Power required for continuous motion of a locomotive is given below, where continuous speed is 65km/hr, using equation (2.12).

$$P_{out} = 400KN*65*.2778 \text{ watt}$$

$$= 7222KW \approx 7200kW \text{ is given}$$

When Ft is in Newton

$$\eta = \frac{P_{out}}{P_{max}} = \frac{7200KW}{19MW} = 0.379$$

Power required for continuous motion of a locomotive is given below, where continuous speed is 65km/hr

$$p_{out} = 400KN * 65 * .2778 \text{ watt}$$

$$= 7222KW$$

2.7 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:

- To accelerate the train
- To overcome the gradient
- To overcome train resistance

- Energy output of deriving axles to accelerate the train

Is assumed trapezoidal speed time curve of figure (2.2)

2.7. 1 Energy output of driving axle to accelerate the train

$$E_a = F_a * \text{distance OAD} \tag{2.14}$$

$$= 277.8\, W_e\, \alpha \left[\frac{1}{2}\frac{V_{mx}*1000}{3600} * \frac{V_{max}}{\alpha}\right] \text{ watt-second}$$

$$= 277.8\, W_e\, \alpha \left[\frac{1}{2}\frac{V_{mx}*1000}{3600} * \frac{V_{max}}{\alpha}\right] \frac{1}{3600} \text{ watt-hours}$$

$$= 0.01072\, V_{max}^2\, W_e \text{ watt-hour} \tag{2.15}$$

2.7.2 Energy output of driving axle to overcome the gradient

$$E_g = F_g * D_1$$

Where D_1 the distance over which power remains on and its maximum value is equal to area OABE.

$$E_g = 9.81 * WG * \text{ joule or watt-second}$$

$$= \frac{9.81*1000}{3600} * WG\, D_1 \quad \text{Watt-hours}$$

$$= 2.725\, WG\, D_1\ whrs \tag{2.16}$$

2.7.3 Energy output of deriving axle to overcome friction.

$$E_r = 1000 * F_r * D_1 \text{ Joule}$$

$$= \frac{W * r * D_1 * 1000}{3600} \text{ whrs}$$

$$= 0.2778 W * r * D_1 \tag{2.17}$$

2.7.4 Energy output of deriving axles to accelerate the train

$$E_{out} = E_a + E_g + E_r \tag{2.18}$$

$$E_{out} = [0.01072\, V_{max}^2\, We \pm 2.725 WG\, D_1 + 0.2778 W * r * D_1] \text{ Whrs} \cdots$$

2.7.5 Specific energy output

$$E_{spo} = \frac{E_{out}}{W * D} = \tag{2.19}$$

$$E_{spo} = [\frac{0.01072 V_{max}^{2}}{D} * \frac{W_e}{W} \pm 2.725 * G \frac{D1}{D} + 0.2778 r \frac{D1}{D}] whrs/ton - km \quad (2.20$$

Where D, is run length in kilometer,

D_1 is the total distance over which power remain ON: it is the maximum value equals the distance represented by the area OABE in fig 2.2 from the start to the end of free running period in case of as per assumption of trapezoidal speed time curve [7].

2.7.6 Energy consumption

Is equal to total energy input to traction motor from the supply ,it is usually expressed in Watt-hour which equals 3600J it can be found by dividing the energy output of the deriving wheels with the combined efficiency of a transmission gear and the motor.

$$E_{con} = \frac{E_{out}}{\eta_{gear} * \eta_{motor}} \text{ Watt-hour} \tag{2.21}$$

2.7.7 Specific energy consumption

It is energy consumed in watt-hour per ton of mass of a train per kilometer length of the run

$E_{spc} = \frac{E_{spo}}{\eta} = \frac{E_{con}}{W * D}$ η = overall efficiency of transmission gear and the motor= $\eta_{gear} * \eta_{motor}$

$$\therefore E_{spc} = [\frac{0.01072 V_{max}^{2}}{\eta * D} * \frac{W_e}{W} \pm 2.725 * G \frac{D1}{\eta * D} + 0.2778 r \frac{D1}{\eta * D}] whrs/ton - km \tag{2.22}$$

If no gradient is involved, specific energy consumption is

$$E_{spc} = [\frac{0.01072 V_{max}^{2}}{\eta * D} * \frac{W_e}{W} + 0.2778 r \frac{D1}{\eta * D}] whrs/ton - km \tag{2.23}$$

$$E_{ov-con} = [E_{spc} * W * D] whr \tag{2.24}$$

2.7.8. The specific energy consumption is influenced by

In general, the specific energy consumption of a train running at a given scheduled speed influenced by, distance between stops, acceleration, retardation, maximum speed, type of train equipment and track configuration[7].

2.7.8.1 Retardation and acceleration

Value for a given schedule speed greater the value of acceleration and retarding more will be the period of coasting and therefore, less the period during which power is on, hence D_1 will be small and, therefore, specific energy consumption will be accordingly less.

2.7.8.2 Gradient:

Steep gradient will naturally involve more energy consumption even though regenerative breaking is employed.

2.7.8.3 Type of train equipment:

Overall efficiency for a given specific energy output at axles, will determine the specific energy consumption. Greater the overall efficiency less will be the specific energy consumption [35].

2.7.8.4 Speed time curve:

It is the curve showing instantaneous speed of train in kilometer per hour along ordinate and time in second along the abscissa. Area in between the curve and the abscissa give the distance travelled during given time interval. Slope at any point on the curve toward the abscissa give the acceleration or retardation at that instant.

2.9 Simplified Speed/Time Curve

For the purpose of comparative performance for a given service, the actual speed/time curve of Fig. 2.2 is represented by a simplified speed/time curve which does not involve the knowledge of motor characteristics. Such a curve has simple geometric shape so that simple mathematics can be used to find the relation between acceleration, retardation, average speed and distance etc. The simple curve would be fairly accurate provided it

(i) retains the same acceleration and retardation and

(ii) Has the same area as the actual speed/time curve. The simplified speed/time curve can have either of the two shapes:

(i) Trapezoidal shape OABC of Fig. 2.2 where speed-curve running and coasting periods of the actual speed/time curve have been replaced by a constant speed Period.

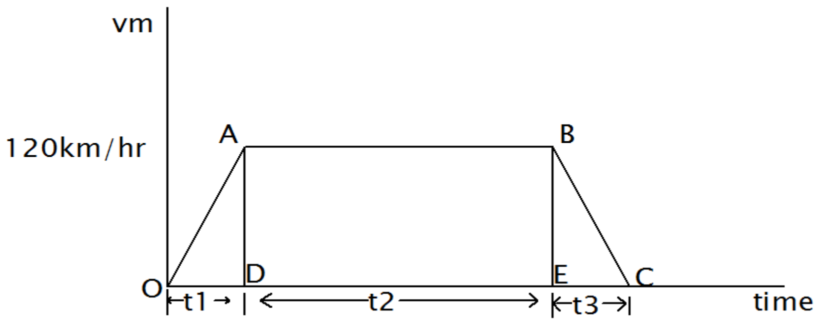

Fig 2.2 Simplified Speed/Time Curve

$$\alpha = \frac{Vmax}{t1} \quad (2.25)$$

$$\beta = \frac{Vmax}{t3} \quad (2.26)$$

D = area OABC

= area OAD + area ABED + area BCE

$$= \frac{1}{2} Vmax * t1 + Vmax * t2 + \frac{1}{2} Vmax * t3, \qquad t = t_1 + t_2 + t_3, \rightarrow t_2 = t-(t_1 + t_3)$$

$$= \frac{1}{2} Vmax * t1 + Vmax [t-(t_1 + t_3)] + \frac{1}{2} Vmax * t3$$

$$= \frac{1}{2} Vmax * t1 + Vmax\ t - Vmax * t1 - Vmax * t3 + \frac{1}{2} Vmax * t3$$

$$= Vmax [\frac{1}{2} t_1 + t - t_1 - t_3 + \frac{1}{2} t_3]$$

$$= Vmax [t - \frac{1}{2}(t_1 + t_3)]$$

$$= Vmax [t - \frac{Vmax}{2}(\frac{1}{\beta} + \frac{1}{\alpha})] \qquad K = \frac{1}{2}(\frac{1}{\alpha} + \frac{1}{\beta})$$

$$D = Vmax [t - Vmax\ K]$$

$$t = [\frac{D}{Vmax} + K\ Vmax] \quad (2.27)$$

Where D= breaking distance +Area (OABE, by using equation (2.26)

Breaking distance =Area (BCE) = $\frac{1}{2} V_{max} * t3$ $\quad t3 = \frac{V_{max}}{\beta} = 80s$

$$= \frac{1}{2}\frac{V_{max}^2}{\beta} = \frac{120km/hr^2}{1.5km/hr/s} = 2.6km$$

2.10 Train operation parameter calculations

Include train position, speed, acceleration, operation conditions, current, and energy consumption. The train operating parameters is the core of the traction calculation which includes traction force calculation, basic resistance and the additional resistance, braking force calculation and the calculation of train speed and time parameters. The main output:

- Running time and traction time, excluding coast (self-service electricity)
- Section up direction and down direction energy consumption
- Speed - distance curve and Train current curve Etc

Energy consumption in the section of Indode substation to Lebu section post at up track

Using equation (2.22)

$$\therefore E_{spc} = [\frac{0.01072 V_{max}^2}{\eta * D} * \frac{We}{W} \pm 2.725 * G \frac{D1}{\eta * D} + 0.2778r \frac{D1}{\eta * D}] whrs/ton-km$$

$$E_{spc} = [0.01072 * \frac{120km/hr^2}{.378 * 18.808} * 1.1 + 2.725 * 0.0183 \frac{10.382}{0.378 * 18.808} + 0.2778 * 5.748683 \frac{16.208}{.378 * 18.808}]$$

= 27.59801214 Whr

Using equation (2.24)

$$E_{ov-con} = [E_{spc} * W * D] whr$$

=27.59801214 whr /ton-km* 1840.955309ton *18.808 km=955,572.5446whr

=955.5725446kwhr

Energy consumption in the section of Lebu section post to Indode substation at down track

using equation (2.23)

$$E_{spc} = [\frac{0.01072 V_{max}^2}{\eta * D} * \frac{We}{W} + 0.2778r \frac{D1}{\eta * D}] whrs/ton-km$$

$$= [\frac{0.01072 * 120km/hr^2}{0.378 * 18.808} * 1.1 + 0.2778 * 5.748683 \frac{16.208}{0.378 * 18.808}] whr/ton-km$$

=27.52525646whr/ton-km

Using equation (2.24)

$$Eov\text{–}con = [E_{spc} * W * D] whr$$

=27.52525646whr/ton-km*1840.955309ton*18.808km

=953,053.402whr

Train energy consumption : Integration of the train current multiply by the traction network voltage.

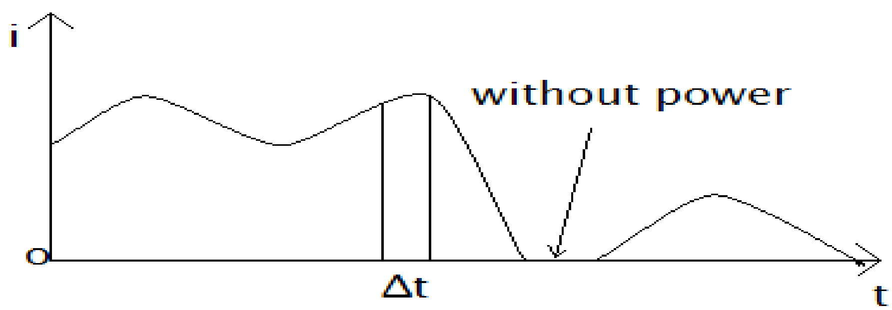

Figure 2.3Train energy consumption [3]

$$Eov\text{–}con = V\int_0^T i(t) * dt \quad kVA.h \tag{2.28}$$

[0, T] divided into n equal parts Δt (minutes), corresponding current i0, i1, i2, In The section running time T=nΔt .Total energy consumption at train running time

$$Eov\text{–}con = V\int_0^T i(t) * dt \quad kVA.h = V * \frac{n\Delta t}{60} * \frac{1}{n+1}\sum_{k=0}^{n} i_k$$

$$= V\frac{n\Delta t}{60} I \quad kVA.h$$ excluding coasting or braking self-electricity energy consumption

$$= \frac{V * I * t}{60} \tag{2.29}$$

Where V is 25KV, is the average of traction network voltage. Δt Unit is in minutes

2.10.1 Train average current:

$$Iavg = \frac{1}{T}\int_0^T i * dt = \frac{1}{n+1}\sum_0^n ik (A)$$

$$Iavg = \frac{60 * E_{ov-con}}{V * t} + 7A(selfelectricity) \quad (2.30)$$

By using equation (2.27), t= [$\frac{D}{V_{max}}$ +K V_{max}]

$$= [\frac{(18.808)km}{120km/hr} + \frac{1}{2}(\frac{1.5+0.8}{1.5*0.8})*120km/hr] = (9.404+1.9166) \text{ minutes}$$

t=11.3206 minutes section running time

$$Iavg = \frac{60 * 1908,625.947VAmin}{25000V * 2 * 11.3206min} + 7A$$

= 209.317A train current per/locomotive

2.10.2 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 arbitrary arrangement in the power supply section, arbitrarily distributed load on the power supply section. Traction load characteristics make the power supply computation complexity. The calculation of the feeder current is described by the three main value feeder average current: The average of the feeder current 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 .Feeder effective current the RMS value of the feeder current day and night .Application: 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.

2.10.2.1 Feeder daily averages current:

The average of the feeder current 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

2.10.2.2 Feeder effective current

The RMS value of the feeder current day and night application: the temperature rise of the electrical equipment; transformer capacity calculation and heat calculation of catenary.

Feeder current maximum value is maximum instantaneous operating current, 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.

- Feeder section segment of n (number of a train which appeared at feeding sections up and down direction.
- Train density N ---daily train operation number (pair).
- t--- Train traction running time when travel through feeding section.
- E_{ov-con} -- train energy consumption when travel through feeding section

Assumption: train average current in segment equal and traction running is the same

$I_1 = \ldots\ldots\ldots\ldots I_n = I_{avg}$, $t1 = \ldots\ldots\ldots\ldots t_n = t/n$

$$I_{avg} = \frac{60 * E_{ov-con}}{V * t} + 7A(\text{selfelectricity})$$

Feeder daily average current of a double track of unilateral power supply in appendix ( )

$$I_F = np\, I_{avg} = \frac{Nt}{T} I_{avg} \qquad (2.31)$$

$$P = \frac{N\, t_{g1}}{n * T} \qquad (2.32)$$

Feeder daily effective current of a double track of unilateral power supply in appendix (G)

$$I_{FE} = I_F \sqrt{1 + \frac{K_{eg}^2 - p}{n * p}} \qquad (2.33)$$

Table 2-0-3 Sebeta to Adama Train Traffic Condition per Day at Double Track [6]

Year	interval	Passenger train	Through and sectional trains	Detaching & Attaching train	Subtotal
Short-term	SEBETA(ADDIS)-DEBREZEYIT	9	8	2	19
Long term	SEBETA(ADDIS)-DEBREZEYIT	16	17	2	35

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

$$P = \frac{2N t_g}{2n * T} \qquad \text{Where } T=2Ntg$$

$$= \frac{19 * 78.789 \min}{2 * 1440 \min} = 0.500625$$

$$I_F = np\, I_{avg} = 2 * 0.500625 * 231.132A = 231.16009A$$

Feeder daily effective current of a double track of unilateral power supply considering over zone feeding

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

$$= \sqrt{1 + \frac{1.08 - 0.500625}{4 * 0.500625}} = 231.16009 * 1.1354848 = 262.480A$$

Section running time + station stopping time =1hr and 42 minutes for one train

Table 2-0-4 Analysis Data of Train Energy Consumption

Station section	E_{ov-con} in double track	Train average current I_{avg}	Section distance	I_F	I_{FE}	Section runtime
Sebeta-Lebu	1826,473.938 whr	259.572A	13.521km	259.572A	269.7550	8.67781min
Lebu-Indeed	1908,625.947 whr	209.317A	18.808km	209.313A	217.524A	11.3206min
Sebeta-Indeed	3735,099.885 whr	231.132A	32.329km	231.16009A	262.480A	19.9977min
Indode-D1k65	1,028,470.75 3whr	162.078A	28km	162.078A	184.034A	15.9166min

3 CONCEPT AND METHODS COMPUTATION OF VOLTAGE DROPS IN A TRACTION NETWORK

3.1 Introduction

The important consideration in design and operation of a transmission line are determination of voltage drop, line loss and efficiency of a transmission. These values are greatly influenced by the line constants R, L, C of the transmission line for instance the voltage drop in the line depends upon the value of the above three line constants. Similarly the resistance of a transmission line conductor is the most important cause of power loss in the line and determines the transmission efficiency;

3.2 Classification of over head transmission lines

A transmission line has *three constant R, L, C distributed uniformly along the whole length of the line. These resistance and inductance form series impedance. The capacitance exists between conductor for 1-phase line or from a conductor to a neutral. Therefore, capacitance effect introduces complication in transmission line calculation. Depend up on the manner in which capacitance taken to account, the over head line are classified, among these classification, in this thesis medium transmission line is considered.

3.3 Medium transmission lines

In short transmission line calculations, the effects of the line capacitance are neglected because such lines have smaller lengths and transmit power at relatively low voltages (<20kV). However, as the length and voltage of the line increase, the capacitance gradually becomes of greater importance.

Since medium transmission lines have sufficient length (50-150 km) and usually operate at voltages greater than 20 kV, the effects of capacitance cannot be neglected. Therefore, in order to obtain reasonable accuracy in medium transmission line calculations, the line capacitance must be taken into consideration.

The capacitance is uniformly distributed over the entire length of the line. However, in order to make the calculations simple, the line capacitance is assumed to be lumped or concentrated in the form of capacitors shunted across the line at one or more points. Such a treatment of localizing the line capacitance gives reasonably accurate results. The most commonly used methods known as localized capacitance methods for the solution of medium transmissions lines

When the length of an over head transmission line is about 50-150km and the line voltage is moderately high (>20KV<100KV), it is considered as a medium transmission line. Due to sufficient length and voltage of the line, the capacitance effect is taken in account. For purpose of calculation the distributed capacitance of the line is divided and lumped in the form of condenser and shunted across the line at one or more point.

Such a treatment of localizing the line capacitance gives reasonably accurate results. The most commonly used methods (known as localized capacitance method) for the solution of medium transmissions lines are transmission circuits that may be represented by an equivalent π or T network using lumped constants as shown in Figure 3.1. *Z* is the total series impedance (R + jX) L and Y is the total shunt admittance (G + jB) *L*, where *L* is the circuit length. The terms inside the brackets in Figure 3.1 are correction factors that allow for the fact that in the actual circuit the parameters are distributed over the whole length of the circuit and not lumped, as in the equivalent circuits.

With short lines it is usually possible to ignore the shunt admittance, which greatly simplifies calculations, but on longer lines it must be included. Another simplification that can be made is that of assuming the conductor configuration to be symmetrical. The self-impedance of each conductor becomes Zp, and the mutual impedance of line-to-line values. Between conductors becomes Zm. However, for rigorous calculations a detailed treatment is necessary, with account being taken of the spacing of a conductor in relation to its neighbour and earth [28].

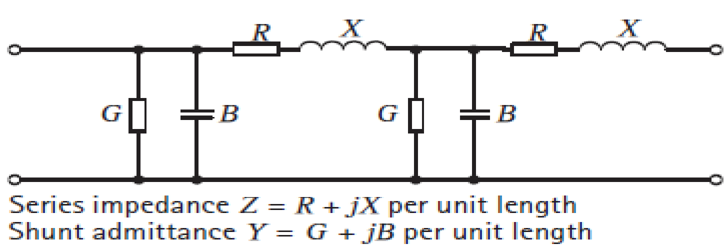

Fig3.1a For medium transmission line representation [28]

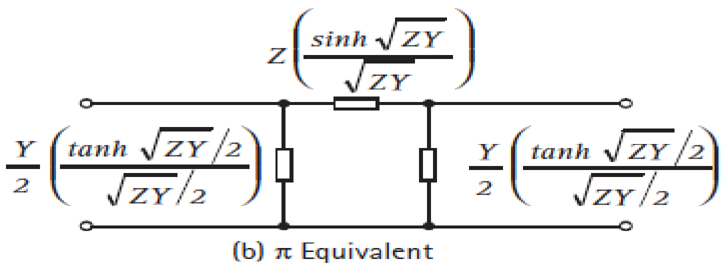

Fig3.1b For circuit model for transmission line between Sebeta to Indode[28]

Expression obtained from [28]

$$\frac{\sinh\sqrt{ZY}}{\sqrt{ZY}} = 1 + \frac{ZY}{6} + \frac{Z^2Y^2}{120} + \frac{Z^3Y^3}{5040} + \ldots \qquad (3.1)$$

$$\frac{\tanh\sqrt{ZY}}{\sqrt{ZY}} = 1 - \frac{ZY}{12} + \frac{Z^2Y^2}{120} + \frac{17Z^3Y^3}{20160} + \ldots \qquad (3.2)$$

3.4 Mutual impedance between phases (catenaries)

The impedance of a conductor –earth loop consists of its resistance and reactance .the reactance depends on the inductance L and the frequency f .The self impedance of the conductor –earth loop is composed of the resistance, the inner self-inductance and external inductance. The self impedance of the loop can be expressed by

$$Z^{\bullet}_{ii} = R^{\bullet} + R^{\bullet}_{E} + j(X^{\bullet}_{ex} + X^{\bullet}_{in}) \qquad (3.3)$$

$R^{\bullet}_{E}$ Resistance of the earth return path and the resistance per unit length is 49.3mΩ/km for 50Hz.

$$X^{\bullet}_{ex} = 2\prod * f * L^{\bullet}_{ex} = 4\prod * 10^{-7} * f * \ln(\delta_E/r)\Omega r)\Omega \qquad (3.4)$$

The inner reactance $X^{\bullet}_{in}$ is obtained from

$$X^{\bullet}_{in} = 2\prod * f * L^{\bullet}_{in} = 4\prod * 10^{-7} * f * \ln(r/r_{eq})\Omega/km \qquad (3.5)$$

The penetration depth δ_E of the current flowing through earth can be taken from

$$\delta_E = \frac{0.738}{\sqrt{f * \mu_0 / \rho_E}} \qquad \delta_E \approx 90\sqrt{\rho_E} \text{ For 50HZ}$$

For calculation of the penetration depth, the simplifying assumption is made that the earth is homogeneous body having a semi circle cross section located under the electrified railway line .this an approximation since the soil resistivity changes with the depth. The inner inductance $L^{\bullet}_{in}$ per unit length is found to be $\frac{\mu}{8\prod}$ for solid conductors with circular cross section independent of the conductor radius. Therefore

$L^{\bullet}_{in} = 2*10^{-7}\ln(\frac{r}{r_{eq}}) = 4\prod*10^{-7}/8\prod$ H/m .The result from the equation it is obtained

$$\ln(\frac{r}{r_{eq}}) = \frac{1}{4} \qquad \text{And} \qquad r_{eq} = r*e^{-0.25} = 0.7788*r$$

The coupling impedance of two conductor –earth loops i and k can be expressed

$$Z^{\bullet}ik = R^{\bullet}E + jX^{\bullet}ik \tag{3.6}$$

The mutual reactance is given by expression defined below [26].

$$X^{\bullet}ik = 4\prod*10^{-7} * f * \ln(\frac{\delta_E}{a_{ik}}) \tag{3.7}$$

3.5 Voltage regulation

When a transmission line is carrying current, there is a voltage drop in the line due to resistance and inductance of the line. The result is that receiving end voltage (VR) of the line is generally less than the sending end voltage (VS). This voltage drop (VS − VR) in the line is expressed as a percentage of receiving end voltage VR and is called voltage regulation mathematically.

$$\%\text{age of voltage regulatiom} = \frac{V_S - V_R}{V_R}*100 \tag{3.8}$$

Voltage regulation can be defined as the proportional change in voltage magnitude at the load bus due to change in load current (say from no load to full load). The voltage drop is caused due to feeder impedance carrying the load current as illustrated in Fig. 3.3(a). If the supply voltage is represented by Thevenin’s equivalent, then the voltage regulation (VR) is given by,

$$V_R = \frac{\bar{E} - \bar{V}}{V} = \frac{\bar{E} - V}{V} \tag{3.9}$$

$\bar{V}$, being a reference phasor. In absence of compensator, the source and load currents are same and the voltage drop due to the feeder is given by,

$$\Delta \bar{V} = \bar{E} - \bar{V} = Z_s \bar{I}_l \tag{3.10}$$

The feeder impedance, Zs = Rs + jXs. The relationship between the load powers and its voltage and current is expressed below

$$\bar{S}_l = \bar{V}(I_l)^* = P_l + jQ_l \tag{3.11}$$

Since $\bar{V}$ = V, the load current is expressed as following

$$I_l = \frac{P_l - jQ_l}{V} \tag{3.12}$$

Substituting, I_1 from the above equation in (3.8)

$$\Delta \bar{V} = \bar{E} - \bar{V} = (R_s + jX_s)(\frac{P_l - jQ_l}{V}) \tag{3.13}$$

$$= \frac{R_s P_l + X_s Q_l}{V} + j\frac{X_s P_l - R_s Q_l}{V} \tag{3.14}$$

$$= \Delta V_R + j\Delta V_X \tag{3.15}$$

Thus, the voltage drop across the feeder has two components, one in phase ΔV_R and another is in phase quadrature ΔV_X this is illustrated in Fig. 3.2(a).

From the above, it is evident that load bus voltage $\bar{V}$ is dependent on the value of the feeder impedance, magnitude and phase angle of the load current. In other words, voltage change (ΔV_X) depends upon the real and reactive power flow of the load and the value of the feeder impedance. When the compensator is added parallel with the load, the question is: whether it is possible to make $\bar{E} = \bar{V}$ in order to achieve zero voltage regulation irrespective of change in the load? , the answer is yes, if the compensator consisting of purely reactive component has enough capacity to supply the required amount of the reactive power. This situation is shown using phasor diagram in Fig. 3.2(b).

The net reactive load bus is now Q_s=Q_γ +Q_1 .the compensator reactive power (Q_γ) has to be adjusted in such a way as to rotates the phasor ΔV until $\overline{E} = \overline{V}$ [29]

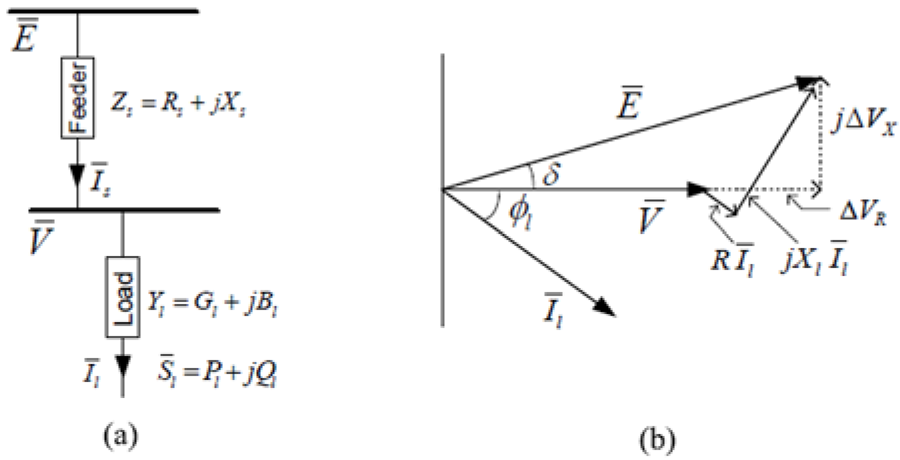

Figure 3.2a Single phase system with feeder impedance, Figure 3.2b Phasor diagram [29].

4. MODELLING OF COMPONENTS

4.1 Substation Model

4.1.1 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 feeding section is about 32.067km long. Conventionally, the power substation is modelled 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 set 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 [22].

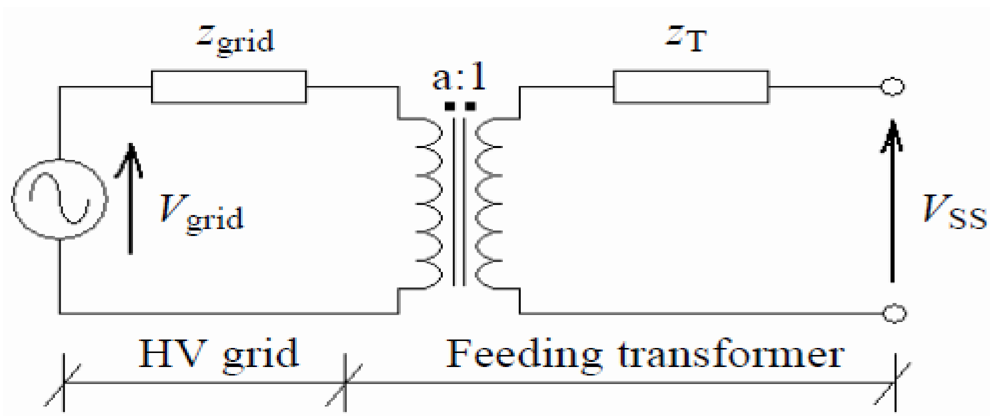

Figure 4.1 Simplified power substation models [22]

The model of the feeding transformer in the 25 kV AC, 50HZ systems under study is as shown in Figure 4.1. The secondary is with the centre solidly grounded. An earthing resistance is included in the model to simulate the effectiveness of the earthing system. The voltage of the catenaries is about 25kV reference direction for the current is positive if the currents are leaving the wire on the secondary side, and entering the positive terminal on the primary side. The three currents leaving the secondary wires are the catenaries current, the rail current, and the feeder current,I_c, $I_{R,}I_F$ respectively [22].

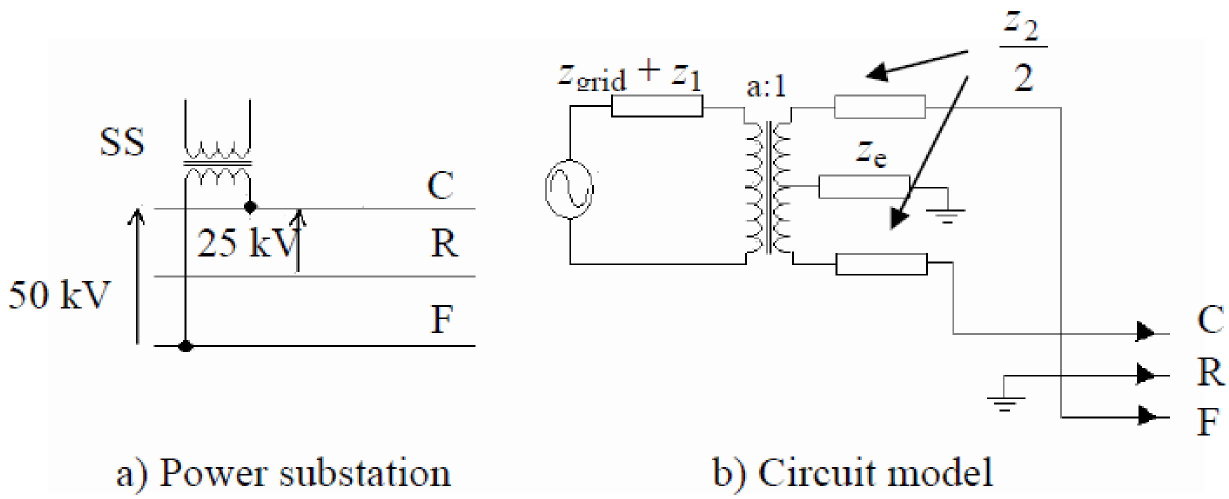

Figure 4.2 Model of a 25KV feeding transformer, Z_e is the earthing resistance, Z_2 is the total leakage impedance of the secondary, Z_l is the primary leakage impedance [22].

4.2 Modeling of AC Railway Power Feeding Systems

The main function of AC railway power supply system is to deliver electric energy to the electric locomotives that are connected to the system, and to do so effectively and economically.

The overhead catenary feeding system is complicated as described in the literature survey. To formulate power flow equations, transmission lines and other network components requires sufficiently accurate modelling. In this thesis, the AC railway power feeding systems can be divided into two categories according to the feeding arrangement:

(i) Single-phase AC railway power feeding systems and

(ii) Bi-phase AC railway feeding systems (Autotransformer scheme).

The modelling approach for each category is described as follows [22]

4.3 Single-phase AC railway power feeding system

Although the properties of the AC railway power feeding systems are intrinsically nonlinear, there are some simplifications of the power network modelling. Impedances of the overhead catenary wire, rails, return conductor and other equipment such as BTs are all added in series. Thus, a single-phase AC equivalent circuit consisting of an average lumped conductor on one side (Line or positive conductor) and a zero-impedance conductor on the other side. (Neutral or negative conductor) is formed as shown in Fig. 3.1. This approach is adequate to calculate voltages across trains and phase-to-ground substation However, rail potential, rail-to-earth leakage current, EMI effect, etc cannot be determined using this simplified model [22].

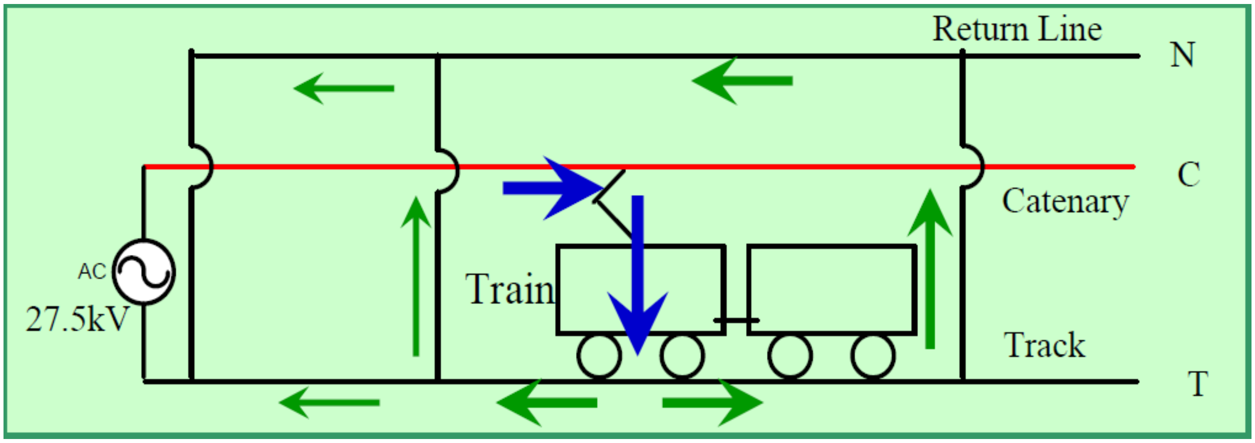

Figure 4.3 Direct powers with return line mode [3]

4.4 Train model

The other key power system component is the electric train. It requires a simple model to reduce problem complexity and overall execution time; directly applying differential equations to obtain a model like that used in traction drive analysis is not appropriate for steady-state power flow calculations [23].

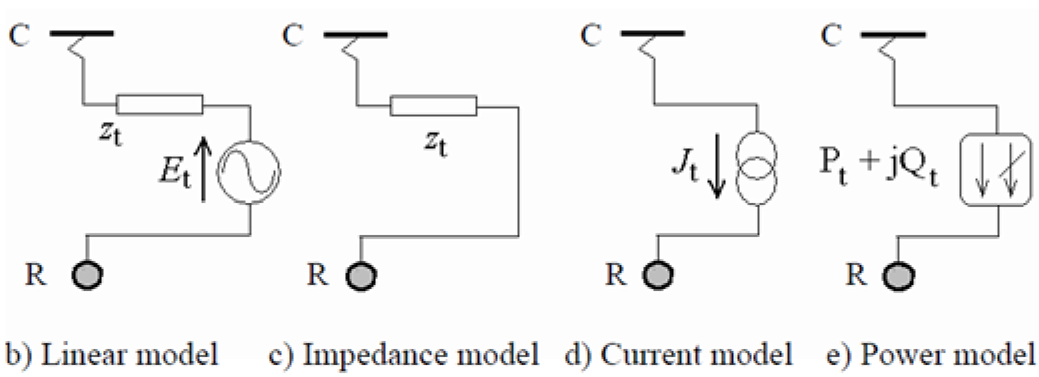

Figure 4.4 Four locomotive models for power flow calculation [22]

In some particular conditions, for example with a current control loop embedded in the onboard Power converter [24], the current load model is reasonable for this thesis.

4.5 Block diagram of an ac locomotive

The various components of an AC locomotive running on single-phase25-kV, 50-Hz AC supply is numbered in. OH contact wire, pantograph, circuit breakers, on-load tap-changers transformer rectifier, smoothing choke DC traction motors. The above components are explained in the block diagram.

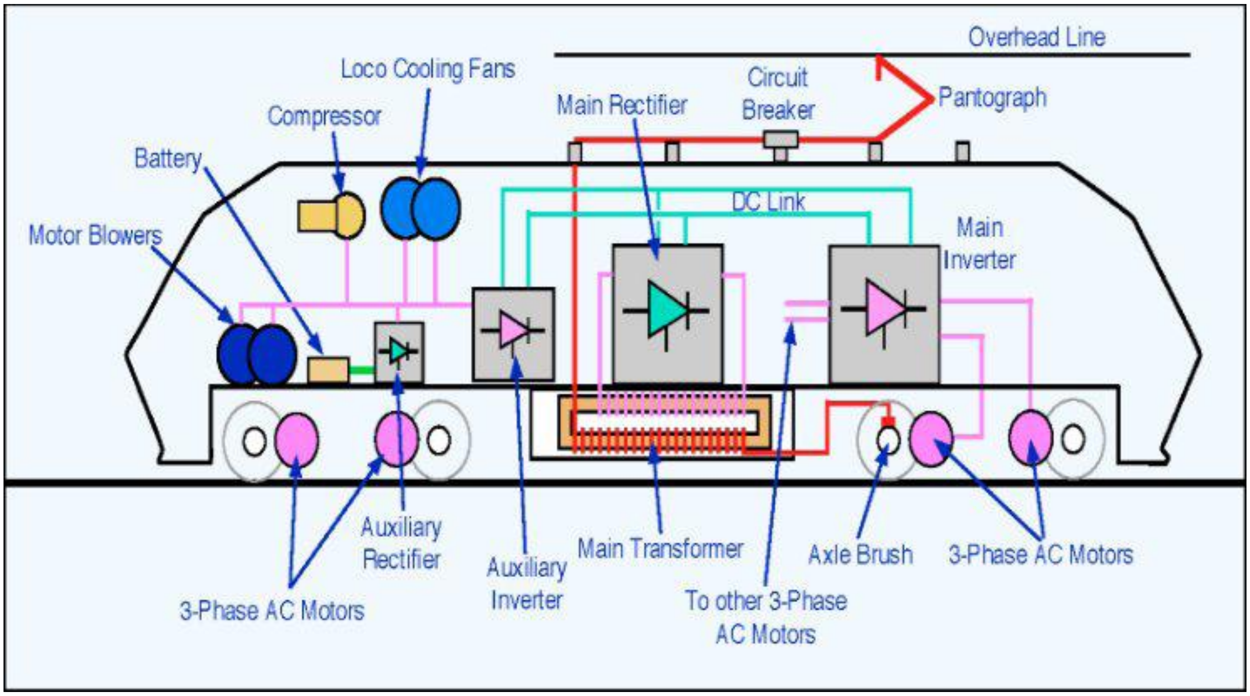

Fig.4.5 Block diagram of an AC locomotive [21]

As seen, power at 25 kV is taken via a pantograph from the overhead contact wire and fed to the step-down transformer in the loco-motive. The low AC voltage so obtained is converted into pulsating DC voltage by means of the rectifier. The pulsations in the DC voltage are then removed by the smoothing choke be-fore it is fed to DC series traction motors which are mounted between the wheels. The function of circuit breakers is to immediately disconnect the locomotive from the overhead supply in case of any fault in its electrical system. The on-load tap-changer is used to change the voltage across the motors and hence regulate their speed.

4.6 Overhead line (catenary)

The mechanics of power supply wiring is not as simple as it looks figure 4.5. Hanging a wire over the track, providing it with current and running trains under it is not that easy if it is to do the job properly and last long enough to justify the expense of installing it. The wire must be able to carry the current (several thousand amps), remain in line with the route, and withstand wind (in Hong Kong typhoon winds can reach 200 km/h), extreme cold and heat and other stile weather conditions.

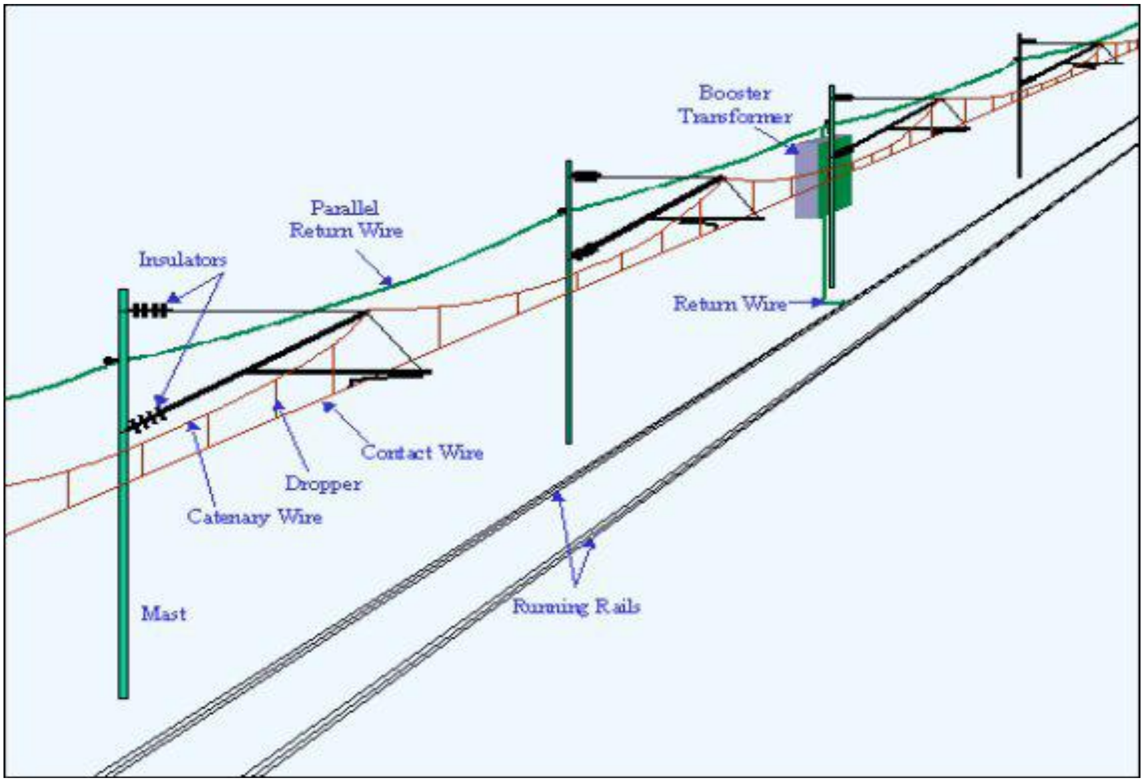

Figure 4.6 Over head line [19].

Overhead catenary systems, called "catenary" from the curve formed by the supporting cable, have a complex geometry, nowadays usually designed by computer. The contact wire has to be held in tension horizontally and pulled laterally to negotiate curves in the track. The contact wire tension will be in the region of 2 tonnes. The wire length is usually between 1000 and 1500 metres long, depending on the temperature ranges. The wire is zigzagged relative to the centre line of the track to even the wear on the train's pantograph as it runs underneath [21].

4.7 Pantograph

Current is collected from overhead lines by pantographs. Pantographs are easy in terms of isolation just lower the pan to lose the power supply to the vehicle. However, do provide some complications in other ways.

Figure 4.7 Pantographs [19]

Since the pantograph is usually the single point power contact for the locomotive or power car, it must maintain good contact under all running conditions. The higher speed the more difficult to maintain and good contact. It is already mentioned the problem of a wave being formed in the wire by a pantograph moving at high speed. Pantograph contact is maintained either by spring or air pressure. Compressed air pressure is preferred for high speed operation. The pantograph is connected to a piston in a cylinder and air pressure in the cylinder maintains the pantograph in the raised condition.

Originally, pantographs were a diamond-shaped "pantograph" with the contact head at the top. Two contact faces are normally provided. More modern systems use a single arm pantograph - really just half of the original shape a neater looking design. The contact strips of the pantograph are supported by a lightweight transverse frame which has "horns" at each end. These are turned downwards to reduce the risk of the pantograph being hooked over the top of the contact wire as the train moves along. This is one of the most common causes of wires "being down". A train moving at speed with its pantograph hooked over the wire can bring down several kilometres of line before it is detected and the train stopped. The most sophisticated pantographs have horns which are designed to break off when struck hard, for example, by a dropper or catenary support arm. These special horns have a small air pressure tube attached which, if the pressure is lost, will cause the pan to lower automatically and so reduce the possible wire damage [20].

5 MATHEMATICAL MODEL FOR TRACTION SUBSTATION AND FEEDER NETWORK VOLTAGE DROP

5.1 Analysis for System impedance from its short circuit characteristics

No power grid research for electrified railway is conducted by power system utility. System short capability is supposed to be 400MVA. Power system voltage loss of traction substation is calculated according to the system traction network voltage 132kV and minimum short circuit capacity 400MVA [6].

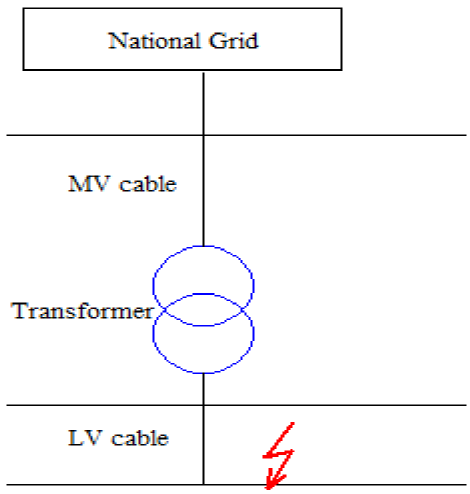

Figure5.1 Short circuit power and current of the supply network [27]

Table 5.1 Calculation in electrical parameter of traction Network [6] and analysis data

Primary voltage V_{2n}	132 kV
Secondary voltage of the transformer	25kV
Minimum short circuit volt-ampere at low voltage side	400MVA
Rated MVA of transformer in Lebu section post to Indode substation	2(16+16)MVA
transformer connection	V-V
Rated percentage reactance U_{kr}	12%
Power factor (cos Θ)	0.95

$$\text{short circuit MVA} = \frac{3 * V_{phase}}{1000} * I_{phase}$$

$$V_{phase} = \frac{132000}{\sqrt{3}} \text{volt}$$

$$I_{sh} = \frac{400*10^{6} \text{VA}}{\sqrt{3}*132*10^{3}} = 1749.54\text{A}$$

As per IEC 60909 tables mentioned in Appendix: E, The equivalent source voltage in RMS is multiplied by correction factor C_{max}=1.1

$$Z_{grid} = \frac{C_{max} * 132\text{KV}}{\sqrt{3} * I_{sh}} = \frac{1.1*132\text{KV}}{\sqrt{3} * 1749.54} = 47.916\Omega$$

System impedance referred secondary side of the transformer is given by

$$Z_{grid} = \frac{Z_{grid}}{K^{2}}$$

$$Z_{grid} = \frac{47.916}{4.8^{2}} = 2.0796875\Omega \qquad \text{where } K = \frac{V_{1n}}{V_{2n}} = \frac{132\text{KV}}{27.5\text{KV}} = 4.8$$

IEC 60909 standard in Appendix: B given the resistance and reactance value is multiplied by factor of 0.1 and 0.995 respectively [27]

$$Z_{grid} = X_{grid} + R_{grid}$$

$$X_{grid} = 0.995 * 2.0796875\Omega = 2.0692\Omega$$

$$R_{grid} = 0.1 * 2.0796875\Omega = 0.20796\Omega$$

$$Z_{grid} = 0.20692\Omega + j2.0692\Omega$$

IEC 60909 standard in Appendix: B given the p_{kr} =0.8

$$Z_T = \frac{U_{kr}\% V_{2n}^2}{100 * S_{tr}} = \frac{12\% * 25KV^2}{100 * 16MVA} = 4.688\Omega$$

$$P_{krT} = \frac{P_{kr} * S_{tr}}{100} = \frac{0.8 * 16 * 10^6}{100} = 128KW$$

$$I_{2n} = \frac{S_{rt}}{\sqrt{3} * V_{2n}} = \frac{16 * 10^2}{\sqrt{3} * 25KV} = 369.504A$$

$$R_T = \frac{P_{krT}}{3 * I_{2n}^2} = \frac{128KW}{3 * 369.504^2 A} = 0.3125\Omega$$

$$X_T = \sqrt{Z_T^2 - R_T^2} = \sqrt{4.688^2 - 0.3125^2} = 4.6776\Omega$$

$$Z_T = 0.3125\Omega + j4.688\Omega$$

Impedance at traction substation is given as the sum of line impedance and impedance of the transformer [27].

$$\sum X_s = \sum X_{grid} + \sum X_T = j2.6092\Omega + j4.6776\Omega = j7.2868\Omega$$

$$\sum R_s = \sum R_{grid} + \sum R_T = 0.20796\Omega + 0.3125\Omega = 0.52046\Omega$$

$$Z_s = \sum X + \sum R = 0.52046 + j7.2868$$

Table: 5-0-1 : Calculation in Electrical Parameters of Traction Network [6] and Analysis.

Type of operation	Normal condition section operation
No of train per section	1
Current per train (I_{FE}) Lebu to Indode	217.524A
Section length in kilometer	18.808km
Transformer impedance Ω	$0.4844 + j6.3966 = 2.4575\Omega$
Line impedance Ω/km	0.130081+j0.392381
Distance between contact wires is (midway between track and half length of the gauge.a_{ik}	4m+0.7175m=4.7175m
Height of contact wire	5750mm

5.2 Analysis of Mutual impedance between catenary cables.

To calculate mutual impedance between lines, the maximum resistance value 30Ω mentioned table (5-0-3) is used and using formula mentioned in appendix C.

$$R = \frac{\rho_E * \ln(\frac{4*l}{d})}{2\prod l} \qquad \Rightarrow \rho_E = \frac{2\prod l * R}{\ln(\frac{4*l}{d})} = \frac{2\prod *0.8*30\Omega}{\ln(\frac{4*0.8m}{0.02m})} = \frac{150.769}{5.075}\Omega m = 29.708\Omega 9$$

By using equation (3.3)

$$\delta_E = 90\sqrt{\rho_E} = 90 * \sqrt{29.708} = 490.545m$$

$$X_{ik} = 4\prod *10^{-7} * f * \ln(\delta_E / a_{ik}) = 4 * \prod *50*10^{-7} * \ln(\frac{490.545}{4.7175}) = 2.918*10^{-4}\Omega/km$$

$$Z_{ik} = R_E{}' + X_{ik} = 0.0493\Omega/km + j2.918*10^{-4}\Omega/km$$

Table: 5-0-2Earth Resistance [6].

category	Earthing resistances （Ω）
Switch and arrester	10
Aerial earthling wire	10
Scattered OCS mast	30

5.3 Voltage drop analysis Normal section operation

5.3.1. Voltage drop at substation in a normal section operation Indode to Lebu

$$\Delta V = I_{FE} * (R\cos\theta + X\sin\theta)$$

$$= 2 * 217.524A * 0.4844 * 0.95 + 6.3966 * 0.312) = 1.068KV$$

Voltage drop at substation in a normal section operation Indode to D1k65 section post because of V-V connection of transformer

$$= 2 * 184.038A * (0.4844 * 0.95 + 6.3966 * 0.312)$$

$$= 0.904KV$$

5.3.2. Voltage drop at feeder network in a normal section operation

$$\Delta V = (I\cos\theta - jI\sin\theta) * L(R + jX) + (I\cos\theta - jI\sin\theta) * L * Z_m)$$

$$= 217.524 * (0.95 - j0.312) * 18.808km(0.130081 + j0.392381)$$

$$+ 217.524(0.95 - j0.312) * 18.808km * (0.0493\Omega 0.m + j2.918 * 10^{-4} \Omega/km)$$

$$= 217.524A * 18.808km[(0.246 + j0.3321) + (0.046925 - j0.0151)\Omega / km]$$

$$= (1006.443 + j1359.60) + (191.961 - j210.717)$$

$$1103.068 + j1148.883 = \sqrt{1198.391^2 + 1148.883^2}$$

$$= 1.660KV$$

Total voltage drop=1.660KV+ (1.068+0.904) KV=3.565KV

Voltage at the end of feeder section =supply voltage –voltage drop at substation-voltage drop at feeder network

$$= 25KV - 3.565KV = 21.435KV$$

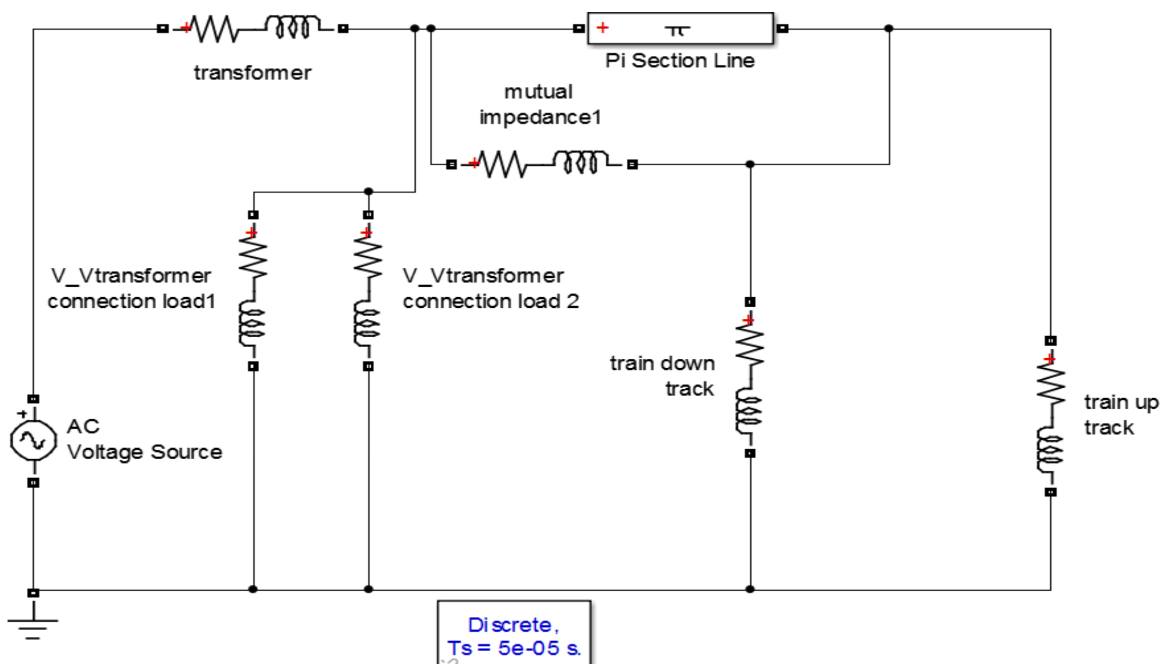

Figure 5.2 Circuit models for normal section operation before compensation

5.4 Voltage drop analysis due to over zone feeding operation.

5.4.1. Section voltage drops between Indode to Sebeta due to over zone feeding and parallel power supply without employing section paralleling.

Voltage drop on a feeder network due to over zone feeding operation from Indode substation by disconnecting 25kV isolator and feeder bus tie circuit breaker from Sebeta substation.

Table: 5-0-3 Calculation on Electrical Parameters of Traction Network [6] and Analysis Data.

Type of operation	Over zone feeding operation
Maximum Number of train per two section	4
Section length in kilo meter	32.329km
Transformer impedance Ω	$0.4844 + j6.3966$
Line impedance Ω/km	0.130081+j0.392381
Equivalent impedance	$Z' \approx 0.2461\Omega/km$
Mutual impedance	$0.0493\Omega/km + j2.913*10^{-4}\Omega/km$ $Z'_m \approx R\cos\phi + x\sin\phi = 0.04458\Omega/km$

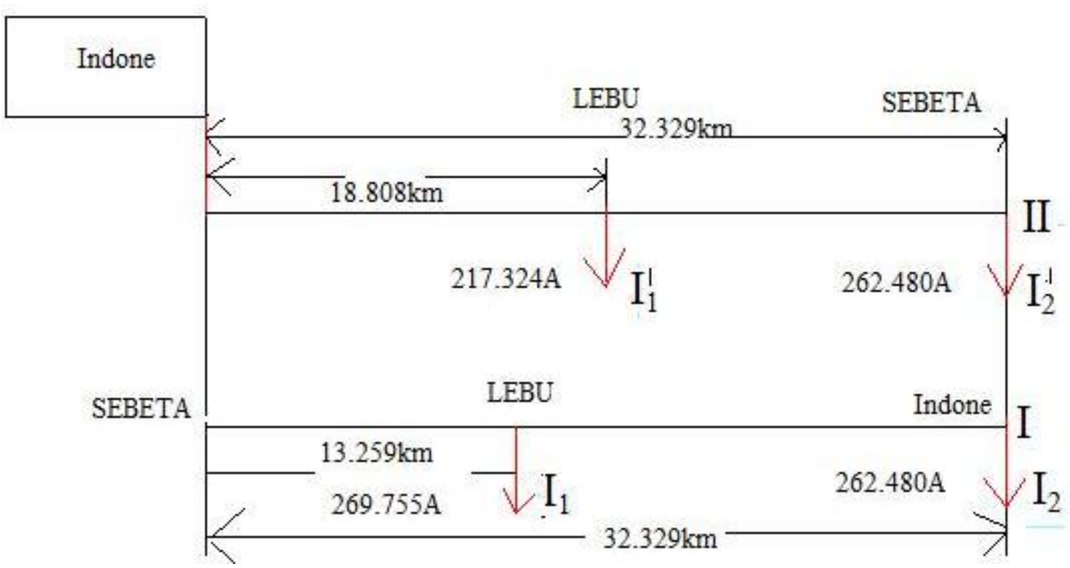

Figure 5.3 over zone current distribution on a double track.

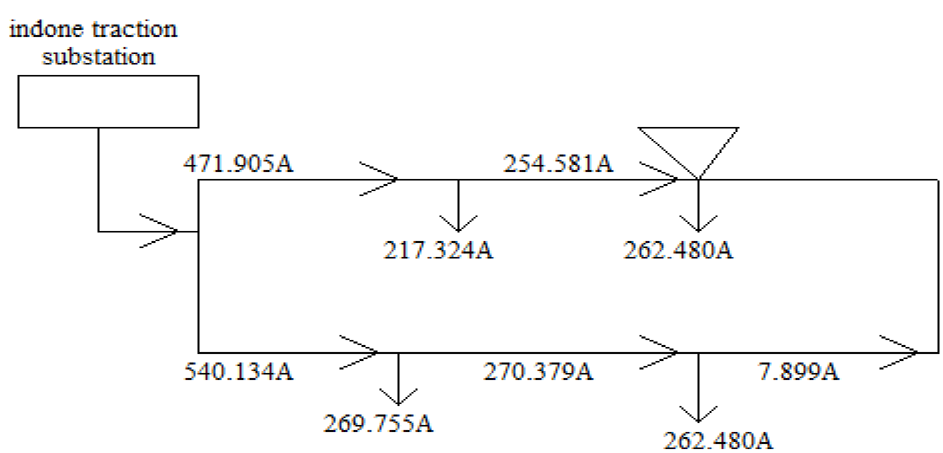

Figure 5.4 parallel power supply (catenary breaker is on the end section)

Train motion in up direction that is from Sebeta substation to Indode substation, power is supplied from Indone substation, then feeder current is given below and using formula derived in appendix: F that is feeder cuurent for up track.

$$\dot{I}_{I} = \sum_{i=1}^{n} \left(\frac{2l - l_i}{2l}\right) \dot{I}_i + \sum_{j=1}^{m} \frac{l_j'}{2l} \dot{I}_j'$$

$$= [\frac{64.658km - 13.259km}{64.658km} * 269.755A + \frac{64.658km - 32.329km}{64.658km} * 262.480A]$$

$$+ [\frac{18.808km}{64.658km} * 217.324A] + \frac{32.329km}{64.658km} * 262.480A]$$

$$= 540.134A$$

Train motion in down direction that is from Indode substation to Sebeta substation, power is

Supplied from Indode substation, then feeder current is given below and using formula derived in appendix: F that is feeder cuurent for down track.

$$\dot{I}_{II} = + \sum_{i=1}^{m} \frac{l'}{2l} \dot{I}_i' + \sum_{j=1}^{n} \left(\frac{2l - l_i}{2l}\right) \dot{I}_j$$

$$= [\frac{13.259km}{64.658km} * 269.755A] + \frac{32.329km}{64.658km} * 262.480A] +$$

$$[\frac{64.658km - 18.808km}{64.658km} * 217.324A + \frac{64.658km - 32.329km}{64.658km} * 262.480A]$$

$$= 471.905A$$

<u>5.4.1.1 Voltage drop on the feeder network at the dividing point</u>

$$\Delta V = Z * L_1 * \dot{I}_{I} + Z_m * L_1 * \dot{I}_{II}$$

$$\begin{aligned}\Delta V = {} & 0.2461\Omega.24\ (18.808km * 471.908A + 254.581A * 13.259km) + \\ & 0.04458\Omega/km(13.259 * 540.134A + 270.379A * 18.808km + \\ & 0.0047175km * 7.899A) \\ = {} & 3.015KV + 0.545KV = 3.561KV\end{aligned}$$

5.5.1.2 Voltage drop in the transformer due to over zone feeding

$$\Delta V = I_{FE}(R\cos\theta + X\sin\theta) = (I_I + I_{II})*(R\cos\theta + X\sin\theta)$$

$$= (540.134A + 471.905A)*2.4575\Omega = 2.487KV$$

<u>5.4.1.3 Voltage drop at substation in a normal section operation Indode to D1k65 section post because of V-V connection of transformer</u>

$$= 2*184.038AA*(0.4844*0.95 + 6.3966*0.312)$$

$$= 0.904KV$$

Total voltage drop= voltage drop in the transformer + voltage drop on the feeder network

$$\Delta V = 3.561KV + 2.487KV + 0.904KV = 6.952KV$$

Voltage at the end of feeder section =supply voltage –voltage drop at substation-voltage drop at feeder network

$$= 25KV - 6.952KV = 18.037KV$$

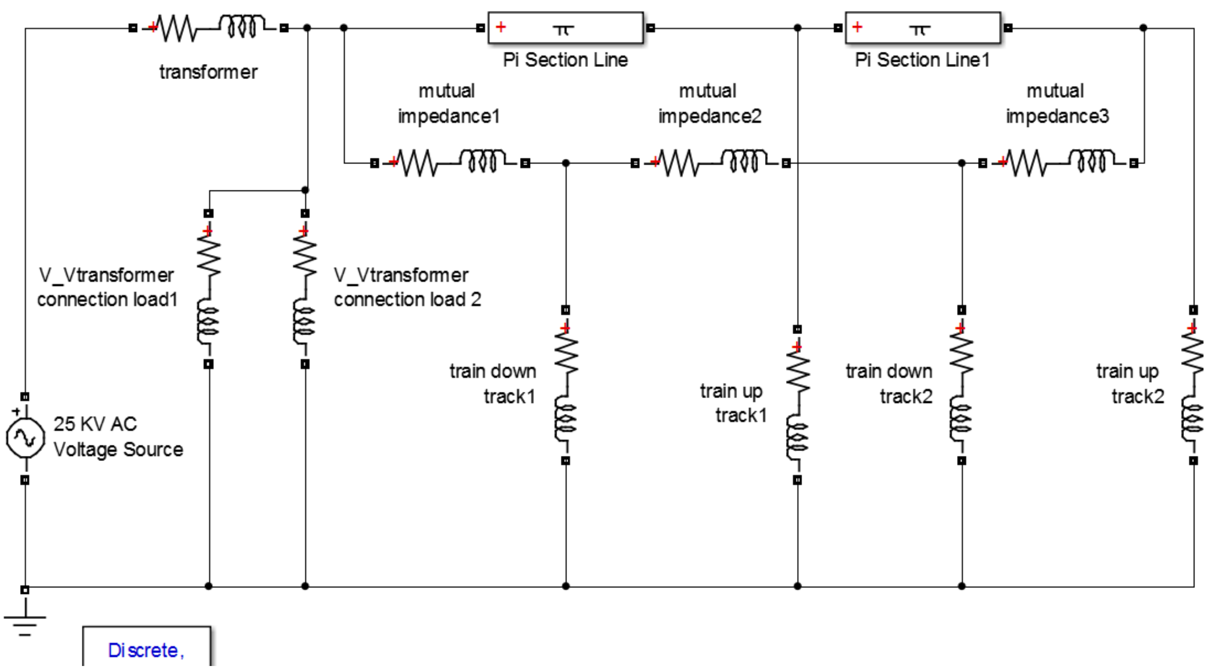

Figure 5.5   Circuit model for over zone feeding operation before compensation.

5.4.2 Section voltage drop between Indode to Sebeta due to over zone feeding and parallel power supply with section paralleling.

Voltage drop on a feeder network due to over zone feeding operation from Indode substation by disconnecting 25KV isolator or feeder bus incoming circuit breaker and feeder bus tie circuit breaker from Sebeta substation.

At intervals, it is usual to parallel the two catenaries at paralleling/sub sectioning substations, as illustrated in the Figure 5.6. Load current can then flow in the parallel paths, which reduces the impedance to the load[28].

5.5.2.1 Sebeta to Indode feeder network impedance model for section paralleling at double track

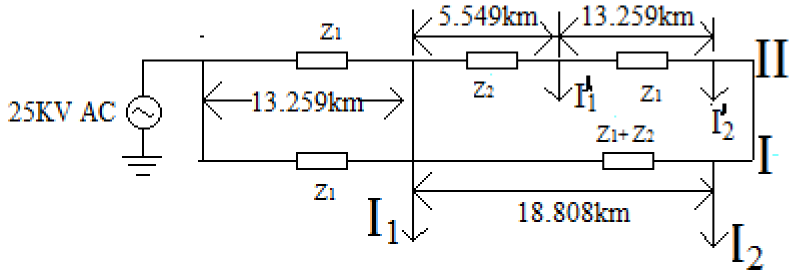

Figure 5.6 Line impedance models for double track feeder network in section between Sebeta to Indode

$$Z_1 = 13.259km * 0.2461\Omega / km = 3.263\Omega$$

$$Z_2 = 5.549km * 0.2461\Omega / km = 1.366\Omega$$

$$Z_1 + Z_2 = 4.629\Omega / km$$

5.4.2.2 Voltage drop on feeder network at dividing point

$$\Delta V = Z * L_1 * \dot{I}_I + Z_m * L_1 * \dot{I}_{II}$$

$$\Delta V = [471.905A * (\frac{Z_1 * Z_1}{Z_1 + Z_1}) + 471.905A * Z_2 + 254.581A * Z_1] + 3.654 * 10^{-3}[(540.134A * \frac{Z_1 * Z_1}{Z_1 + Z_1} +$$

$$270.379A * (Z_1 + Z_2) + 0.00471475km * 0.7899A * 0.2461\Omega.24]$$

$$= [471.905A * (\frac{3.263\Omega * 3.263\Omega}{3.263\Omega + 3.263\Omega}) + 471.905A * 1.366\Omega + 254.581A * 3.263\Omega. +$$

$$0.04458\Omega.0m[(540.134A * (\frac{3.263\Omega * 3.263\Omega}{3.263\Omega + 3.263\Omega}) + 270.379A * 4.629\Omega +$$

$$0.00471475km * 0.7899A * 0.2461\Omega.24]$$

$$= 2.340KV$$

Total voltage drop= voltage drop in the transformer + voltage drop on the feeder network

$$\Delta V = 2.340KV + 2.487KV + 0.904KV = 5.731KV$$

Voltage at the end of feeder section =supply voltage –voltage drop at substation-voltage drop at feeder network

$$= 25KV - 5.731KV = 19.268KV$$

5.4.3 over zone feeding by considering one train per track in section between Indode to Sebeta

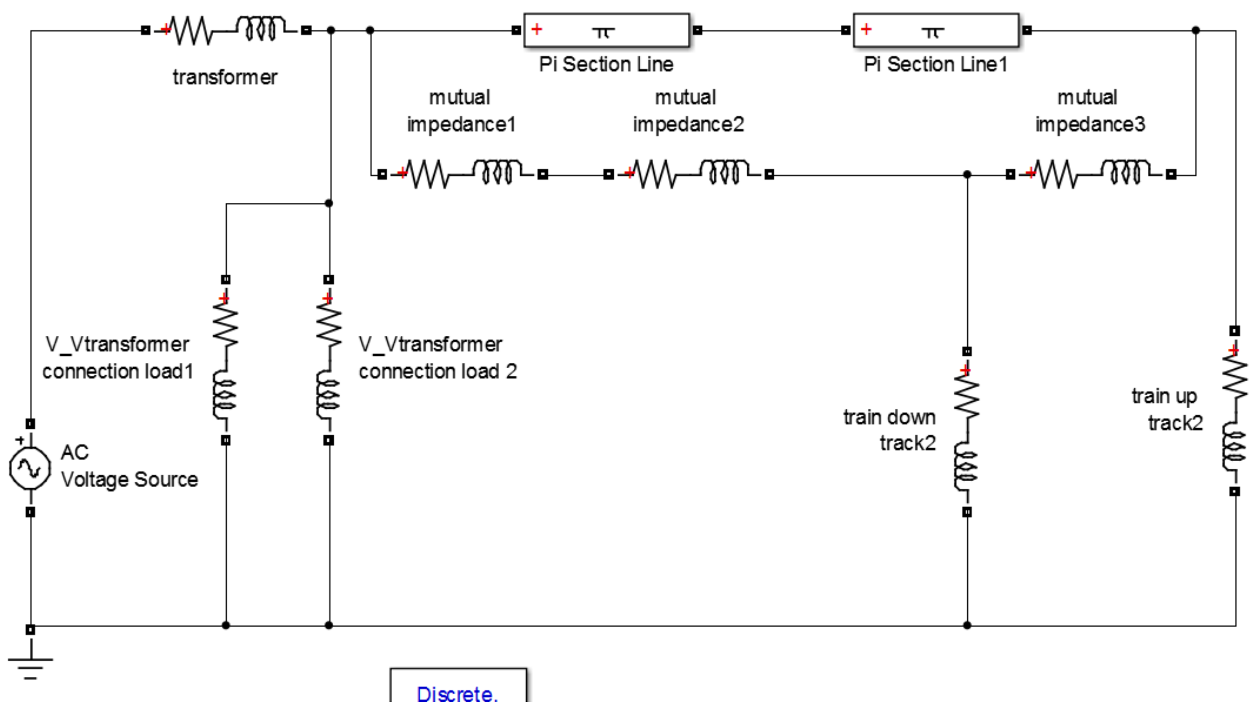

Figure 5.7 circuit model for over zone feeding operation before compensation

6 COMPENSATOR IN TRACTION POWER SUPPLY SYSTEM

In general, the loads which have poor power factor, unbalance, harmonics, and DC components require compensation. These loads are arc and induction furnaces, sugar plants, steel rolling mills (adjustable speed drives), power electronics based loads, large motors with frequent start and stop etc. All these loads can be classified into three basic categories

1. Unbalanced ac load
2. Unbalanced ac + non linear load
3. Unbalanced ac + nonlinear ac + dc component of load [29]

The DC component is generally caused by the usage of half-wave rectifiers. These loads, particularly nonlinear loads generate harmonics as well as fundamental frequency voltage variations. For example arc furnaces generate significant amount of harmonics at the load bus. Other serious loads which degrade power quality are adjustable speed drives which include power electronic circuitry, all power electronics based converters such as Thyristor controlled drives, rectifiers, cyclo converters etc. In general, following aspects are important, while we do provide the load compensation in order to improve the power quality [30].

In this thesis fundamental load compensation technique for unbalanced linear loads, such as combination of resistance, inductance, capacitance and their combinations. The objective here will be to maintain currents balanced and unity factor with their voltages.

To serve as one of the main transportations and carriers of the world nowadays, electrified railway is developing rapidly in its speed and length of line. In order to improve the power supply capability and power quality of traction system, scientific researchers have put forward many methods. Adding shunt capacitor compensator or series capacitor compensator in traction system are both effective methods. They can filter, regulate voltage, raise the utilization rate of the power supplying equipment capacity, and improve power factor.

6.1 Series compensator of traction power supply system

Series compensation of traction power supply system is a capacitor group and control and protection device connected on feeder line or supply arm. Its function is to raise terminal. Voltage of supply arm and the power factor, then improve power quality.

6.2 The principle of series compensator of traction power supply system

Connect a capacitor in series on traction substation or power-supply section. The capacitor could offset part of inductance of traction power supply system, and reduce voltage loss.

The voltage loss is:

$$\Delta V_C = -IX_C \sin\Phi = -I\sin\Phi * X_C \tag{6.1}$$

Where, Φ is the angle between load-terminal current vector and voltage vector. The voltage loss is negative when load current running through series capacitor. It means output voltage of capacitor is greater than entrance voltage. The effect of voltage improvement has some connection with load current and power factor. The higher the load current, and the lower the power factor, the better the effect. The absolute value of voltage loss of capacitor is proportional to load current. It has automatic regulation to the voltage of supply arms, which is compatible with the drastic changes of the load of electric traction.

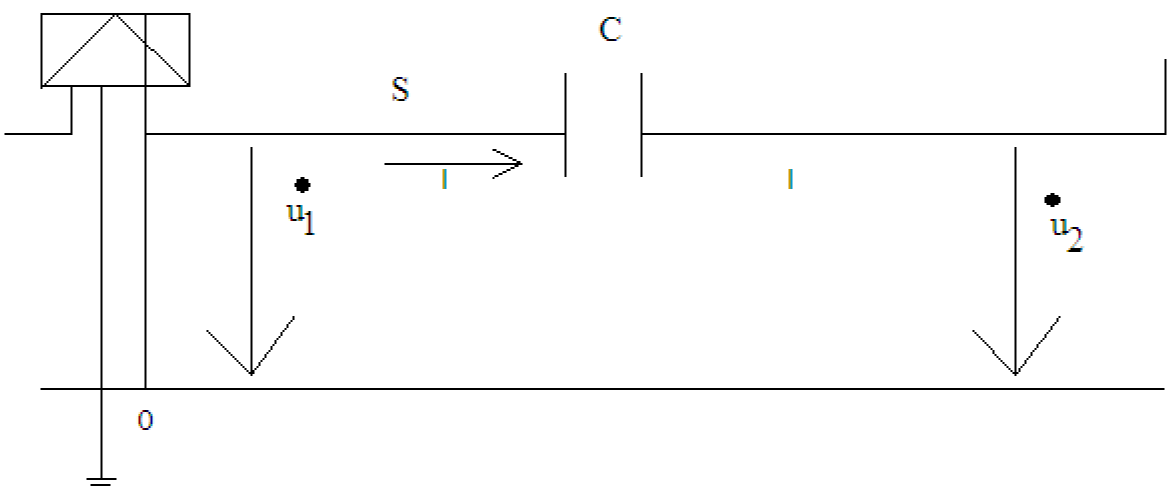

Figure6.1 the graphic of series compensation of power supply system of electric traction

The installed capacity of the series compensation is decided by its rated current and rated voltage. Series compensation is different from other electric devices for its working voltage is proportional to its current. Therefore, when choosing the content of the series compensation, the higher the rated current, the lower the working voltage. It means the lower the compensative voltage, the worse the compensative effect. That is the compensative effect is in inverse proportion to the installed capability.

The working voltage of series capacitor is proportional to its current. When choosing the series capacitor, the higher the rated current, the lower the working voltage. It means the lower the compensation voltage, the worse the compensation effect. The compensation capability is in inverse proportion to the installed capability. So the key point to meet the demands of compensation effect is to choose the rated current of series capacitor.

Series capacitor X_C can be calculated through rated Voltage U_{CN}, rated current I_{CN}, and the power factor cosΦ of the line. $X_C = \frac{UCN}{ICN}$ that is

$$\Delta U_C = I_C * \frac{U_{CN}}{I_{CN}} \sin\Phi = I_C \frac{U_{CN}}{Q_{CN}} \sin\Phi \qquad (6.2)$$

Obviously, when the rated voltage U_{CN} and the current flow through are the same, the higher the I_{CN}, Q_{CN} the lower the ΔU_C .ΔU_C is proportional to I_{CN}, $Q_{CN.}$ In order to meet the demand of compensation effect, the key point is choosing the rated current of series capacitor.

6.3 Thyristor Controlled Series Capacitor (TCSC*)*

Thyristor controlled series capacitor is series compensated FACTS device which consists of a series capacitor bank shunted by a Thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance. Figure 6.2 shows a single line diagram of TCSC controller.

The TCSC is based on Thyristor without gate turn-off capability. In TCSC a variable Thyristor controlled reactor is connected across a series capacitor. When the firing angle of the TCR is 180 degrees, the reactor becomes nonconducting and the series capacitor has the normal impedance. As the firing angle is decreased below 180 degree the capacitive reactance increases when the firing angle is 90 degrees, the reactor becomes fully conducting and the total impedance becomes inductive. With the 90 degrees firing angle, the TCSC helps in limiting fault current [17].

The compensator TCSC mounted on figure 6.2a is a type of series FACTS compensators. It consists of a capacitance (*C*) connected in parallel with an inductance (*L*) controlled by a valve mounted in anti-parallel Thyristors conventional (*T1* and *T2*) and controlled by an extinction angle (α) varied between 90° and 180°.This compensator injects in the transmission line a variable reactance (*XTCSC*) indicated by figure 6.2b. The characteristics of the TCSC are determined from the series capacitor (*C*) and reactor (*L*) circuit parameters shown in figure 6.2b.

The steady-state TCSC power frequency reactance *XTCSC* (α) as a function of Thyristors control angle (α) can be calculated from equation (6.3), based on an analysis of Thyristors current.

$$X_{tcsc}(\alpha = X_C[1-\frac{K^2}{K^2-1}(\frac{\sigma+\sin(\sigma i)}{\Pi})+\frac{4K^2}{K^2-1}\cos^2(\frac{\sigma}{2})\frac{K\tan(\frac{K\sigma}{2})-\tan(\frac{\sigma}{2})}{\Pi}] \qquad (6.3)$$

$$\sigma = 2(\Pi - \alpha) \quad , \quad K = \frac{\lambda}{\omega} \quad , \quad \lambda = \frac{1}{\sqrt{LC}}$$

The σ is a part of a cycle during which a Thyristors valve is in the conducting state, and firing angle α is the time expressed in electrical angular measure from the capacitor voltage (*VC*) zero crossing to the starting of current conduction through the Thyristors valve. The curve of *XTCSC* as a function of angle α is divided into three different regions which are inductive, capacitive and resonance [15].

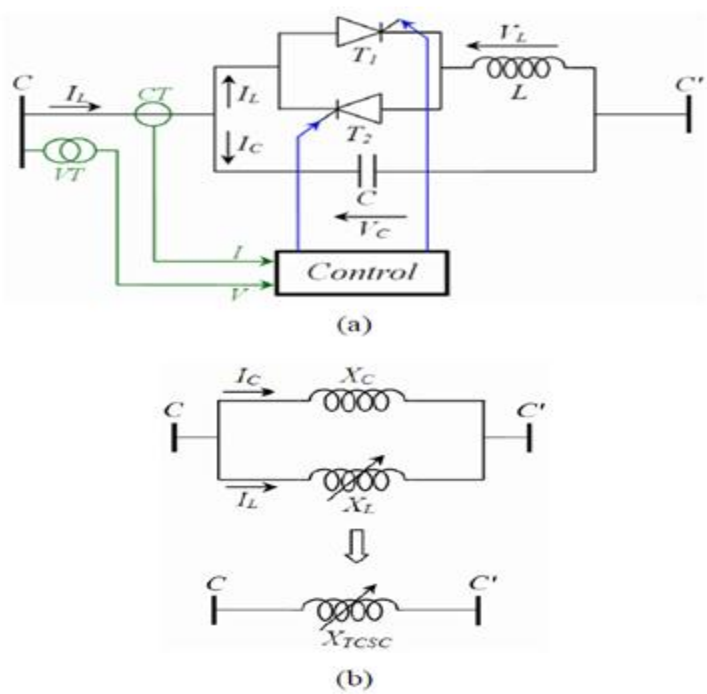

Figure 6.2 Transmission lines with TCSC system [17].

a)System configuration b) Apparent reactance

6.3.1 Modes of operation of TCSC

There are three modes of operation of TCSC depending upon the firing angle of the pulses fed to the Thyristor [17][18] [16].

- Thyristor blocked mode

- Thyristor by passed mode
- Vernier operating mode

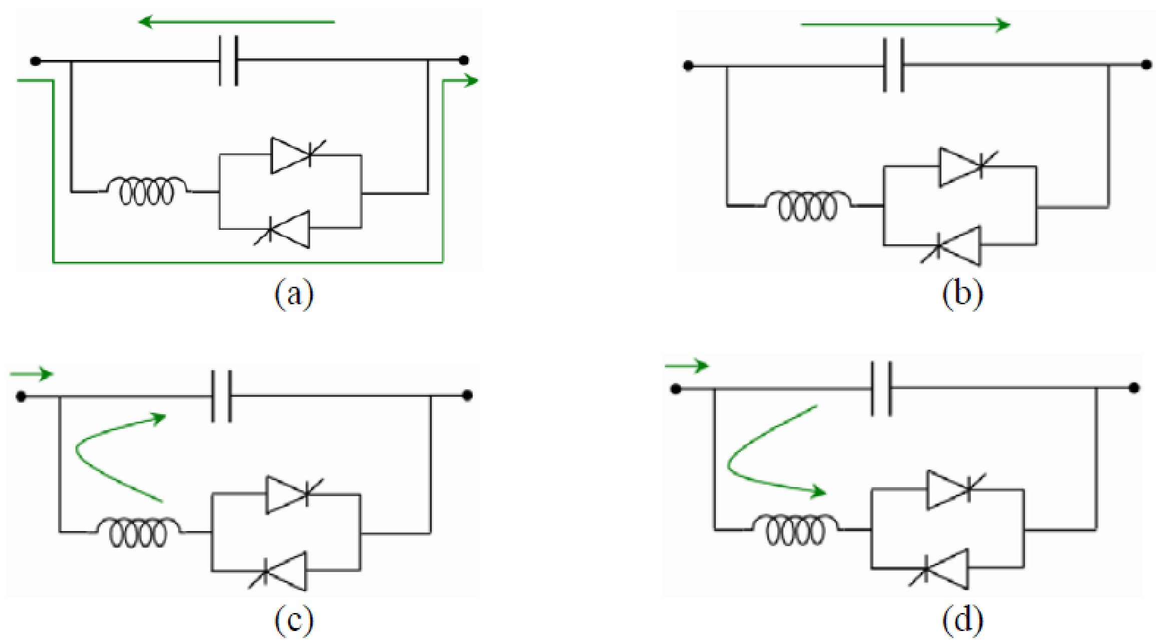

Figure 6.3 Differential operating modes of TCSC.

a) Bypassed mode; b) Blocked mode; c) Capacitive mode; d) Inductive mode [17].

<u>6.3.1.1 Bypassed-Thyristor Mode:</u>

In the bypassed mode, the Thyristors are made to fully conduct with a conduction angle of 180°. Gate pulses are applied as soon as the voltage across the Thyristors reaches zero and becomes positive, resulting in a continuous sinusoidal of flow current through the Thyristors valves. The TCSC module behaves like a parallel capacitor–inductor combination. However, the net current through the module is inductive; the susceptance of the reactor is chosen to be greater than that of the capacitor. For practical TCSC's with ratio (X_L/X_C) between 0.1 to 0.3 ranges, the capacitor voltage at a given line current is much lower in bypass than in blocking mode. Therefore, the bypass mode is utilized as a means to reduce the capacitor stress during faults [10] [11] [9].

<u>6.3.1.2 Blocked-Thyristor Mode:</u>

In this mode, also known as the waiting mode, the firing pulses to the Thyristors valves are blocked. If the Thyristors are conducting and a blocking command is given, the Thyristors turn off as soon as the current through them reaches a zero crossing.

6.3.1.3 Vernier Operating Mode:

In Vernier control the TCSC dynamics are varied continuously by controlling the firing angle. The firing angle is possible from 0^o to 90^o for each half cycle when it is generated from the zero crossing of the line current hence divided into two parts [8] [10].

6.3.1.4 Capacitive Boost mode:

In capacitive boost mode a trigger pulse is supplied to the Thyristor having forward voltage just before the capacitor voltage crosses the zero line, so a capacitor discharge current pulse will circulate through the parallel inductive branch. The discharge current pulse adds to the line current through the capacitor and causes a capacitor voltage that adds to the voltage caused by the line current. The capacitor peak voltage thus will be increased in proportion to the charge that passes through the Thyristor branch. The fundamental voltage also increases almost proportionally to the charge. From the system point of view, this mode inserts capacitors to the line up to nearly three times the fixed capacitor. This is the normal operating mode of TCSC [12] [9].

6.3.1.5 Inductive Boost Mode:

In inductive boost mode the circulating current in the TCSC Thyristor branch is bigger than the line current. In this mode, large Thyristor currents result and further the capacitor voltage waveform is very much distorted from its sinusoidal shape. The peak voltage appears close to the turn on. The poor waveform and the high valve stress make the inductive boost mode less attractive for steady state operation. This mode increases the inductance of the line, so it is in contrast to the advantages associated with the application of TCSC [12] [13] [9].

6.4 Shunt capacitor compensation of traction power supply system

Shunt capacitor compensation of traction power supply system means to connect a capacitor group and control device in parallel on feeder line or supply arm so as to improve power factor and power quality. Now dynamic capacitor compensation is used primarily [14].

6.4.1 Principle of shunt capacitor compensator

The connection and equivalent circuit diagram of shunt capacitor compensator is shown as figure 1, where $\dot{U}_1$ is supply voltage, and $\gamma_1 + jX_1$ is each phase impedance of power that converting into low-voltage side by internal impedance, line impedance and traction transformer. $\dot{U}_2$ is traction bus bar voltage of traction substation, *Xc* is capacitor of shunt compensative capacitor banks, X_L is inductance of reactor connected with capacitor group in series, *Z* is traction load impedance, *Ic* is static VAR compensator current of shunt condenser, and *Iq* is current of traction load. Before installing traction shunt capacitor compensator, current flow through the traction transformer is

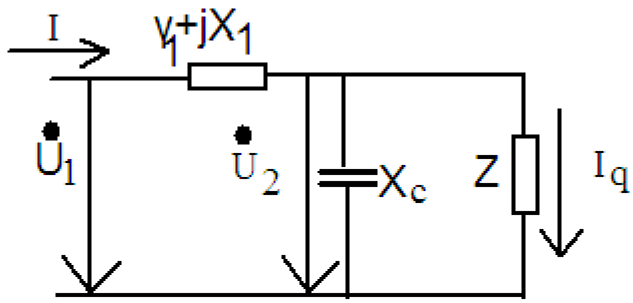

Figure 6.4 chart of traction power supply shunt capacitor compensator

$$I_q = \frac{V_{1n}}{Z + \gamma_1 + jX_1} \tag{6.5}$$

$$I = \frac{V_{1n}}{\frac{Z * j(X_C + X_L)}{Z + j(X_C + X_L)} + \gamma_1 + jX_1} \tag{6.6}$$

As two equations above indicates, after installing, the current flow through the traction transformer *Iq* reduces to *I*, active power remains unchanged, and reactive power decreases
After installing, the current flow through the traction transformer is, as two equations above indicates, after installing, the current flow through the traction transformer *Iq* reduces to *I*, active power remains unchanged, and reactive power decreases.

$$p = V1n * I_q \cos\varphi_1 = V_{1n} * I\cos\varphi_2 \tag{6.7}$$

$$Q_1 = V_{1n} * I_q \sin\varphi_1 \tag{6.8}$$

$$Q_2 = V_{1n} * I_q \sin\varphi_2 \le Q_1$$

It can be seen from 3 equations above, after installing, traction power factor can increase from $\cos\Phi_1$ to $\cos\Phi_2$ as figure shown below.

$$I_C = I_q \sin\phi_1 - I \sin\phi_2 = \frac{P(\tan\phi_1 - \tan\phi_2)}{V_{1n}} \tag{6.9}$$

While $I_C = V_{1n} / X_C = 2\pi f C V_{1n}$ in order to make power factor increase from $\cos\Phi_1$ to $\cos\Phi_2$, the capacitor it needs to compensate is capacitor C.

$$C = \frac{p(\tan\phi_1 - \tan\phi_2)}{2\prod f * V_{1n}{}^2} \tag{6.10}$$

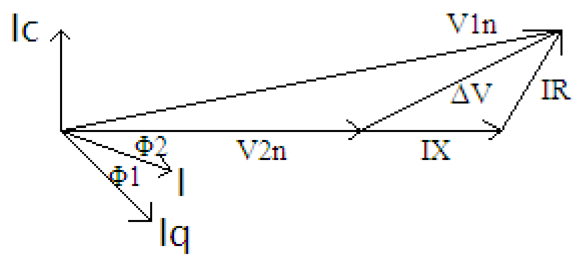

Figure 6.5 the column picture of parallel compensation.

In traction power supply system, when calculating and defining the capability of shunt capacitor, we should be based on the maximum average of traction load to choose shunt capacitor [14].

6.4.2 Dynamic shunt capacitor compensator

Nowadays in order to track changing traction loading timely, provide with rational reactive power compensation, and save the energy cost, dynamic compensator with shunt capacitor is widely used in electric railway. There are 3 commonly used devices [14].

6.4.3 Static VAR compensator (SVC)

The immediate purpose of parallel VAR compensator is to lower reactive current and negative sequence current. Three-phase SVC is an effective mature technology of improving harmonics, negative sequence and voltage fluctuation caused by the load of electric railway. SVC is by means of Thyristor controlled reactance (TCR) and the strategy of three-phase balanced control based on "Steinmetz" to make dynamic reactive power compensation, control voltage, and improve negative sequence. This method can not only balance three-phase reactive power, but also balance three-phase active power. Therefore, it is an effective method [14].

6.4.4 Static synchronous compensator (STATCOM)

In contrast with SVC, STATCOM has its advantages of fast speed, great loading rate adaptation, high work efficiency, and small output harmonic content. Especially, adopting two-phase structure can achieve four-phase control of active and reactive power, provide two supply arms of power substation with dynamic reactive compensation, besides, regulate active flow of two supply arms, so as to dynamically balance the loading. Since 1980s, the researches on the technology of STATCOM dynamic voltage compensation have become one of the hot topics in the field. Because STATCOM is usually supported by DC voltage provided by capacitor on DC side, it can't provide continues active power. But if change a power supply on DC side, STATCOM, served as voltage source inverter, can exchange energy with system. Connect a single-phase converter on both supply arms of Scott transformer, which are interconnected through intermediate links. The work mode of controlling two transformers makes them be DC power supply of the other one so as to achieve active power facility between both supply arms. When adopting impedance matching balance transformer or Scott wiring transformer, active load of both supply are balanced. Therefore it can eliminate the negative sequence completely. Accordingly, in order to achieve power factor compensation and negative sequence improvement of traction substations, we can install two single-phase STATCOM on traction transformer secondary side to carry on reactive compensation and phase transformations of active power [14].

6.5 Design parameter of TCSC

6.5.1 Voltage drop at substation in a normal section operation Indode to Lebu.

$$X_C = \frac{V_{2n}^2}{Q}\sin\varphi = \frac{25000^2\,V}{6.2612374*10^6\,VAR} * 0.312 = 31.144\Omega$$

$$C = \frac{1}{2\prod f * X_C} = \frac{1}{2*\prod*50*31.144\Omega} = 1.02205*10^{-4}\,F$$

$$\frac{X_L}{X_C} = 0.3 \Rightarrow X_L = 0.3*X_C = 0.3*31.144\Omega = 9.3342\Omega$$

$$X_L = \frac{V_{2n}^2}{Q}\sin\varphi \Rightarrow L = \frac{X_L}{2\prod f} = \frac{9.3342\Omega}{100\prod} = 0.029711H$$

6.5.2 Voltage drops between Indode to Sebeta due to over zone feeding and parallel power supply without employing section paralleling.

Equation (6.2) is used.

$$X_C = \frac{V_{2n}^2}{Q}\sin\varphi = \frac{25000^2\,V}{14.3277383*10^6\,VAR}*0.312 = 13.6103\Omega$$

$$C = \frac{1}{2\prod f * X_C} = \frac{1}{2*\prod*50*13.6103\Omega} = 2.338*10^{-4}F$$

$$X_L = 0.3*X_C = 0.3*13.6103\Omega = 4.08309\Omega = 0.012996879\Omega$$

$$X_L = \frac{V_{2n}^2}{Q}\sin\varphi \Rightarrow L = \frac{X_L}{2\prod f} = \frac{13.6103\Omega}{100\prod} = 0.0432H$$

6.6 Advantages of TCSC.

Shunt compensation is ineffective in controlling the actual transmitted power which, at a defined transmission voltage, is ultimately determined by the series line impedance and the angle between the end voltages of line. The ac power transmission line over long line has some series reactance and this will limited the power flow in the line. Series capacitive compensation is cancel a portion of the reactive line impedance and thereby increase the transmittable power. Due to the initiative off acts controller’s variable series compensation is highly effective in both controlling power flow in the line and in improving stability. With the use of fast controls minimizing the effect of system disturbances, thereby reducing traditional stability margin requirements [34].

7 System simulation and result discussion

7.1 System Simulation result without using compensator

7.1.1 Simulation result for voltage drop at substation in a normal section operation

If the drop due to complex part of the traction network (including substation, feeder network) and by taking the reactive power to zero due to an assumption that unity power factor, the feeder voltage drop become 1.182kV rather than 1.660kVas it is shown and the remaining complex voltage drop due to load current at substation with power factor of 0.95. As a result, the receiving end voltage become 21.8401kV but if it is considered the drop due to the complex part of the load and voltage drop due to reactive power the receiving end voltage become 20.250kV.This shows 21.840kV-20.777kV=1.063kV is due to the reactive load. The rest voltage drop 3.16kV due to active component of the traction network· (Refer appendix: H).

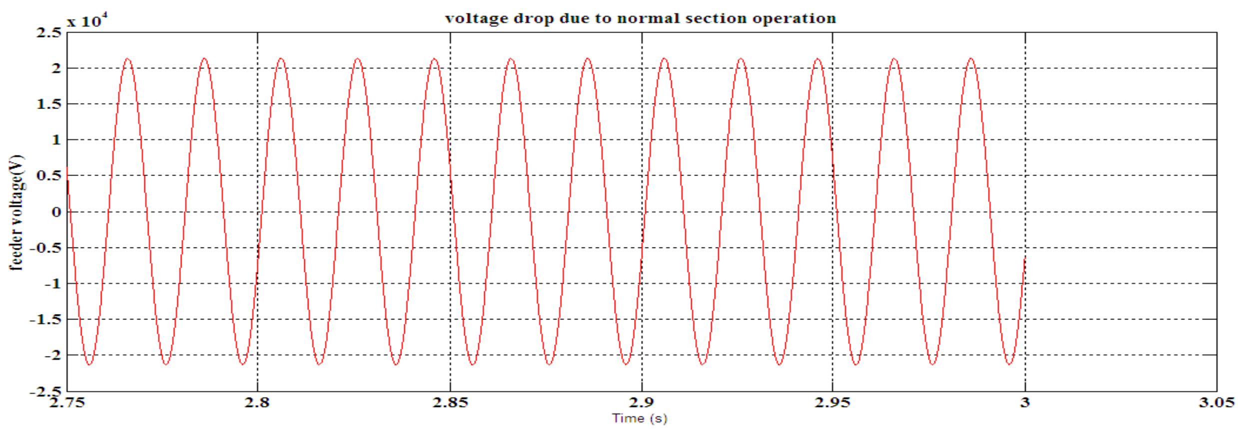

Figure 7.1 simulation result for normal section operation

$$\%\text{age of voltage regulation} = \frac{V_S - V_R}{V_R} * 100$$

$$\%V_R = \frac{25KV - 21.840KV}{21.840KV} * 100 = 14.46\%$$

7.1.2 Simulation result section voltage drop between Indode to Sebeta due to over zone feeding and parallel power supply without employing section paralleling

If the drop due to complex part of the traction network including substation, feeder network and by taking the reactive power to zero due to an assumption that unity power factor, the receiving end, voltage become19.135kV but the receiving end voltage become 18.037kVvoltage drop for only active component with power factor of 0.95 as it is calculated above but if it is considered the drop due to the complex part of the load and voltage drop due to reactive power by taking 0.95 power factor, then receiving end voltage become 17.130kV.this shows (19.135kV-18.037kV)=1.1kV is due to the reactive load and the rest voltage drop 6.073kV due to active component of the traction network. (Refer appendix: H).

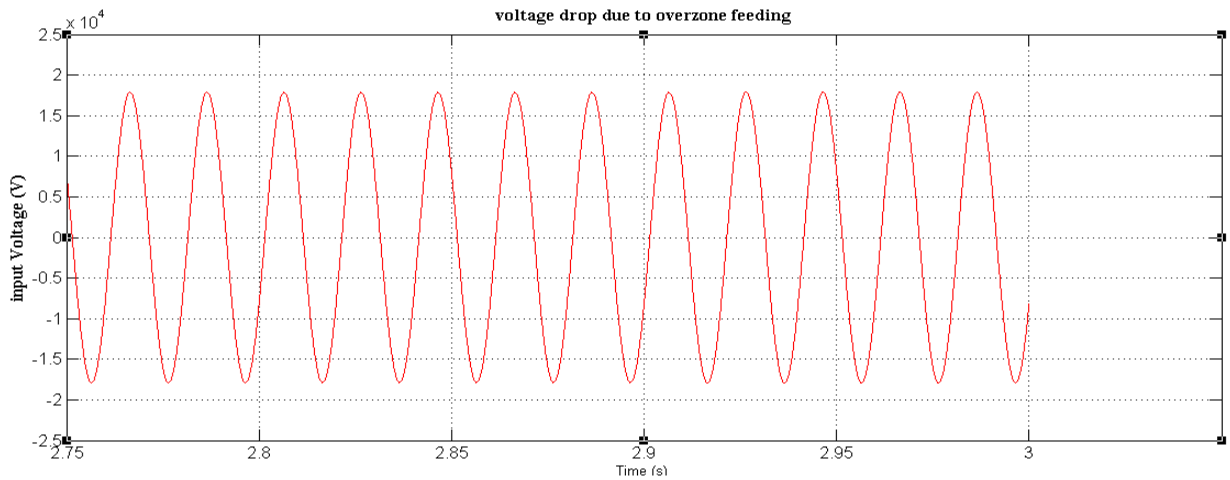

Figure 7.1 simulation result for normal section operation

$$\%V_R = \frac{25KV - 17.30KV}{17.30KV} * 100 = 44.55\%$$

7.1.3 Simulation result over zone feeding by considering one train per track in section between Indode to Sebeta

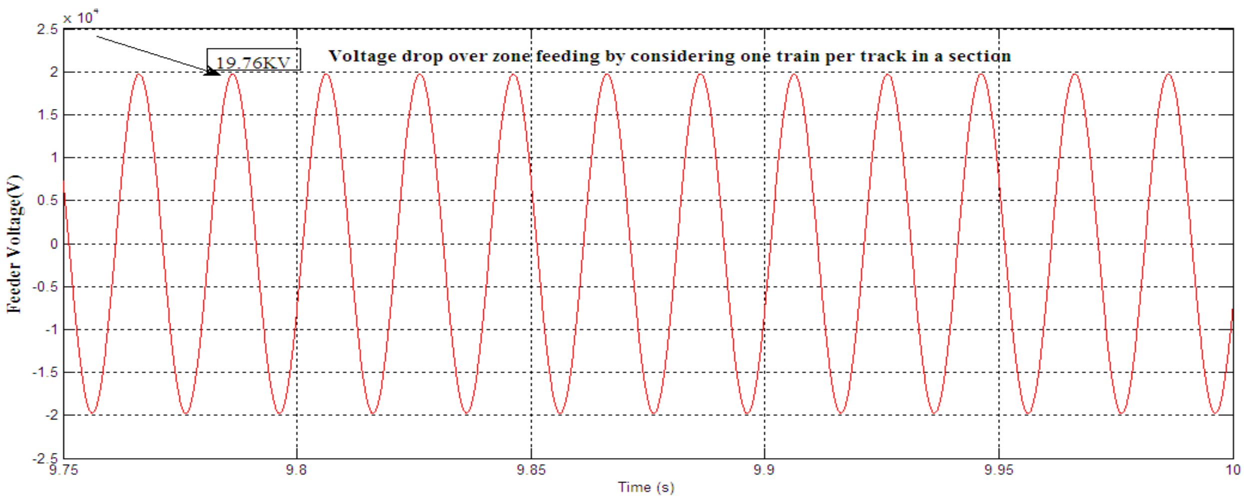

Figure 7.2 Simulation result over zone feeding operation.

$$\%V_R = \frac{25KV - 19.76KV}{19.76KV} * 100 = 26.51\%$$

7.2 Simulation results after Compensator is undertaken

7.2.1 Improving Voltage drop feeder side in a normal section operation

Table 7-0-1 Simulation Result in Normal Section Operation for Thyristor Firing α

s/no	Firing angle(α)	Receiving end voltage
1	180°	24.16KV
2	120°	24.16KV
3	90°	23.95KV
4	60°	24KV
5	30°	24.05KV

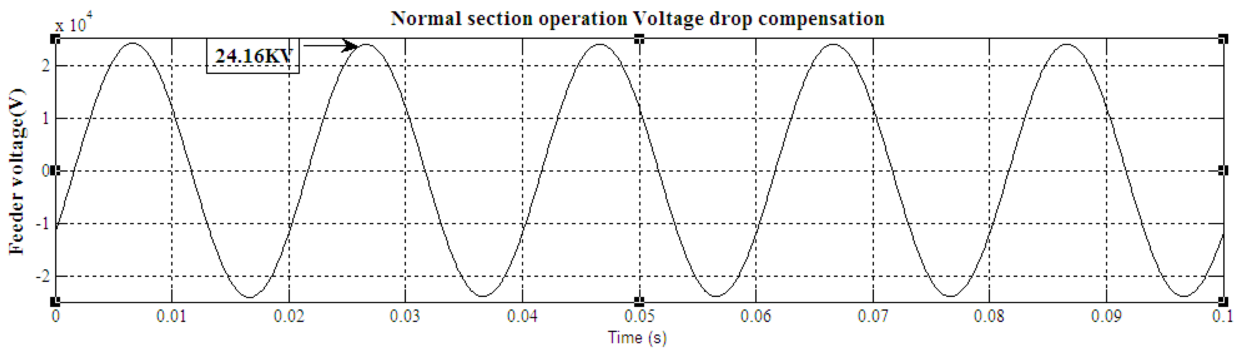

***Figure7.3 Simulation result normal section operation with compensator*.**

Output voltage

$$\%\text{age of voltage regulatiom} = \frac{V_S - V_R}{V_R} * 100$$

$$\%V_R = \frac{25KV - 24.16KV}{24.16KV} * 1000 = 3.48\%$$

7.2.2 Simulation of TCR (180 degree)

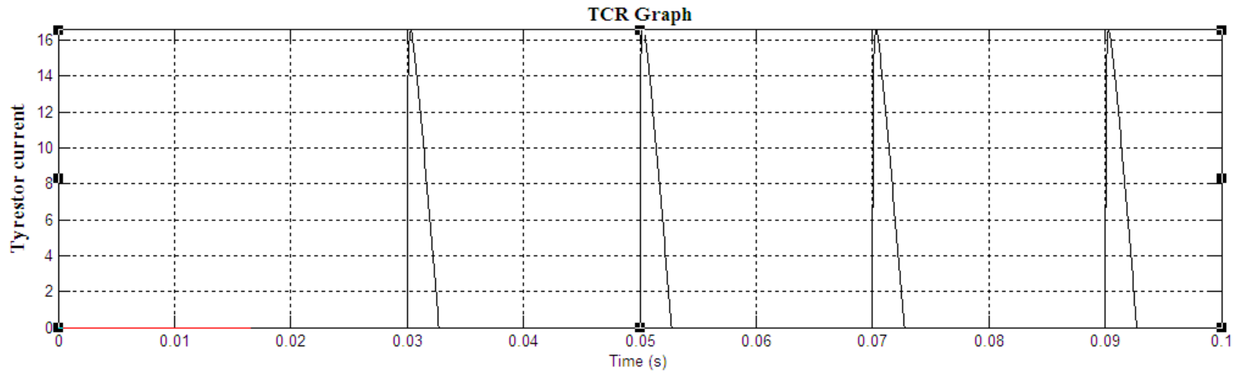

Figure 7.4 simulations TCR current

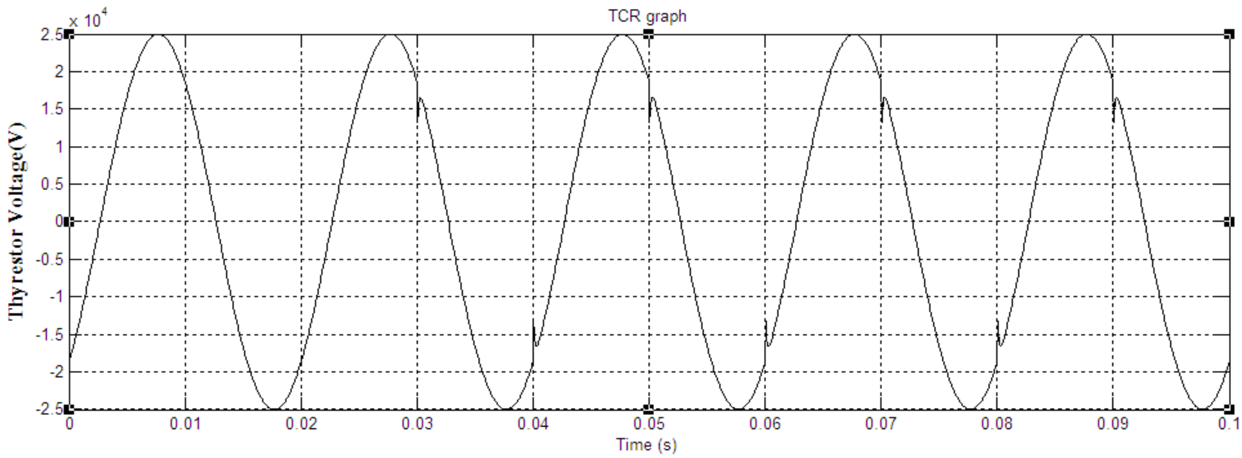

Figure 7.5 simulations TCR Voltage

7.2.3 Improved Voltage drop by placing compensator near to the load side in a normal section operation

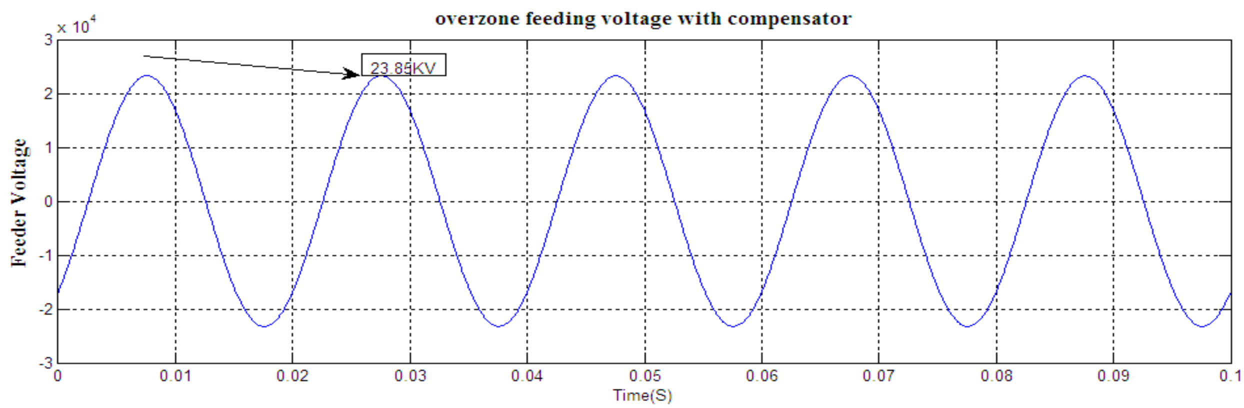

Figure 7.6 over zone feeding with compensator

Table 7-0-2 Simulation Result in Normal Section Operation for Thyrestor firing α

s/no	Firing angle(α)	Receiving end voltage
1	180°	23.85KV
3	90°	23.64KV
4	60°	23.86KV
5	30°	23.73KV

$$\%V_R = \frac{25KV - 23.85KV}{23.85KV} * 100 = 4.82\%$$

7.2.4 Section voltage drop between due to over zone feeding and parallel power supply without employing section paralleling near to a substation

Table 7-0-3 Simulation Result in Over Zone Feeding Operation for Thyristor Firing α

s/no	Firing angle(α)	Receiving end voltage
1	180°	23.25KV
3	90°	23.10KV
4	60°	23.5KV
5	30°	23.25KV

Minimum voltage regulation is

$$\%V_R = \frac{25KV - 23.25KV}{23.25KV} * 100 = 7.52\%$$

Maximum voltage regulation is

$$\%V_R = \frac{25KV - 23.1KV}{23.1KV} * 100 = 8.23\%$$

7.2.5 Section voltage drop due to over zone feeding and parallel power supply without employing section paralleling and placing compensator near the load side.

Minimum voltage regulation is

$$\%V_R = \frac{25KV - 23.25KV}{23.25KV} * 100 = 7.52\%$$

Table 7-0-4 Simulation Result Over zone Feeding Operation for Thyrestor firing α

s/no	Firing angle(α)	Receiving end voltage
1	180°	21.7kV
3	90°	23.10kV
4	60°	23.5kV
5	30°	23.25kV

The maximum voltage regulation is

$$\%V_R = \frac{25\text{KV} - 21.7\text{KV}}{21.7\text{KV}} * 100 = 15.21\%$$

7.3 Conclusion and discussion

This thesis is realized as per professional standard of the people's republic of china Design Code of Railway Electric Traction Feeding TBl 0009- 2005 that is to design voltage regulation for AC traction network. Therefore by compensating the above voltage drop taking the rated voltage of the electric locomotive and pantograph centenary is 25kV and maintaining the maximum voltage 28kV and the minimum operating voltage at 20kV.Under abnormal condition the operated voltage not less than 19kV as per standard of TB10009-2005 railway traction power supply design specification. Eventually, the power reliability of a traction network and the rail transportation become safe and efficient, having this design codes standard as a tool to evaluate different scenarios mentioned, that is for normal section operation and over zone feeding operation.

First of all, analysis of voltage drop has been done for normal section operation by taking in to consideration of one train per section in between Indode substations to Lebu section post, then the receiving end voltage is 20.25kVwith a maximum voltage drop of 4.7kV and with 14.46% of voltage regulation, as per standard mentioned above this much voltage drop is allowable. Therefore it is not as such bad scenario to design compensator but for reliability and safety purpose. It is susceptible for minimum supply voltage variation ,therefore this thesis recommend compensator, and when it is placed near substation then receiving end voltage is improved to 24.16kV with 3.48% of voltage regulation. But when the compensator is placed near the load, the receiving end voltage becomes 23.85kV with 4.82%of regulation.

Secondly, analysis of voltage drop has been done for over zone feeding operation for various cases by taking in to consideration two trains in section between Indode substations to Sebeta substation .Then receiving end voltage is become 17.13kV, a maximum voltage of 7.87kV and with 44.55% of regulation, as per standard mentioned above, this much voltage drop is not allowable it is bellow 19kV, which is the worst operation condition. For such operation condition it is crucial to design compensator to have reliable and safe railway transportation. Therefore, this thesis recommends voltage regulator (compensator) using Thyristor controlled series compensator and when it is placed near substation, then receiving end voltage improved to 23.25kV with 7.52% maximum Voltage regulation. But when the compensator is placed near the load, the receiving end voltage becomes 21.7kV with 15.21% of regulation.

7.4 Recommendation

In general, this thesis recommends that, it is crucial to design voltage regulator (compensator) for reliable and safe operation of railway transport. This sample selected section between Sebeta to Indode is the best representative for other sections between Sebeta to Adama because of its highest gradient and smallest section distance with higher energy consumption. Therefore compensator designed for this section is vital to other section by taking in to consideration feeder over voltage. In addition, we have to place the compensator near to the substation because of two reasons

(1.) Eliminate the catenary opening; easy maintenance and management other than place it on the catenary.

(2.) For a better percentage of voltage regulation as it is shown simulation above.

7.5 Future Work

Some suggestions for further works that can be used as input or idea to formulate new research in the traction system, it is better to implement voltage regulation for future railway transportation traffic by considering more than one train per section according to the signalling level advancement.

In this paper, the analysis is undertaken for double rail track, direct power supply with return line mode. It is good if we undertake analysis for single track from Adama to Mieso taking in to consideration different power supply mode for better voltage regulation.

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APPENDIX A: Simulation block without voltage regulator

Voltage drop at traction network in a normal section operation Indode to Lebu

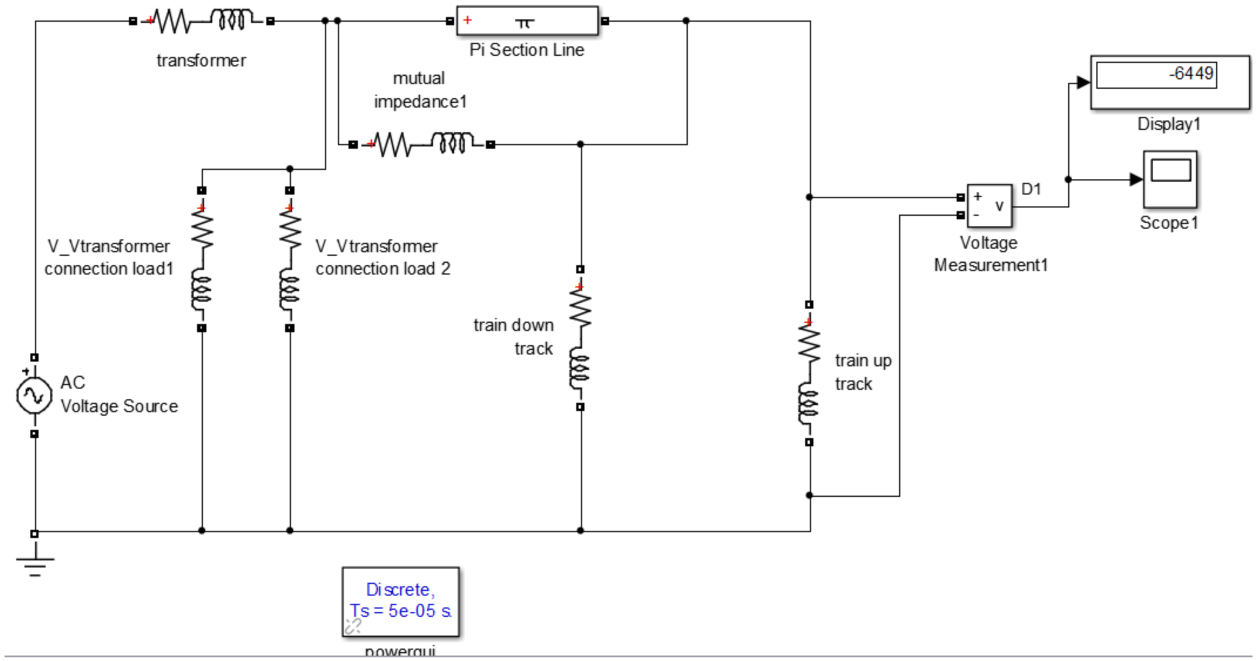


Figure A1. Voltage drop at a traction network in a normal section operation indode to Lebu

Voltage drop at traction network due to over zone feeding operation from Indode to Sebeta

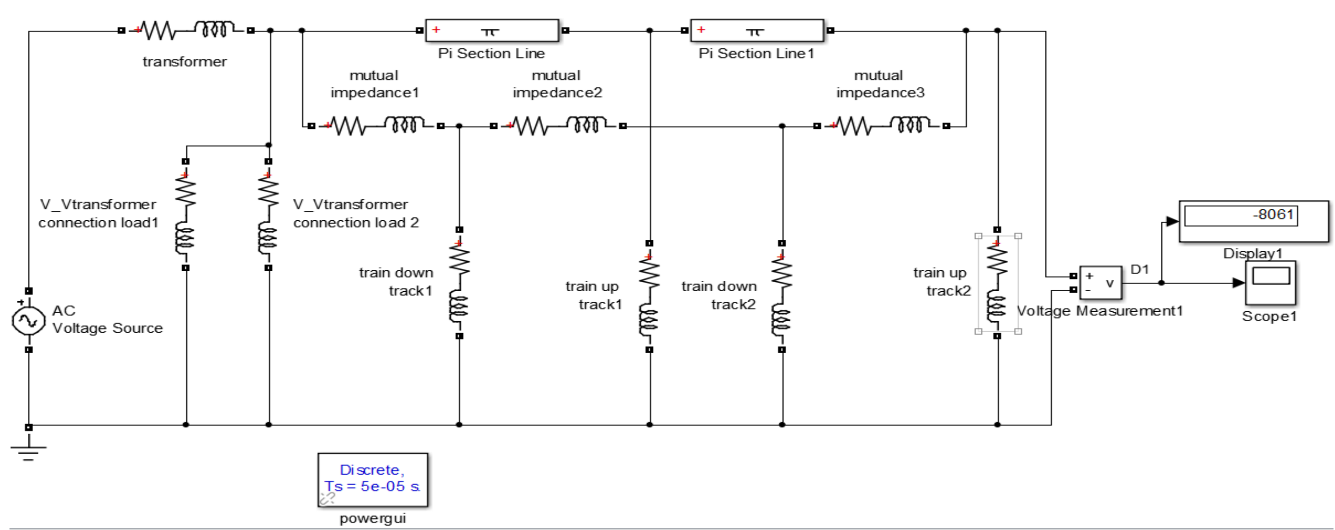


Figure A2.Voltage drop at traction network due to over zone feeding operation from Indode to Sebeta

Over zone feeding if at most one train is considered section between Indode to Sebeta

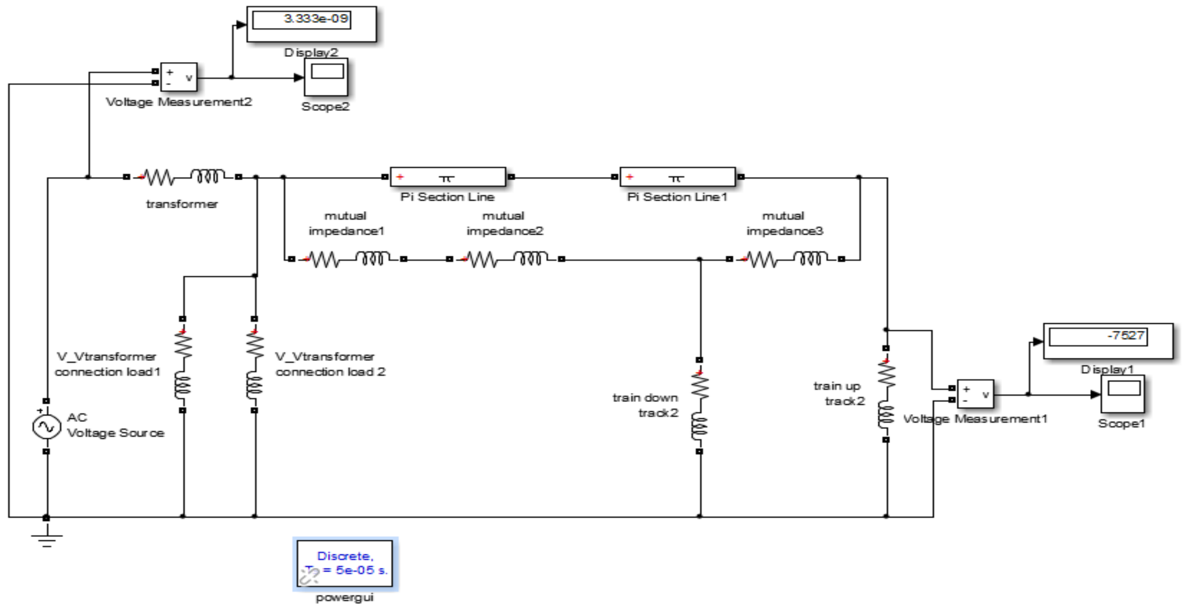
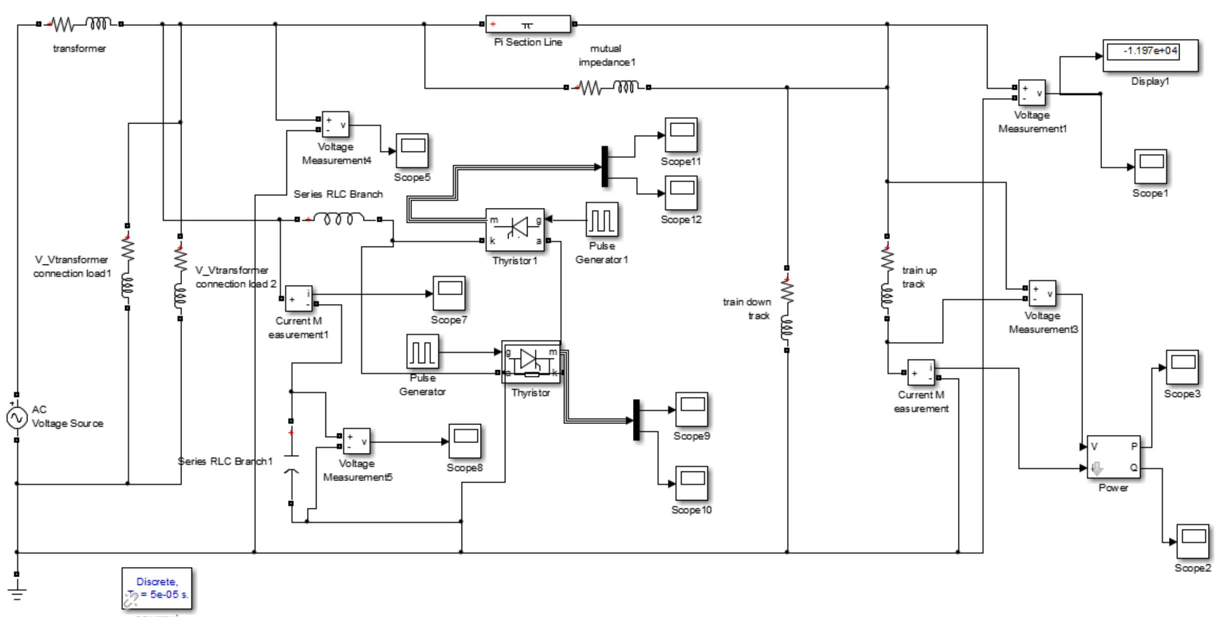


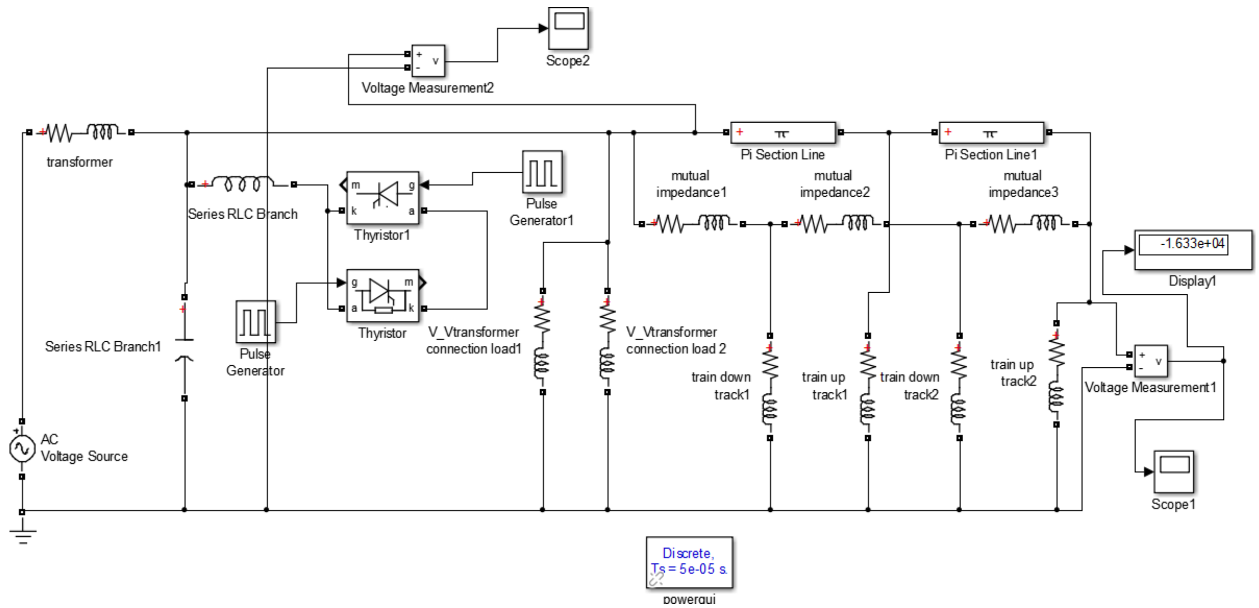
Figure A3.Over zone feeding, if at most one train is considered section between Indode to Sebeta

Voltage drop compensation at traction network in a normal section operation Indode to Lebu



FigureA4.Voltage drop compensation at traction network in a normal section operation Indode to Lebu

Compensated Voltage drop at traction network due to over zone feeding operation from Indode to Sebeta



FigureA5. Compensated Voltage drop at traction network due to over zone feeding operation from Indode to Sebeta

APPENDIX B: Power transformer parameters

The impedance module ZT can be calculated from the rated transformer data as follows:

$$ZT = \frac{Ukr\%\,V2n^{2}}{100 * Str}.$$

Where:

U_{rT} is the rated voltage of the transformer, on the high-voltage or low-voltage side.

S_{rT} is the rated apparent power of the transformer.

U_{kr} is the short-circuit voltage at rated current in percent.

The positive-sequence short-circuit resistance R_T of a two-winding transformer is given by the Relationship:

$$R_T = \frac{PkrT}{3 * I^{2}_{2n}}.$$

Where:

P_{krT} is the total loss of the transformer in the windings at rated current.

I_{rT} is the rated current of the transformer on the high-voltage or low-voltage side.

Note:

The resistance R_T is to be considered if the peak short-circuits current ip or the DC component I_{DC} is to be calculated.

For large transformers, the resistance is so small that the impedance is represented by the reactance only, when calculating short-circuit currents.

The positive-sequence short-circuits reactance X_T of a two-winding transformer results as follows: The positive-sequence short-circuit reactance XT of a two-winding transformer results as follows:

$$X_T = \sqrt{ZT^2 - RT^2}$$

[Short Circuit Analysis Program ANSI/IEC/IEEE &Protective Device Evaluation User's Guide]

APPENDIX C: voltage drop approximation [3]

Voltage drop is given by ΔV

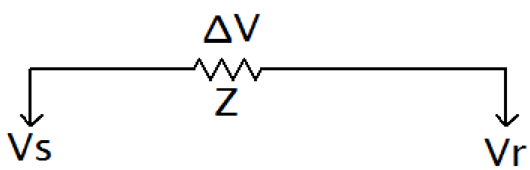
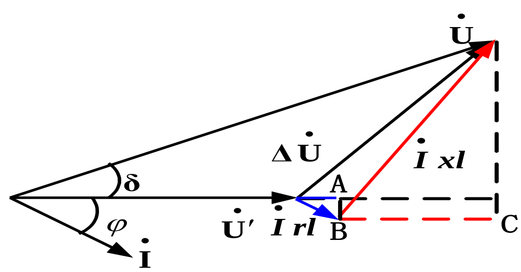


Figure C1.Voltage drop approximation



FigureC2.phasor representation of voltage drop

$$\Delta V = V_S - V_r$$

$$\Delta V \approx V_S \cos\delta - V_r$$

$$\Delta V = \text{Re}(\Delta V)$$

$$\Delta V = RI\cos\phi + XI\sin\phi$$

$$\Delta V = V_r \angle 0^\circ \ (R + jX)LI\angle - \varphi = RLI\angle - \varphi + jXLI\angle - \varphi = RLI\angle - \phi + XLI\angle 90 - \phi$$

$$\Delta V = \text{Re}(\Delta V) = (R\cos\phi + X\sin\phi)LI = Z^{'}LI$$

Appendix D: earthing used for railway

When l»d, the earthling resistance of upright earthling body can be calculated with the following formula:

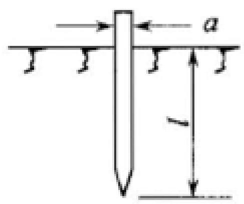
$$R = \frac{\rho}{2\prod l}\ln\frac{4l}{d}$$

Where--the the earthling resistance of upright grounding bodyCD);

p--the soil resistivity

l--the length of the upright earthling body

d- The diameter (m) of the round steel bar used as the earthling body. The equivalent diameter shall be calculated with the following formula when other profile-type steel is used (Figure C.O.1-2)



FigureD1. Up right earting body

Appendix E: IEC voltage factor

As per IEC 60909 the equivalent voltage source (rms) is given by the relations

IEC voltage factor

$$U_{es} = \frac{C * U_n}{\sqrt{3}}, V,$$

Nominal voltage U_n, V	Voltage factor *c* for the calculation of Minimum short-circuit currents, c_{min}	Maximum short-circuit currents, c_{max} 1)	Tolerance, %
Low voltage, $U_n \in [100,1000] kV$	0.95	1.05	6
		1.10	10
Medium voltage, $U_n \in (1,35] kV$ High voltage 2), $U_n > 35 kV$	1.00	1.10	-

APPENDIX F: The voltage drop of double-track traction network [3]

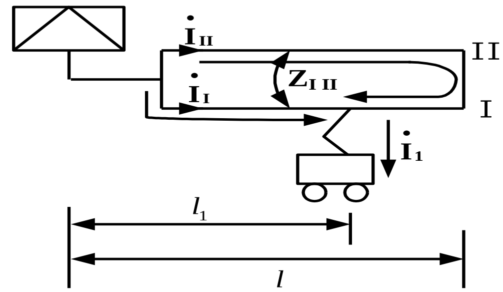
Current distribution principle of a double traction network

Known: double-track traction network

$$\text{self impedance} = Z_I = Z_{II} = Z \quad (\Omega/\text{km})$$

$$\text{mutual impedance} = Z_I = Z_{II} = Z_m \,\Omega/\text{km}$$

The voltage drop equation from substation to the locomotive



$$\text{short} - \text{loop} = \Delta V = Z * L_1 * \dot{I}_I + Z_m * L_1 * \dot{I}_{II}$$

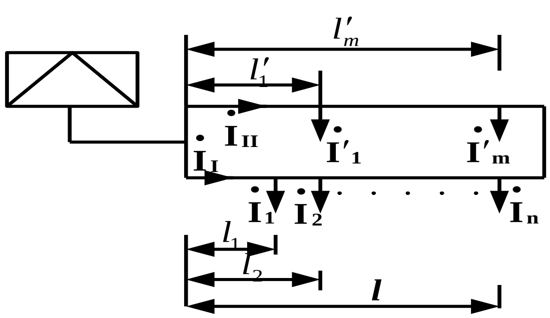
$$\text{long loop} = Z(2l - l_1)\dot{I}_{II} + Z_m \; l_1 \dot{I}_I - 2Z_m(l - l_1)\dot{I}_{II}$$

$$\dot{I}_1 = \dot{I}_I + \dot{I}_{II}$$

$$(Z - Z_m) l_1 \dot{I}_I = (Z - Z_m)(2l - l_1)\dot{I}_{II}$$

$$\text{Solution:} \begin{cases} \dot{I}_I = \dfrac{2l - l_1}{2l}\dot{I}_1 \\ \dot{I}_{II} = \dfrac{l_1}{2l}\dot{I}_1 \end{cases}$$

Traction network: The current of long loop Current distribution principle of double-track and short loop is inversely proportional to through path.



$$\dot{I}_I = \sum_{i=1}^{n} \frac{2l - l_i}{2l}\dot{I}_i + \sum_{j=1}^{m} \frac{l'_i}{2l}\dot{I}'_j$$

$$\dot{I}_{II} = \sum_{i=1}^{n} \frac{l_i}{2l}\dot{I}_i + \sum_{j=1}^{m} \frac{2l - l'_i}{2l}\dot{I}'_j$$

Appendix G: feeder current numerical characteristics [3]

- Traction probability

$$p_F = \frac{T_g}{T} \quad \text{……………………..}$$

No-load probability

$$p_0 = 1 - p_F$$

- Traction average current

$$I_g \triangleq \frac{1}{T_g}\int_0^T i_F dt$$

Traction effective current

$$I_{\varepsilon g} \triangleq \sqrt{\frac{1}{T_g}\int_0^T i_F^2 dt}$$

- Daily average current

$$I \triangleq \frac{1}{T}\int_0^T i_F dt$$

Daily effective current

$$I_\varepsilon \triangleq \sqrt{\frac{1}{T}\int_0^T i_F^2 dt}$$

$$I_\varepsilon^2 T = I_{\varepsilon g}^2 T_g = \int_0^T i_F^2 dt$$

$$I_{\varepsilon g} = \frac{I_\varepsilon}{\sqrt{1-p_0}}$$

- Daily effective coefficient, traction effective coefficient

$$k_\varepsilon = \frac{I_\varepsilon}{I} \qquad k_{\varepsilon g} = \frac{I_{\varepsilon g}}{I_g} \Longrightarrow k_\varepsilon = \frac{k_{\varepsilon g}}{\sqrt{1-p_0}}$$

$$k_{\varepsilon g} = 1.04 \sim 1.08 \quad k_{\varepsilon g} = 1.10 \quad p_0 = 0.2 \sim 0.5 \quad k_\varepsilon = 1.23 \sim 1.41$$

Traction aaverage current in feeding section

$$I_g = \frac{60 * A}{t_g U} + 7A$$

Where 7A—Self-electricity for locomotive

A—The total energy consumption when train travel through feeding section kVA.h

V_{2n}, Traction network voltage 25kV

t_g— The traction running time of the train, minutes

- Train effective current under traction running time

$$I_{eg} = \sqrt{\frac{1}{t_g}\int_0^{t_g} i^2 dt} = K_{eg} I_g$$

if $I_{eg} = K_{eg} * I_g$, so K_{eg} is train effective current coeffecient, Generally $K_{eg} = 1.03 \approx 1.05$

Usually $K_{eg} = 1.04, K^2_{eg} = 1.08$

Feeding section segment n

Train density N — daily train operation number (pairs)

t_g -Train traction running time when travelling through a feeding section

A -Train energy consumption when travelling thr

$$I_1 = I_2 = ...I_n = Ig \quad , \qquad t_{g1} = t_{g2} = ...t_{gn} = \frac{t_g}{n}$$

$$I_g = \frac{60 * A}{t_g U} + 7A \quad i = 1.2......n$$

Feeder current daily average value

$$I_F = i_1 + i_2 + i_3 + ...i_n = \sum_{k=1}^{n} i_k$$

$$I_F = \frac{1}{T}\int_0^T i_k dt$$

$$I_F = \sum_{k=1}^{n} \left(\frac{2Nt_{gk}}{T} \frac{1}{2Nt_{gk}} \int_0^{2Nt_{gk}} i_k \, dt\right)$$

$$I_F = \sum_{k=1}^{n} p_k I_k$$

$$P_k = p = \frac{2Nt_g}{nT} \text{ traction probablity for section}$$

$$I_F = npI_g = \frac{2Nt_g}{T} I_g$$

Feeder current effective value

$$I_{FE} = \sqrt{\frac{1}{T}\int_0^T i_F{}^2 dt}$$

$$i_F{}^2 = (i_1 + i_1 + i_1.................i_n)(i_1 + i_1 + i_1.................i_n)$$

$$\sum_{k=1}^{n} i_K{}^2 + \sum_{k=1}^{n} \sum_{l \neq k}^{n} i_k i_l$$

$$\overline{i_k{}^2} = \frac{1}{T}\int_0^{2Nt_{gk}} i_k{}^2 dt = \frac{2Nt_{gk}}{T} \frac{1}{2Nt_{gk}} \int_0^{2Nt_{gk}} i_k{}^2 dt = p_k I_{egk}{}^2$$

$$\overline{i_k i_l} = \frac{1}{T}\int_0^{2Nt_{gk}} i_k \, dt \frac{1}{T}\int_0^{2Nt_{gk}} i_l \, dt = p_k I_{gk} p_l I_{gl}$$

$$i_F^2 = \sum_{k=1}^{n} i_k^2 + \sum_{k=1}^{n-1}\sum_{l \neq k}^{n} i_k i_l \qquad \overline{i_k^2} = p_K I_{egk}^2 \qquad \overline{i_k}\,\overline{i_l} = p_k I_{gk} p_l I_{gl}$$

$$\overline{i_F^2} = npI^2_{eg} + n(n-1)p^2 I_g^2 \qquad I_{eg} = K_{eg} I_g$$

$$\overline{i_F^2} = npK^2_{eg} I^2_g + n(n-1)p^2 I^2_g$$

$$= (npI_g)^2 [1 + \frac{K^2_{eg} - p}{np}] \qquad I_F = npI_g$$

$$= I^2_F [1 + \frac{K^2_{eg} - P}{np}]$$

$$I_{FE} = I_F \sqrt{1 + \frac{K_{eg} - p}{np}} \qquad K_{eF} = \sqrt{1 + \frac{K_{eg} - p}{np}}$$

Feeder of double track unilateral power

Feeder daily average current (same as Single track)

$$I_F = npI_g = \frac{2Nt_g}{T} I_g$$

Feeder daily effective current Double track feeder effective current

- ❖ Feeder daily effective current Double track feeder effective current formula is same as the single track, but not the same value of n.
- ❖ At double traction situation, n is represented as the largest number of train (under traction operation) which appeared at the feeding sections up and down direction.

$$I_{FE} = I_F \sqrt{1 + \frac{K^2_{eg} - p}{np}}$$

Appendix: H system simulation parameters

Table H.1 Simulation parameters Normal section operation

Parameters	
Feeder voltage	25KV
Transformer	R=,0.52046,L= 0.023194604H
Catenarry Mutual impedance	R= 0.9272344,L= 9.2882828e-7H,
Line impedance indone-Lebu	R=0.130081,L=1.2489e-3 H,C=11e-12F ,l=18.808km
Train down track Active power	10.292e6
Reactive power	1.695127e6
Feeder current	217.524A
Train up track Active power	10.292e6
Reactive power	1.695127e6
V-V transformer connection load	
Feeder current	184.034A
Active power	10.292e6
Reactive power	1.435496e6
System Nominal frequency	50HZ

TableH.2 Simulation parameters over zone operation

Parameters	
Feeder voltage	25KV
Transformer impedance	R= 0.52046,L= 0.023194604H
Catenarry Mutual impedance	R=0.6536687,L=1.231533374e-5H
Line impedance indode-Lebu	R=0.130081,L=1.2489e-3 H,C=11e-12F ,l=18.808km
Lebu-sebeta	R=0.130081,L=1.2489e-3 H,C=11e-12F,l=13.259km
Train down track1 Active power	10.292e6
Reactive power	1.695127e6
Feeder current	217.524A
Train up track 1 Active power	10.292e6
Reactive power	1.695127e6
V-V transformer connection load	
Feeder current	184.034A
Active power	10.292e6
Reactive power	1.435496e6
System Nominal frequency	50HZ