ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING FOR RAILWAY

COMPENSATION OF REACTIVE POWER BY STATIC VAR COMPENSATOR IN CASE OF SEBETA-DEWELE

BY
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THESIS SUBMITTED TO ADDIS ABABA INSTITUTE OF TECHNOLOGY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE
IN
ELECTRICAL ENGINEERING FOR RAILWAY

ADVISOR:
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MARCH, 2015

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Declaration

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

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Mr. Getu Gabisa ___________________________________

Advisor's Name Signature

Acknowledgement

Foremost, I would like to express my sincere gratitude and appreciation to my advisor, Getu gabisa, for his support, patience, and encouragement throughout my thesis. His technical and editorial advice was essential to the completion of this research. He is not only my supervisor but also encouraged and challenged me throughout my academic researches.

My thanks also go to kiros for his valuable comments and suggestions.

Furthermore, I would like to thank all members of the institute for contributing to such an inspiring and pleasant atmosphere.

Finally, I would like to acknowledge the ERC for giving me the opportunity to pursue my second degree in Addis Ababa University.

Abstract

With increasing focus on economic as well as environmentally friendly means for mass transit, electric rail transport is getting renewed momentum in Ethiopia. The feeding of heavy rolling stock from AC grids cause unacceptable voltage drops, high reactive current, low power factor and asymmetry between phases of the feeding grid. The reactive current raises the dissipation of power in the network and depresses the power supply capability of supply network.

The aim of this thesis is to design and simulate static Var compensator connected in shunt that offers means of remedy to these problems. Static var compensator (SVC) is basically a shunt connected static var generator whose output is adjusted to exchange capacitive or inductive current so as to maintain or control power variables.

The modeling of Sebeta-Dewele power network is done and simulated with and without applying reactive power compensation.

A power flow analysis is done to determine the placement of the compensator. A compensator is installed at Wachulalu, Haro and Meiso. The reactive power loss is minimized, and the terminal voltage is kept 0.975 pu after compensation is done. The rest of traction substations don't require a compensator.

A PI controller is used to control the firing angle of thyrstor control reactor of the static Var compensator and achieve better and smooth control of reactive power.

A Matlab Simulink is used to simulate the system. The power flow is done by using newton raphson iterative method on powerworld simulating software.

Key word: Sebeta-Dewele railway; Power flow; Static Var compensator; PI controller; power factor

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LIST OF ABBREVIATIONS AND SYMBOLS

A: Amperes
ac: Alternating current
ANSI: American National Standards Institute
BT Booster Transformer
C: Catenary
DC: Direct current
EPRI: Electric Power Research Institute
F Feeder wire
FACT flexible AC transmission
FC fixed capacitor
H: Henry
Hz: Hertz; cycles per second
I Current
IEC International Electro technical Commission
IEEE Institute of Electrical and Electronics Engineers
L Inductance

ms	Millisecond
MPTSC	Mid-Point Track-Sectioning Cabin
MW	Mega watt
MVA:	Mega volt ampere
MVar Mega	Volt-Ampere Reactive
NA	Total number of additional equipment in the system
NR, NRPFM	Newton-Raphson and Newton-Raphson Power Flow Method
OCCW	Overhead Catenary Contact Wire
P:	Active power
PCC:	Point of common coupling
PF, pf:	Power factor
PFC:	Power factor corrector
PQ:	Power quality
PWD	Powerworld simulator
Ps	active power at supply
pu:	Per unit
R	Rails
RC	Return conductor
Q	Reactive power
Q	reactive power at supply
rms	Root-mean-square (effective value)
SVC	Static Var Compensator
TCR	Thyristor-controlled Reactor
TCSC	Thyristor-controlled Series Compensator
TR	Train
Tx	Feeder section (Transmission line)
UPF	Unity Power Factor
UPFC	Unified Power Flow Controller
Vgrid	Nominal voltage of the utility supply grid
Vi	Voltage vector at bus i
VSS	Thevenin voltage of the substation

Chapter 1
Introduction

1.1 Background

Now a day, electrified railways are under expansion to different regions of Ethiopia. An issue such as increase mass transit over long distance brings to attention alternative way of transport. Sebeta-Dewele AC- railway which covers 670.7km will provide new transportation way for Addis Abeba-Adama-Dire Dawa-Djibouti route [1]. The AC railway systems generate various power quality problems that have impact on its distribution network and show typically poor power quality due to their inherent electrical load characteristics. The moving and non-linear load characteristics of the locomotives consume the large reactive power so that the total power factor becomes adversely affected [2, 3].

Traction load takes high reactive current and have serious impact on themselves as well as on the public grid [4]. Traction load and other connected equipment cause a phase angle between current and voltage. When the current is phase-shifted, it takes more current to deliver the same amount of active power.

The aim of this paper is to design and simulate static var compensator that helps to improve performance of traction network installations through energy savings and bring economic benefits. AC railway power flows are modeled and the results are used to achieve the system objective via PI controller to control the firing angle of thyristor control reactor. The system voltage profile and the total power losses is improved.

The voltage drop affects the performance of electric railway network. The maintenance of a minimum voltage level, so that the trains can operate normally, involves a limit in the maximum length of the feeder, and consequently to the distance between feeding substations. In this research a shunt compensation approach has been studied, based on the application of thyristor control reactor. They are cheaper devices that allow achieving suitable results in the reactive power compensation for electrified railway systems. In the case of compensating the voltage drop, it is more effective to locate the SVC at a sectioning post than at a substation. [7]

This research focus on designing of static var compensator to compensate the reactive power of sebeta-dewele electric traction power network and give good line of regulation at desired voltage rating while the traction load is under variation. The modeling is done to static Var compensator and regulating circuits. PI controller is used to control the gate signal of Thyristor control reactor where the purpose is to produce or absorb reactive power to/from the feeding line. Power flow modeling is made to traction substation, catenary feeder, train and static var compensator. Simulation is done in Matlab Simulink at different load with and without compensation.

1.2 Statement of the Problem

To ensure the stability of the railway system, regarding power quality and voltage level, the reactive power level of the railway network should be compensated. Reactive current cause to increases the dissipation of power network and decreases the power supply capability of transformer in traction substation and leads to addition of investment cost. This is due to the heavy dynamic traction load and equipment connected in the train. One solution is to use an external reactive power compensation which is done by static Var compensator.

1.3 Motivation

The motivation of this thesis is to supply reliable, efficient and economic power supply to the train by designing appropriate SVC. The train load is inductive load that takes high amount of reactive power, and installation spacing is large there is unacceptable voltage drop. Since ac electric railway of sebeta-dewele is not equipped with reactive power compensation devices, the network is suffered by power quality problems. The variation of pantograph voltage causes the electric railway power system equipment to be out of use and depressed.

1.4 Objective

1.4.1 General objective

- To compensate reactive power by designing appropriate static Var compensator for Sebeta-Dewele ac power network.

1.4.2 Specific objective

- To reduce the reactive current present in ac electric traction network
- To model and simulate Sebeta-Dewele ac railway power
- To keep catenary voltage at rated value under changing load conditions.
- To design PI controller

1.5 Scope of the project

In this research the focus is to compensate the reactive power of sebeta-dewele electric traction power network by using static Var compensator and give good line of regulation at desired voltage rating while the traction load is under variation. The modeling is done to static Var compensator and regulating circuits. PI controller is used to control the firing anglel of thyristor control reactor. Simulation will be done in Matlab Simulink.

1.6 Significance of the thesis

- Minimize the payment for the energy consumption
- Reduce investment cost
- Ensure the power demand in the public grid by energy saving
- Ensure the security of electric railway power system

1.7 Literature review

Electric traction systems generate various power quality problems that have an impact on its distribution network. There are a lot of literatures to give the remedy to these problems occurred in electric traction network. Many researchers tried to solve the problem caused by electric traction loads and uses different techniques to give the remedies.

Optimizing the Location and Size of SVC to Compensate the Railway's Voltage Drop and a Novel Approach for Controlling SVC. In this paper, the location and size of SVC over the main line of the railway was optimized using PSO. Also, a novel approach for controlling the SVC was proposed. The proposed method unlike the conventional method is able to regulate the voltage in all locomotive connection points to the railway line. It was shown that with the proposed method, only one SVC is enough for a railway with length equal to 75 km. The simulation results showed the satisfying performance of the proposed method for compensating the voltage drop in the railway feeders. [2]

Reactive power compensation using power electronics, in this research he investigated the various fact device and he come up with the best compensator for ac railway that is the shunt compensator. It gives a good line of regulation of the power transfer capability. SVC is a very good compensator for dynamic heavy electrical loads. [5]

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optimising ac electric railway power flows with power electronic control.In this thesis, AC railway power flows are optimised in real time and the results are used to achieve some particular system objective via control of the PWM equipment as mobile reactive power compensators. The system voltage profile and the total power losses was improved while the overall power factor at the feeder substation is also made nearer to unity.[6]

Investigation of Power Factor Behavior in AC Railway System Based on Special Traction Transformers.In this paper, the detailed characteristic of the power factor behavior has been simulated and analyzed. To evaluate the power factor behavior for a variety of appli-cations, five special traction transformers (i.e. single- phase, V/V, Wye-Delta, Scott, and Le Blanc) have been compared in detail, and its effects on the utility grid have been investigated. Simulation results are different due to the unbalance loading and asymmetry in transformer structures. Using the single-phase transformer culminates in the most trouble unbalance circumstances. Within the scope of three phase transformers, the V/V and Wye-Delta im-pose undesired imbalances on the utility grid compared to other connections. Having changed unbalance index from zero (complete balance state) to 100 percent, the PFe and PFA are considerably affected assuming fixed active and reactive powers, while more stability is observed in PFV and PF1 definitions and they demonstrate less failure subject to asymmetric loading in both sides of traction substation. [7]

Power Compensation in Transmission Line by Using Online Static Var Comensator with Fuzzy Control Method. This paper presents an "online fuzzy control scheme for SVC" and it can be concluded that the use of fuzzy controlled SVC (FC-TCR) compensating device with the firing angle control is continuous, effective and it is a simplest way of controlling the reactive power of transmission line. It is observed that SVC device was able to compensate both over and under voltages. The use of fuzzy logic has facilitated the closed loop control of system, by designing a set of rules, which decides the firing angle given to SVC to attain the required voltage. With MATLAB simulations and actual testing it is observed that SVC (FC-TCR) provides an effective reactive power control irrespective of load variations. The transmission line without any compensation was not satisfying the essential condition of maintaining the voltage within the reasonable limits. The effect of increasing load was to reduce the voltage level at the load end. At light loads, the load voltage is greater than the sending end voltage as the reactive power generated is greater than absorbed. At higher loads the load voltage drops, as the reactive power absorbed is greater than generated.[8]

Compensation Strategies of Railway Power Conditioner for Railway Traction Power Supply System this works shows new railway negative unbalanced load system based on multiple RPC compensation with using Proportional Integral Derivative (PID) to reduce the high compensator capacity and simulated in Matlab Simulink and results are compared with the reference Paper [PI Controller] and PID Controller and the Total Harmonic Distraction (THD) with three different cycles values are observed in the given table to make unbalanced conduction to balanced conduction ,when the breaker is operated is at 0.5sec to reduce the Complex Power, High Negative Sequence Component including Harmonics and Power Factor with PID controller .[9]

Reactive Power Compensation Technologies, Stateof-the-Art Review (Invited Paper). This paper presents an overview of the state of the art in reactive power compensation technologies. The principles of operation, design characteristics and application examples of VAR compensators implemented with thyristors and self- commutated converters are presented. Static VAR Generators are used to improve voltage regulation, stability, and power factor in ac transmission and distribution systems. Examples obtained from relevant applications describing the use of reactive power compensators implemented with new static VAR technologies are also described.[10]

Using Smart Devices To Provide Distributed Reactive Power Support This paper has discussed the use of smart devices for distributed reactive voltage support. The sensing and processing required is within the capability of target systems and in many cases, devices could continue operating normally without inconveniencing the user. This presents new possibilities to supply reactive power, both duringactive and standby modes. Although several control schemes can be remotely implemented, communication, security and consumer confidence still remain a challenge. Cost and robustness of such energy storage and auxiliary technologies would be a major driver in the consumer's willingness to opt in or out of such schemes. Distributed voltage support has the potential to transform the electric grid, empowering the industry to expand its capability of emergency response measures for maintaining stability.[11]

FACTS Powerful Means for Dynamic Load Balancing and Voltage Support of AC Traction Feeders. The paper treats dynamic load balancing of grids supplying power to rail transport, as well as dynamic voltage support, by means of Thyristor-controlled Var Compensation (SVC) as well as Voltage Source Converters (VSC). The feeding of heavy rolling stock from AC grids will in many cases cause unacceptable voltage drops as well as unsymmetry between phases of the feeding grid. FACTS devices offer means of remedy, restoring grid symmetry as well as voltage stability.[12]

The literatures state the dynamic properties of AC railway system and uses different technique to compensate the reactive power produced. In this research I will design and simulate the AC railway network, Sebeta-Dewele which is the first electric railway expansion in Ethiopia using static var compensator which is more robust, easy to apply and economically.

1.8 Methodology

Reading literature relevant to ac electric railway is first done. The necessary data for the Sebeta-Dewele electric traction network will be collected and the collected data will be analyzed to model the whole system in Matlab Simulink and bring mathematical expression with variation of any parameter within the system. Simulate the system by varying the load since the railway electric traction load is dynamic. Then identify the feeder that has voltage variation and poor power factor. Make appropriate design of static var compensator by using thyristor control reactor. The thyristor control reactor firing circuit receives signal from PI controller and then static var compensator gives/absorb reactive power to the line feeder for achieving desired voltage and power factor. After obtaining the complete model of static var compensator, the model is simulated using MATLAB (SIMULINK).The simulation of Sebeta-Dewele ac railway power network is done. The power flow problem is done using Newton Raphson using power world simulator.

1.9 Outlines of the thesis

This research thesis is organized as follows:

Following the Introduction, in Chapter 2, the FACTS modeling and compensation techniques are discussed. SVC for compensation of reactive power and the various commonly used FACTS devices are also introduced in this chapter.

In Chapter 3, AC Railway power supply and mathematical modeling of electric railway power system components is discussed. Furthermore, the per unit system and svc design is done.

In Chapter 4, the power flow calculation of ac railway is introduced. The Newton Raphson iterative is discussed. In addition, the one line diagram of electric railway power system and power flow solution is introduced.

In Chapter 5, the simulation result and analysis is presented.

Finally, in Chapter 6, the conclusions and recommendation of this research work can be found. Moreover, some suggestions on the extensions to potential topics for future research are presented.

CHAPTER 2
FACTS DEVICES AND COMPENSATION TECHNIQUES

2.1 Introduction

With the rapid development of power electronics, Flexible AC Transmission Systems (FACTS) devices have been proposed and implemented in power systems. FACTS devices can be utilized to control power flow and enhance system stability. Particularly with the deregulation of the electricity market, there is an increasing interest in using FACTS devices in the operation and control of power systems with new loading and power flow conditions. A better utilization of the existing power systems to increase their capacities and controllability by installing FACTS devices becomes imperative.

In order to improve the power system stability and to solve the reactive power planning problem, flexible alternating current transmission systems (FACTS) are widely used by power system utilities [7-9]. The main role of FACTS devices is to control the network condition in a very fast manner, the transmission voltage and power flow. Accordingly, FACTS controllers can be used to improve the power system stability and to solve the reactive power planning problem. Static var compensator (SVC) is one of the important FACTS devices which is a shunt component that can control the power flow of reactive power through the network and maintain the bus voltage in power system by changing its susceptance characteristic from inductive to capacitive [14-17].

2.2 FACTS categories and their functions

In general, FACTS devices can be divided into four categories [11,12]:

2.2.1 Series FACTS devices:

Series FACTS devices could be variable impedance, such as capacitor, reactor, etc., or a power electronics based variable source of main frequency, sub synchronous and harmonic frequencies (or a combination) to serve the desired need. In principle, all series FACTS devices inject voltage in series with the transmission line. Typical series compensators use capacitors to reduce the equivalent reactance of a power line at rated frequency, thus increasing the voltage at the load terminals.

The connection of a series compensator generates reactive power that, in a self-regulated manner, balances a fraction of the line's reactance.

2.2.2 Series Compensation Principles

Like shunt compensation, series compensation may also be implemented with current- or voltage-source converters. In this type of compensation, the compensator injects a voltage in series with the load, eliminating voltage unbalance at the load terminals, and supplying the voltage component required to operate with rated, balanced, and constant value.

Figure 2 shows a radial power system, with the reference angle in V_2, and the results obtained with the series compensation using a voltage source, which has been adjusted to have unity power factor operation at V_2. However, the compensation strategy is different when compared with shunt compensation. In this case, the voltage V_{COMP} has been added between the line and the load to change the angle of V_2, which becomes the voltage at the load terminals. With the appropriate magnitude and phase-shift adjustment of V_{COMP}, unit y power factor can be reached at V_2. As can be seen from the phasor diagram of Fig. 2b, V_{COMP} generates a voltage phasor with opposite direction to the voltage drop in the line inductance. In this type of compensation, the load current cannot be changed, which means that the compensator voltage must be adjusted to reach the required voltage at the load terminals. Moreover, the amount of apparent power interchanged with the series compensator in this case depends on the V_{COMP} phase and magnitude. Real and reactive power can be generated from the series compensator, depending on the load and the system requirements. In most cases, series compensation is used to control voltage at the load terminal, so that only reactive power needs to be exchanged. In this case, series capacitors represent a good alternative.

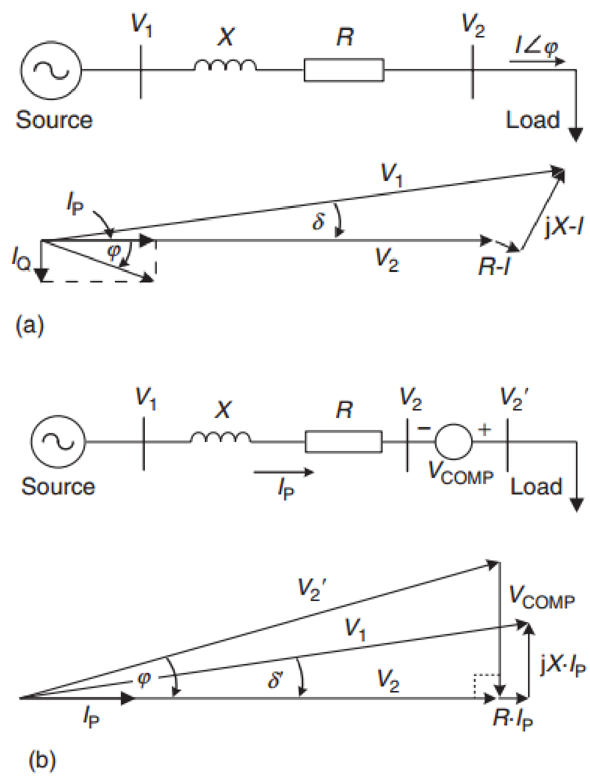


Figure 1 Principles of series compensation. (a) The radial system without compensation. (b) Series compensation with a voltage source.

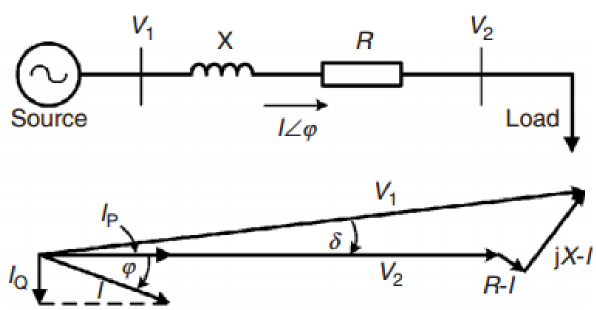
2.2.3 Shunt FACTS devices:

Shunt FACTS devices may be variable impedance, variable source, or a combination of these. They inject current into the system at the point of connection.

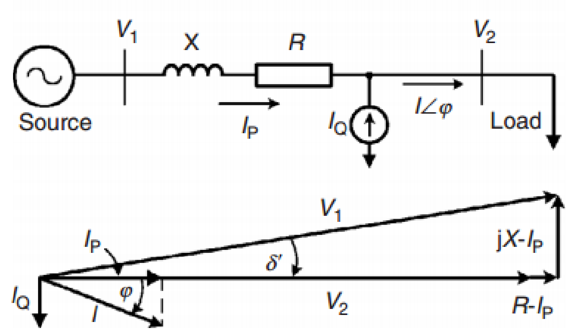
Shunt compensation is used basically to control the amount of reactive power that flows through the power system. In a linear circuit, the reactive power is defined as the ac component of the instantaneous power, with a frequency equal to 100/120 Hz in a 50 or 60 Hz system. The reactive power generated by the ac power source is stored in a capacitor or a reactor during a quarter of a cycle, and in the next quarter cycle is sent back to the power source. The reactive power oscillates between the ac source and the capacitor or reactor, and also between them, at a frequency equal to two times the rated value (50 or 60 Hz). For this reason it can be compensated using static equipment's or VAR generators, avoiding its circulation between the load (inductive or capacitive) and the source, and therefore improving voltage regulation and stability of the power system. Reactive power compensation can be implemented with VAR generators connected in parallel or in series [11].

2.2.4 Shunt Compensation Principles

Figure 4 shows the principles and theoretical effects of shunt reactive power compensation in a basic ac system, which comprises a source V1, a transmission line, and a typical inductive load. Figure 4a shows the system without compensation, and its associated phasor diagram. In the phasor diagram, the phase angle of the current has been related to the load side, which means that the active current I_P is in phase with the load voltage V2 Since the load is assumed inductive, it requires reactive power for proper operation, which must be supplied by the source, increasing the current flow from the generator and through the lines. If reactive power is supplied near the load, the line current is minimized, reducing power losses and improving voltage regulation at the load terminals. This can be done with a capacitor, with a voltage source, or with a current source. In Fig. 3b, a current-source device is being used to compensate the reactive component of the load current (IQ). As a result, the system voltage regulation is improved and the reactive current component from the source is almost eliminated.



(a)



(b)

Figure 2 Principles of shunt compensation in a radial ac system. (a) System phasor diagram without reactive compensation. (b) Shunt compensation of the system with a current source.

A current source or a voltage source can be used for reactive shunt compensation. The main advantages of using voltage- or current-source VAR generators (instead of inductors or capacitors) are that the reactive power generated is independent of the voltage at the point of connection and can be adjusted in a wide range.[15]

Since shunt compensation is able to change the power flow in the system by varying the value of the applied shunt equivalent impedance, changing the reactive power flow in the system, during and following dynamic disturbances, the transient stability limit can be increased and effective power oscillation damping can be provided. Thereby, the voltage of the transmission line counteracts the accelerating swings of the disturbed machine and therefore damps the power oscillations.

Independent of the source type or system configuration, different requirements have to be taken into consideration for a successful operation of shunt compensators. Some of these requirements are simplicity, controllability, time response, cost, reliability, and harmonic distortion.

2.2.5 Combined series-series FACTS device:

Combined series-series FACTS device is a combination of separate series FACTS devices, which are controlled in a coordinated manner.

2.2.6 Combined series-shunt FACTS device:

Combined series-shunt FACTS device is a combination of separate shunt and series devices, which are controlled in a coordinated manner or one device with series and shunt elements.

TCSC (Thyristor Controlled Series Capacitor): TCSC is a typical series FACTS device that is used to vary the reactance of the transmission line. Since TCSC works through the transmission system directly, it is much more effective than the shunt FACTS devices in the application of power flow control and power system oscillation damping control [11, 12].

Static Var Compensator (SVC)

SVC is a shunt FACTS device that can be used to control the reactive compensation. According to the IEEE definition, a Static Var Compensator (SVC) is a shunt connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current to maintain or control specific parameters of the electrical power system [1].

Typical SVCs can be classified on Thyristor-Controlled Reactor (TCR), Thyristor-Switched Reactor (TSR) or Thyristor-switched capacitors (TSCs). Figure8 shows a TCR single-phase equivalent circuit in which the shunt reactor is dynamically controlled from a minimum value (practically zero) to a maximum value by means of conduction control of the by-directional thyristor valves. By this controlled action the SVC can be seen as a variable shunt reactance established by the parallel connection of the shunt capacitive reactance XC and the effective inductive reactance XL controlled by the thyristor switching.

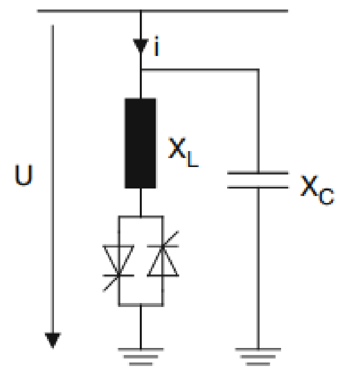


Figure 3 Single-phase equivalent circuit of the shunt SVC (TCR)

Mode of Operation

The instantaneous current supplied by SVCs is given by:

$$I = \begin{cases} \frac{U}{X_L}(\cos\alpha_{svc} - \cos\omega t) & \alpha_{svc} \leq \omega t \leq \alpha_{svc} + \varepsilon \\ 0 & \alpha_{svc} + \varepsilon \leq \omega t \leq \alpha_{svc} + \pi \end{cases} \quad (2.1)$$

Where:

U represents the SVC voltage at the Point of Common Coupling (PCC).

XL is the SVC total inductance.

α_{svc} is the firing delay angle.

ε is the SVC conduction angle given by

$$\varepsilon = 2(\pi - \alpha_{svc}) \quad (2.2)$$

It can be seen that as the delay angle α_{svc} increases, the conduction angle ε of the valve decreases.

Figures 9, 10, and11 show different current wave-shapes injected by the TCR for diverse firing delay angles.

The SVC's control of the output current is based on the control of the firing delay of thyristors. Hence, the maximum injected current is obtained by a firing delay of 90^0 (full conduction). Meanwhile, the firing angle delays between 90^0 and 180^0 electrical degrees only indicate a partial current contribution. This fact contributes to enhancing the device's inductance and makes it possible, at the same time, to decrease its contribution of reactive power and current.

The fundamental component of current is obtained by means of a Fourier analysis (2.3) or in a reduced version (2.4):

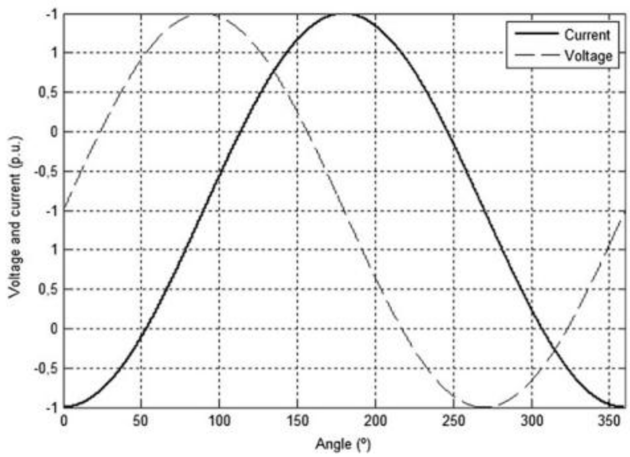


Figure 4 AC current wave shape for $\alpha_{svc} = 90^0$

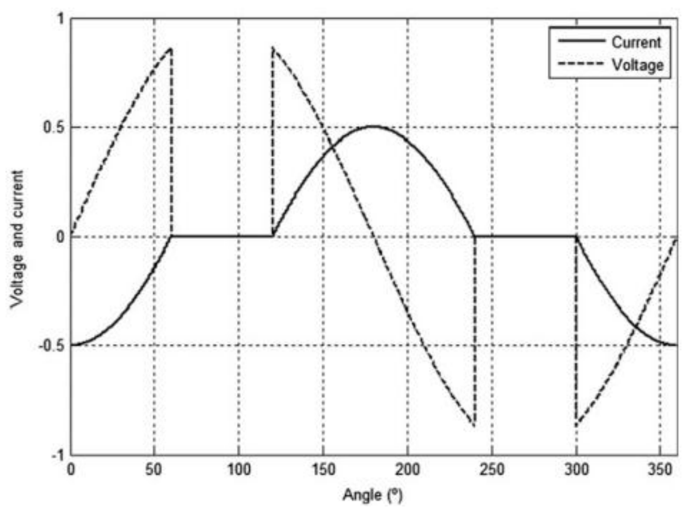


Figure 5 AC current wave shape for $\alpha_{svc} = 120$

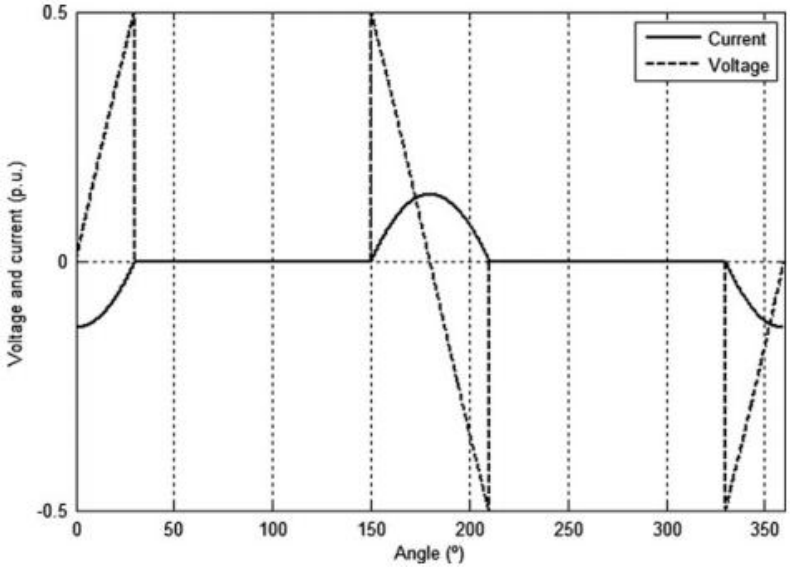


Figure 6 AC current wave shape for α_{svc} = 150^0

$$I_1 = \frac{2(\pi - \alpha_{SVC}) + \sin 2\alpha_{SVC}}{\pi X_L} U \qquad (2.3)$$

Which can be expressed as:

$$I_1 = B_{SVC}(\alpha_{SVC})\mathrm{U} \qquad (2.4)$$

Where:

$$B_{SVC}(\alpha_{SVC}) = \frac{2(\pi - \alpha_{SVC}) + \sin 2\alpha_{SVC}}{\pi X_L}$$

The maximum value of Bsvc is 1/XL, which corresponds to a conduction angle of 180^0 and represents the condition for maximum conduction of the thyristor's group.

The lowest value of Bsvc is 0 and it is obtained from a conduction angle equal to zero or from a firing angle of 180^0. Thyristor firing angles lower than 90^0 are not allowed because they generate an asymmetric current wave with a high component of continuous current.

The slope defined as the ratio between the voltage variation and the variation of the SVC compensating current over the whole control range could be thus expressed via the voltage–current characteristics:

$$U = U_{ref} + X_{SL} I \qquad (2.5)$$

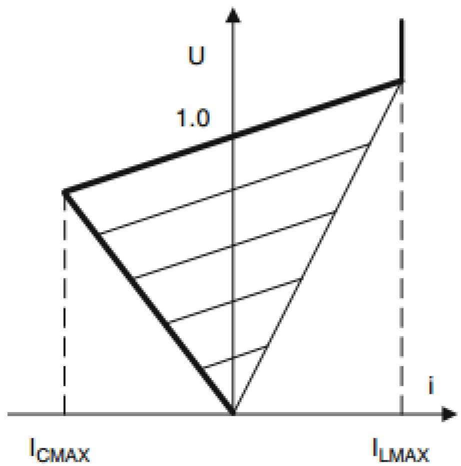


Figure 7 Voltage–current characteristics of the SVC

Typical values of XSL are located within the interval ranging from 0.02 to 0.05 p.u., referring to the SVC's base magnitude. Under limit conditions the SVC will become a fixed reactance. Figure 12 shows the characteristic curve of an SVC. The reactive power supplied by the TCR could thus be calculated using (2.6):

$$Q_{SVC}(\alpha_{SVC}) = \frac{U^2}{X_C} - U^2 B_{SVC}(\alpha_{SVC}) \qquad (2.6)$$

From the point of view of power system planning, localization and optimum sizing of FACTS devices are the most important aspects for operating electric networks with high wind power penetration while at the same time maintaining the security and efficiency of the whole electric system.

2.6 Power System Control and Reactive Power Compensation

To supply electric energy to loads in AC power transmission or distribution systems, the voltage waveform is regulated at the supply point to have nearly constant voltage magnitude, nearly constant operating frequency and no harmful harmonics. In fact, voltage drop, harmonic interference and poor power-factor operation are unavoidable due to non-linearity of loads and imperfection of power systems. Therefore, to minimise those effects, power filters or compensators have to be designed and installed. With the availability of high power semiconductor devices, powerelectronic-controlled power compensators were invented and have been successfully used for this purpose [14,15]. Self-commutated devices such as GTOs or IGBTs have been developed with high-speed switching ability and have characteristics close to ideal switches. Therefore, more effective PWM techniques for controlling output magnitude and harmonic distortion are possible. By controlling shunt or series compensators with such switching devices, the power flow through transmission lines can considerably be improved in both real and reactive powers.[13]

Principles of AC Power Transmission and Power Compensation

To draw out the main features, the following simple power circuit is considered as in below.

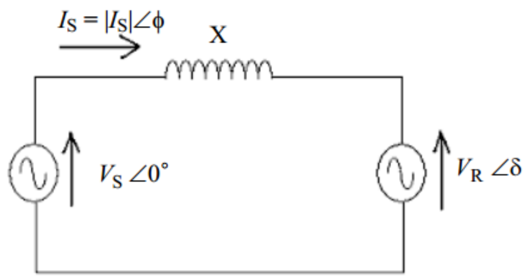


Figure 8 A two-machine model for an AC transmission system

Neglecting line resistance, the power flow through the line can be expressed by the following equations [26].

$$P_S = \frac{|V_S||V_R|}{X} \sin\delta$$

$$Q_S = \frac{|V_S|^2}{X} - \frac{|V_S||V_R|}{X}\cos\delta$$

With specified X, |VS| and |VR|, real and reactive power are both controlled by adjusting the variable δ. This conventional adjustment limits real power flow from

$$-\frac{|V_S||V_R|}{X} \text{ to } +\frac{|V_S||V_R|}{X}.$$

In the same manner, reactive power is also restricted from

$$\frac{|V_S|^2 - |V_S||V_R|}{X} \; to \; \frac{|V_S|^2 + |V_S||V_R|}{X}.$$

These limitations are the so-called steady-state power transmission limits [13]. To improve power flow capability, power system compensation with modern power-electronic control has been introduced and developed.

Power flows depend on the three basic parameters of voltage magnitude, line reactance and phase angle. Therefore, shunt, series and phase-angle compensation are used to control power flows as shown in Figure below. The power flow equations are thus modified to equations below for shunt, series and phase-angle compensation, respectively.

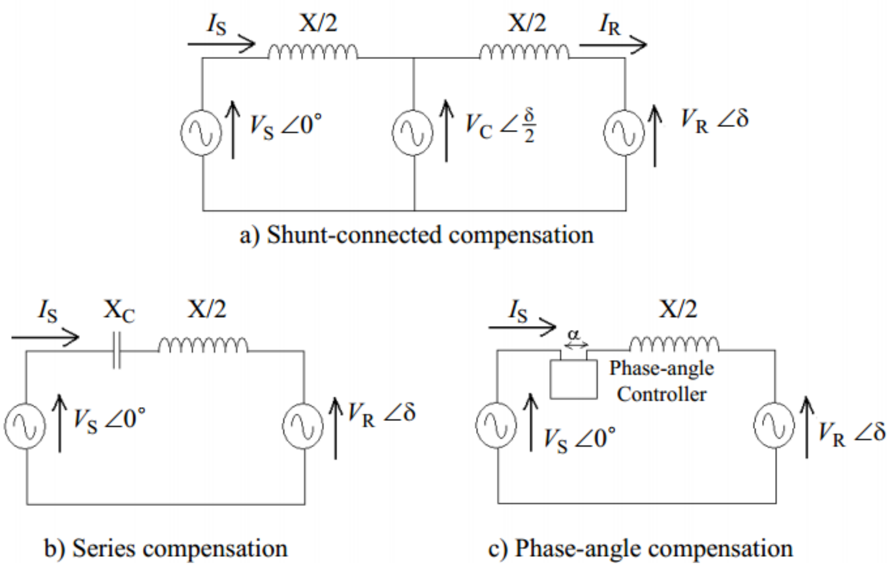


Figure 9 Three basic compensation methods

Mathematical equation for the different compensation methods

For shunt compensator $$P_S + jQ_S = 2\frac{|V_S||V_C|}{X}\sin\delta + j\left(2\frac{|V_C|^2}{X} - 2\frac{|V_S||V_C|}{X}\cos\frac{\delta}{2}\right)$$

For series compensator, $$P_S + jQ_S = \frac{|V_S||V_R|}{(X-X_C)}\sin\delta + j\left(\frac{|V_C|^2}{(X-X_C)} - \frac{|V_S||V_C|}{(X-X_C)}\cos\frac{\delta}{2}\right)$$

For phase angle compensator, $$P_S + jQ_S = \frac{|V_S||V_R|}{X}\sin(\delta-\alpha) + j\left(\frac{|V_S|^2}{X} - \frac{|V_S||V_R|}{X}\cos(\delta-\alpha)\right)$$

The reactive power flows from the higher voltage to the lower voltage. So the change of the effective value of the voltage in the terminal will affect the reactive power flow and the values. So if there is large reactive power supplied from the generator, the voltages on the power flowing way will be degraded, in worst case the voltage won’t meet the quality requirement.

Chapter 3
AC Railway power supply and modeling of components

3.1 AC Railway Overhead Catenary Feeding Systems

To begin with, the electric railway needs a power supply that the trains can access at all times. It must be safe, economical and user friendly. It can use either DC (direct current) or AC (alternating current), the former being, for many years, simpler for railway traction purposes, the latter being better over long distances and cheaper to install but, until recently, more complicated to control at train level. Transmission of power is always along the track by means of an overhead wire or at ground level, using an extra, third rail laid close to the running rails. AC systems always use overhead wires, DC can use either an overhead wire or a third rail; both are common. Both overhead systems require at least one collector attached to the train so it can always be in contact with the power. Overhead current collectors use a "pantograph", so called because that was the shape of most of them until about 30 years ago. The return circuit is via the running rails back to the substation. The running rails are at earth potential and are connected to the substation.

An AC railway power supply system has several configuration features different to an industrial power system; notably, it is single phase. First, a typical AC railway feeder substation is directly connected to the three-phase high-voltage supply grid. The single-phase 25 kV is now the Ethiopia's standard overhead catenary feeding system. Each feeder substation in Ethiopia typically consists of two 132/25 kV power transformers. The high-voltage side is connected to the utility's three phase bus bar whereas its low-voltage side is connected to a single-phase bus bar. [1]

3.2 Traction power supply schematic diagram

Sebeta-Adama (included) is double truck and Adama (excluded) –Meiso is single truck, and the whole route of Sebeta-Meiso is shown below:

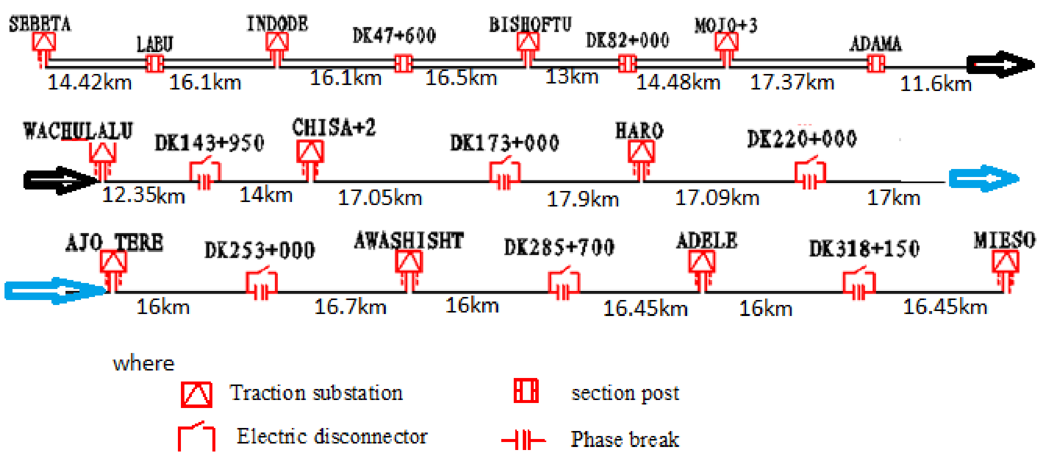


Figure 10 schematic diagram of Sebeta- Meiso power supply

There are some basic feeding configurations that are widely used for feeding electric energy to electric trains in mainline AC railways [7,8].

1. Direct feeding configuration

Direct connection of the feeding transformer to the overhead catenary and the rails at each substation is quite simple and cheap. However, there are some disadvantages to this scheme (high impedance of feeders with large losses, high rail-to-earth voltage and the interference to neighboring communication circuits). To reduce those effects, the addition of an extra conductor (Return Conductor) paralleled and tied to the rails at typically 5 or 6 km is needed and this can reduce electromagnetic interference in parallel communication lines by 30% [7].

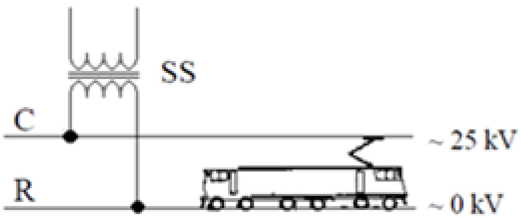


Figure 11 direct feeding

2. Booster transformer feeding configuration

This method employs booster transformers (BT) added along the catenary at every 3-4 km. To force the return current to flow in the return conductor rather than in the rails to suppress the magneto-motive force resulting from the catenary current, the turn ratio needs to be unity [10]. Although this feeding reduces electromagnetic interference with about 0.025 screening factor (the ratio of the induced voltage in a disturbed circuit in a presence of compensation to the induced voltage obtained without compensation) at 50 Hz and 1 mile BT spacing, the leakage inductance of BTs with a return conductor increases the total feeding impedance by approximately 50% compared with the direct feeding. Thus, the distance of two adjacent feeder substations is reduced because of the voltage drop along the contact wire.

Furthermore, when a large-power train passes through a BT isolated overlap, severe arcing can occur. This arcing produces extra interference and damages the contact wire and the train pantograph.

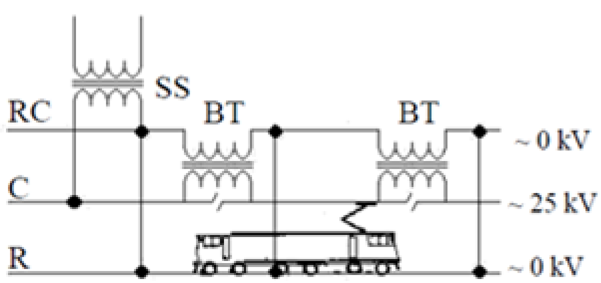


Figure 12 BT feeding

3. Autotransformer feeding configuration

Adding autotransformer (AT) at every 8-15 km intervals can increase substation distance up to 50-100 km. The AT has two equal-turn windings, whose middle tap is connected to the rails to provide earth potential for balancing a voltage between the contact wire and the return conductor [10-11]. The electromagnetic interference in an AT system is normally lower than that in the BT system. However, the size and MVA rating of the AT are much larger and more expensive than the BT. In addition, its protection equipment is more complicated and it needs more installation space.

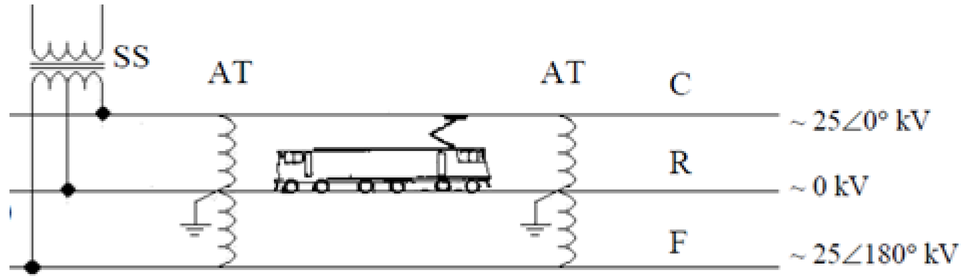


Figure 13 AT feeding

3.3 fundamentals of AC Railway Power Feeding Systems

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 modeling.

3.3.1 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 modeling. 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. 20. This approach is adequate to calculate voltages across trains and phase-to-ground substation and MPTSC voltages. However, rail potential, rail-to-earth leakage current, EMI effect, etc cannot be determined using this simplified model.

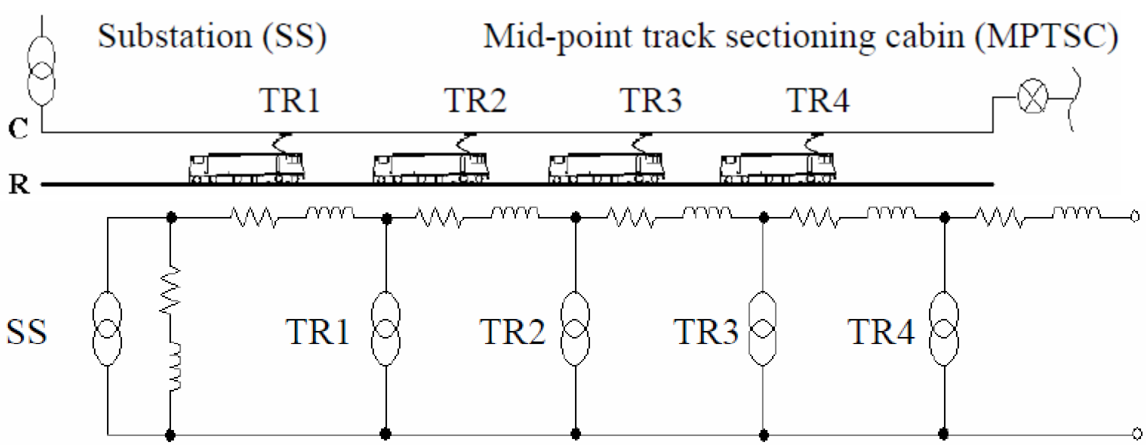


Figure 14 Single-phase AC railway power feeding model

To present the lumped impedance model for this system, the simplest way is the addition of any transformer's or other equipment's impedances on the trackside all together with the overhead catenary, rails and return-conductor impedances (if used). Therefore, the average lumped impedance per unit length can be defined by the following equation [36].

$$z_1 = \frac{z_{OH} \cdot FD + \sum_{i=1}^{N_A} z_{a,i}}{FD}, FD = \text{Feeding distance}$$

Where,

NA Total number of additional equipment in the system

za,i Impedance of the ith additional equipment on the system

z_{OH} Average impedance per length of C, R and F conductors

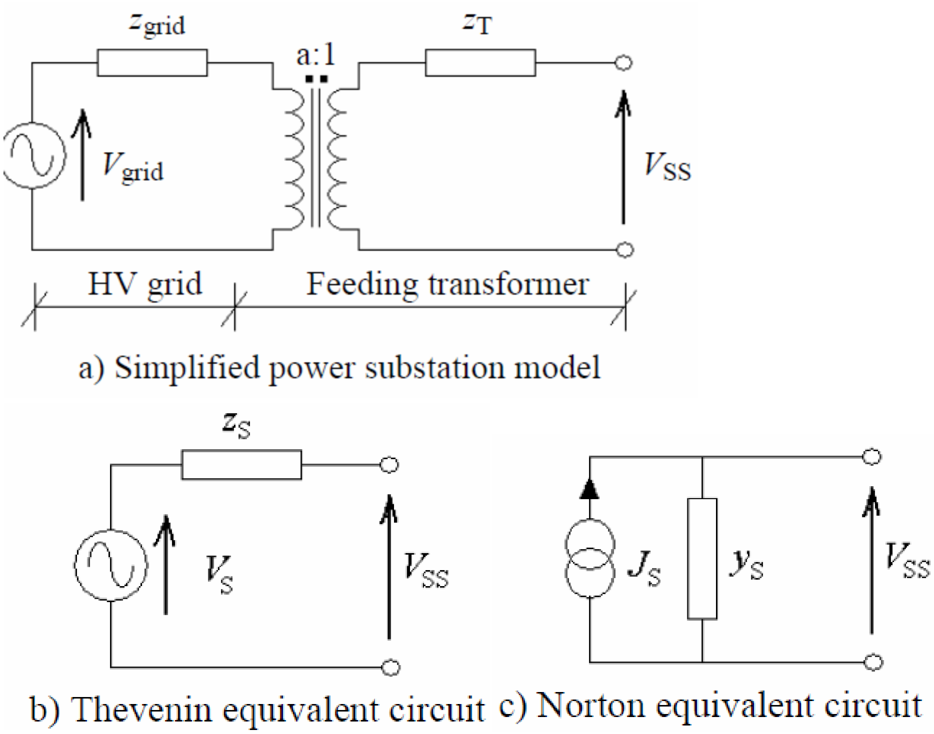
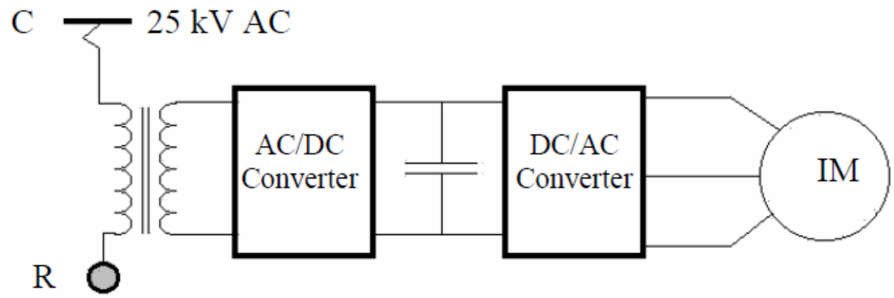


Figure 15 Power substation model

A typical AC railway power feeding system receives the electric energy at the substation. For some technical reasons, i.e. feeding reliability, protection, rotation of phases, etc, any feeding section is isolated from the others with only one power substation. Conventionally, the power substation is modeled by a combination of an infinite bus bar (ideal voltage source) in series with equivalent high-voltage grid impedance connected to a feeder transformer with on-load tap changer as shown in Fig. 19a. This circuit is then simplified to either Thevenin or Norton equivalent circuits as shown in Figs 19b and Fig. 19c, respectively. The parameters of these circuits can be easily computed by the following relations.

$$V_S = \frac{V_{grid}}{a}, \quad z_S = z_T + \frac{z_{grid}}{a^2}, \; y_S = \frac{1}{z_S}$$

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 [13].



a) AC electric locomotive

In some particular conditions, for example with a current control loop embedded in the onboard power converter [37], the current load model is reasonable. However, during simulation, the pantograph voltage is an unknown and needs to be solved for by a power flow program. The phase angle of the locomotive current must be specified with respect to the phase angle of the substation voltage. It cannot be specified unless the power flow solution has been successfully obtained. In practice, only four electrical quantities (Pantograph voltage-magnitude, input current-magnitude, power and power factor) can be measured on-board a train. Any model that uses a well-chosen sub-set of these quantities is satisfaction. The following presents four locomotive models that are used by at least some multi-train simulators [2].

Linear model

The voltage source (*E*t) and the series impedance (*z*t) representing this model can be determined as a function of speed, pantograph voltage and tractive effort over the whole range of operation. The direct calculation cannot be done because of the phase angle of the internal voltage source, which must be referenced to the substation. Thus, a look-up table is used to define the model parameters at any instance according to train speed, voltage and tractive effort.

When the locomotive model is needed, the relevant values can be loaded and used in the power flow program. The inevitable disadvantage of this model is that a substantial database for each locomotive must be prepared for the simulation program. The linear model is shown in Fig. 20.

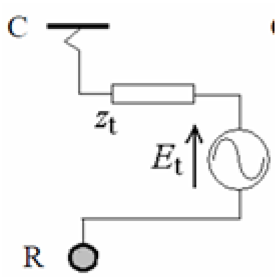


Figure 16 Linear model

Impedance or admittance model

The effective model is the one that uses only the four measured quantities. The impedance magnitude is calculated by the ratio between the voltage and current magnitudes whereas the phase angle is simply determined from the power factor interpretation. The impedance model is given in Fig. 21.

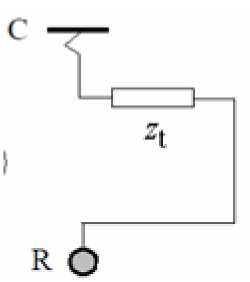


Figure 17 Impedance model

Constant current model

Although, as previously described, the current model is not appropriate due to the unknown phase angle, a numerical database stored for this model with respect to train speed, pantograph voltage and tractive effort like the linear model is another effective way. The lookup table is required to obtain its parameters at any simulated time step. Fig. 22 presents the current model.

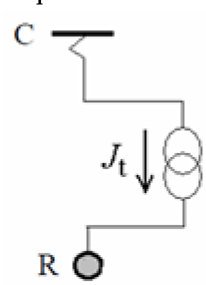


Figure 18 Constant current model

Constant power model

This model is widely used in three-phase power flow problems. Also, it is mainly used in this research because powers and power factor are the two quantities that can be measured by the on-board traction controller. Furthermore, applying tractive effort vs speed and train running information with the Newton's second law of motion can alternatively calculate the model parameters [38,39]. Fig. 23 shows the power model.

Both direct and BT feeding configurations are in this category.

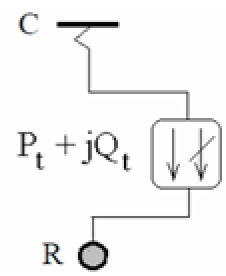


Figure 19 power model.

Electric System Losses

As power is transferred from one point to another, some of the power is dissipated along the route due to the natural properties of the conductors and equipment the power is carried upon.[4].

Loss in Overhead Lines

Power losses in overhead lines are the representation of the amount of lost power from the generated power that did not deliver to load. These losses are attributed to the resistance of various components of the power network mainly transmission lines. Losses depend on the network conditions such as loading, network topology, type of network, location of generation and load as well as power demand. The average power loss in transmission lines would be 3% of the transmitted power, with maximum loss occurring at peak power demand.[23]

Transformer loss

A practical transformer cannot be 100% efficient, due to various losses. Nevertheless, a typical EI power transformer might be around 85% to 90% efficient, while a toroidal transformer will usually achieve better than 90% efficiency, which is remarkably good for Victorian technology. Some energy will be lost due to the fact that the iron cores itself looks like shorted turn as far as the (leakage) magnetic field is concerned, and so electrical currents are set up in the core, which of course demand power from the primary. These are called eddy currents, and in the case of ordinary EI transformers are minimized by using silicon steel (which has high electrical resistance) and by separating the core into thin sheets or laminations, each of which is given a chemical coating to insulate it from its neighbors. The greatest transformer loss is due to heating of the copper windings by the current passing through them, since they do not have zero resistance as we would like.

Transformers with small cores only have a small amount of space available to fit the windings into, so they must necessarily use thin wire. Therefore the resistance of the windings will be higher than those of a large transformer using thick wire. [23]

3.4 THE PER-UNIT SYSTEM

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

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

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

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

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

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

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

$V_{pu} = \frac{V}{V_{base}}$

$I_{pu} = \frac{I}{I_{base}}$

$S_{pu} = \frac{S}{S_{base}}$

$Z_{pu} = \frac{Z}{Z_{base}}$

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

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

$I_{base} = \frac{S_{base}}{V_{base}}$

$Zbase = \frac{V_{base}}{I_{base}} = \frac{V^2{}_{base}}{S_{base}}$

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

$Zp.u.new = \frac{Z_{actual}}{Z_{basenew}} = \frac{Z_{p.u.old}Z_{base.old}}{Z_{basenew}}$

Substituting Z_{base} from the above equation

$Zp.u.new = Z_{p.u.old}(\frac{V_{baseold}}{V_{baenew}})^2(\frac{S_{basenew}}{S_{baseold}})$

If I also assume that:
(1) The value of S_{base} is constant for all points in the power system, and
(2) The ratio of voltage bases on either side of a transformer is chosen to equal the ratio of the transformer voltage ratings, and then the transformer per-unit impedance remains unchanged when referred from one side of a transformer to the other. This will allow me to eliminate the ideal transformer from the transformer model (i.e., i will not have to reflect impedances from one side of the transformer to the other.)

3.5 Mathematical modeling of power system components

All analysis in power system starts with the formulation of appropriate models. A model is a set of equations or relations, which appropriately describes the interactions between different quantities in the time frame studied and with the desired accuracy of a physical or engineered component or system. Hence, depending on the purpose of the analysis different models of the same physical system or components might be valid. [8]

3.5.1 Infinite grid

Infinite grid is the indication that it has infinite power capacity as impedance is very less near to zero because all the generators in interconnected power system are connected in parallel. What this means is that the voltage at this bus or node is always constant and any downstream disturbances do not affect the voltage. Obviously, there is no such thing as an infinite bus in practice, but it is a useful approximation to make when modelling a connection to a large utility or grid network (that is, large relative to the downstream system). [1]

The Ethiopia Electric Power Corporation provides power supply for the traction substations along the whole Line. The power supply includes two independent and reliable 132KV or above power loops for each traction substation. The system short circuit capacity at 132kV incoming line side of the traction substation shall be temporarily calculated as per 300MVA during the feasibility study.

For simulation infinite grid is model by voltage source in series with impedance, i.e.

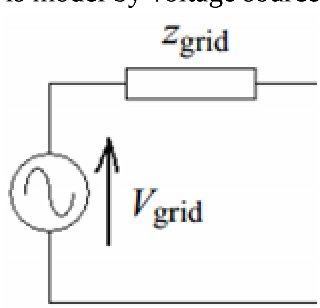


Figure 20 modeling of infinite grid

Vgrid is the incoming line side voltage of traction substation which is 132kv **[2]**

To calculate the grid impedance (grid resistance and grid reactance) it is necessary to know short circuit power (Scs), the line voltage (Vgrid) and the ratio of reactance to resistance in the supply(X/R).

From feasibility study I take the following data:-

Scs =300MVA

Vgrid=132KV
The X/R is not given in the feasibility study and the following assumption can be taken**.**

1. **When the Power Factor (PF) is given instead of X/R**

Power factor (PF) is sometimes specified instead of X/R. This must be the short circuit power factor. Power factor is defined as the cosine of the angle between voltage and current. X/R is the tangent of this same angle. X/R can be found from power factor by taking the tangent of the inverse cosine of the power factor (PF).[c]
$X/R=\tan(\cos^{-1}PF)$

2. **When neither the X/R nor the Power Factor is given**

When neither X/R nor power factor are specified, it is usually safe to assume the impedance of the utility is all reactance and X/R is infinite. Unless there are many miles of transmission line, the impedance of the utility will be mainly reactance in the generator. This is all the data needed for the utility. From this data, the impedance (Z), resistance (R), and reactance (X) can be calculated manually as follows:

Calculating Impedance (Z)

Impedance is calculated from VLL and short circuit kVA (KVAsc)
$Z_{grid} = V^2_{grid}/(KVAsc*1000)$

Calculating Resistance (R) and Reactance (X)

Resistance and reactance are then calculated from the impedance using X/R.[3]
Since $Z= \sqrt{R^2 + X^2}$
$R=\frac{Z}{\sqrt{1+(\frac{X}{R})^2}}$
$X=R*(\frac{X}{R})$

Neither X/R data nor PF is given I will use the second option, that is:
Zgrid = V^2_{grid} / S_{cs}
$=(132kV)^2/300MVA$
$=58.08\Omega$
Where,
Zgrid is the grid impedance
Scs is system short circuit capacity at 132kV incoming line side
Vgrid is grid voltage
And the ratio of grid reactance to grid resistance(X/R) is infinitive because no specification is given during feasibility study.
Xgrid =j58.071Ω

The per unit value

The actual value of the grid impedance will be converted to it per unit value due to superior advantages explained previously as follow:

$Z_{base} = \frac{V_{base}}{I_{base}} = \frac{V^2{}_{base}}{S_{base}}$

$Z_{pu}\text{ (grid)} = \frac{Z_{grid}}{Z_{base}}$

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

Zbase = $\frac{V^2{}_{base}}{S_{base}} = \frac{132^2}{100}$ = 174.24Ω

Zpu (grid) = $\frac{Z_{grid}}{Z_{base}} = \frac{j58.07}{174.24}$ = j0.333

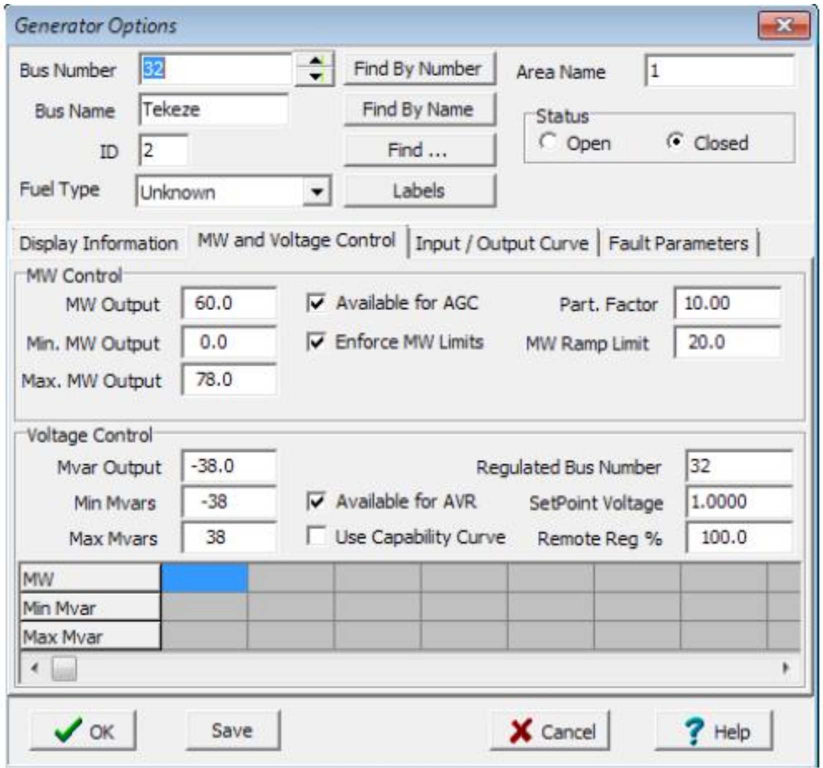


Figure 21 generator input option in power world simulator

3.5.2Traction substation

Two independent 132kV power incoming lines are supplied into traction substation in branch connection mode; for 27.5kV side, single-bus sectional connection is adopted.

The traction substation has two main transformers (one in operation and the other one standby) and power automatic switch device; fixed back-up is applied for feeder circuit breaker with HV failure judgment device arranged in phase. The traction substations are built in INDODE, BISHOFTU, WACHULALU, CHISA, AJO TERE, AWASHISHT and MIESO traction substation together with 15kV power distribution substation to supply two 15kV power supplies to the power system.

The traction substations use the three-phase Vv traction transformers. The installed capacity of the traction transformer is as follows:

Table 1 installed capacity of the traction transformer

Traction substation	Incoming voltage	Installed capacity(MVA)
Sebeta	132KV	2*25
Indode		2*(25+25)
Bishoftu		2*(25+20)
Mojo		2*(20+25)
Wachulalu		2*(10+10)
Chisa		2*(16+16)
Haro		2*(20+16)
Ajo-Tere		2*(10+16)
Awashisht		2*(20+16)
Adele		2*(20+16)
Mieso		2*20
AK20		2*(16+16)
Subur2		2*(12.5+12.5)
Subur3		2*(12.5+12.5)
DireDawa		2*(12.5+12.5)
Subur4		2*(12.5+12.5)
Subur5		2*(12.5+12.5)
AK248		2*(12.5+12.5)
Lasarat		2*(12.5+12.5)
AK324		2*(12.5+12.5)
AK20		2*(12.5+12.5)

TRANSFORMERS

Transformers are specified by output voltage (V), kVA rating, percent impedance (%Z), and X/R ratio. All this information, with the exception of X/R, is usually on the transformer nameplate. If X/R is not specified on the nameplate, a value of 4.9 is typical and can be used in calculations. Impedance (Z) is calculated from V, kVA, and %Z.

$$Z=\frac{\%Z*V^2}{KVA*100000}=\frac{\%Z*V^2}{VA*100}$$

X/R=4.9

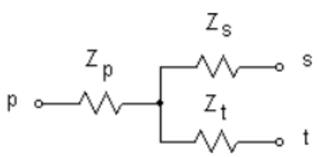
$$R=\frac{Z}{\sqrt{1+(\frac{X}{R})^2}}$$

$$X=R*(\frac{X}{R})$$

Note that to use the above formula the voltage should be in volt.

Three Winding Transformers

The most common three winding transformers are usually specified like two separate transformers with no inter-winding impedance. When three winding transformers have separate inter-winding impedance specified, it is usually specified as reactance (X) and resistance (R) in ohms. Three sets of X and R must be supplied; primary-secondary (ps), primary-tertiary (pt), and secondary-tertiary (st). Xps and Rps are measured in the primary with the secondary short circuited and the tertiary open. Xpt and Rpt are measured in the primary with the tertiary short circuited and the secondary open. Xst and Rst are measured in the secondary with the tertiary short circuited and the primary open. The three winding transformer is modeled as follows.



The impedances are related by the following formulas.

$Z_{ps}=Z_p+Z_s$

$Z_{pt}=Z_p+Z_t$

$Z_{st}=Z_s+Z_t$

$Z_{st}=Z_s+Z_t$

Solving simultaneously I get:

$Z_p=0.5*(Z_{ps}+Z_{pt}-Z_{st})$

$Z_s=0.5*(Z_{ps}+Z_{st}-Z_{pt})$

$Z_t=0.5(Z_{pt}+Z_{st}-Z_{ps})$

In the equations, all impedances must be referred to a common voltage. Note that X St and Rst are measured at the secondary voltage. If all impedances are to be at the primary voltage, Xst and Rst must be transferred.

The traction transformer is usually designed with impedance of 10-12%. For simulation purpose I select Z% = 12%, even though the exact value is given from the name plate of transformer which is not available in the system design.

The per unit value of transformer impedance:

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

The actual value of the transformer impedance will be converted to it per unit value as follow:

$Z_{base} = \frac{V^2{}_{base}}{S_{base}}$

Z_{pu} (transformer) = $\frac{Z_{transformer}}{Z_{base}}$

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

$V_{base(primery\ side)}$ = 132kV

$V_{base(secondary\ side)}$ = 27.5kV

Zbase = $\frac{V^2{}_{base}}{S_{base}} = \frac{27.5^2}{100}$ = 7.5625Ω

Zpu (transformer) = $\frac{Z_{transformer}(actual\ value\ )}{Z_{base}}$

The per unit value will be calculated using the above equation and will be inserted in the table below:

Table 2 transformer impedance actual and per unit value

Traction Sub	Sebeta	Indode	Bishoftu	Mojo
Secondary voltage(kV)	27.5			
Transformer capacity(MVA)	2*25	2*(25+25)	2*(25+20)	2*(20+25)
$Z_T = \frac{\%Z*V^2}{MVA}$	2*(3.63)	2*(3.63+3.63)	2*(3.63+4.537)	2*(4.537+3.63)
Zpu(transformer) $=Z_T/Z_{base}$	2*(0.48)	2*(0.48+0.48)	2*(0.48+0.6)	2*(0.6+0.48)

Traction Substation	Wachulalu	Chisa	Haro	Ajo Tere	Awashisht	Adele	Meiso
Secondary voltage(kV)	27.5						
Transformer capacity(MVA)	2*(10+10)	2*(16+16)	2*(20+16)	2*(10+16)	2*(16+16)	2*(16+20)	2*20
$Z_T = \frac{\%Z*V^2}{MVA}$ (Ω)	2*(9.075+ 9.075)	2*(5.671+ 5.671)	2*(4.537+ 5.671)	2*(9.075+ 5.671)	2*(5.671+ 5.671)	2*(5.671+ 4.537)	2*(4.537+ 4.537)
Zpu (transformer) $=Z_T/Z_{base}$	2*(1.2+ 1.2)	2*(0.75+ 0.75)	2*(0.56+ 0.75)	2*(1.2+ 0.75)	2*(0.75+ 0.75)	2*(0.75+ 0.56)	2*(0.56+ 0.56)

Even though the ratio of transformer reactance to resistance (X/R) is taken from the name plate of the traction transformer, I select X/R=4.9 which is usually used to approximate the transformer parameter since no data can I find.

Using X_{pu}/R_{pu}= 4.9

The per unit value can be obtained by:

$Z_{pu} = \sqrt{X_{pu}^2 + R_{pu}^2}$

Substituting $X_{pu} = 4.9R_{pu}$

$Z_{pu} = \sqrt{(4.9R_{pu})^2 + R_{pu}^2}$

$R_{pu} = \frac{Z_{pu}}{\sqrt{4.9^2+1^2}} = 0.2*Zpu$ ……………………………………………...…..…(*)

Substituting Rpu to find Xpu

Xpu = 4.9*Rpu = 4.9*(0.2*Zpu)

Xpu = 0.98*Zpu.……………………………………….…………(**)

The value of Zpu is calculated in the above table I can determine the values of Rpu and Xpu from equation (*)and(**) respectively.

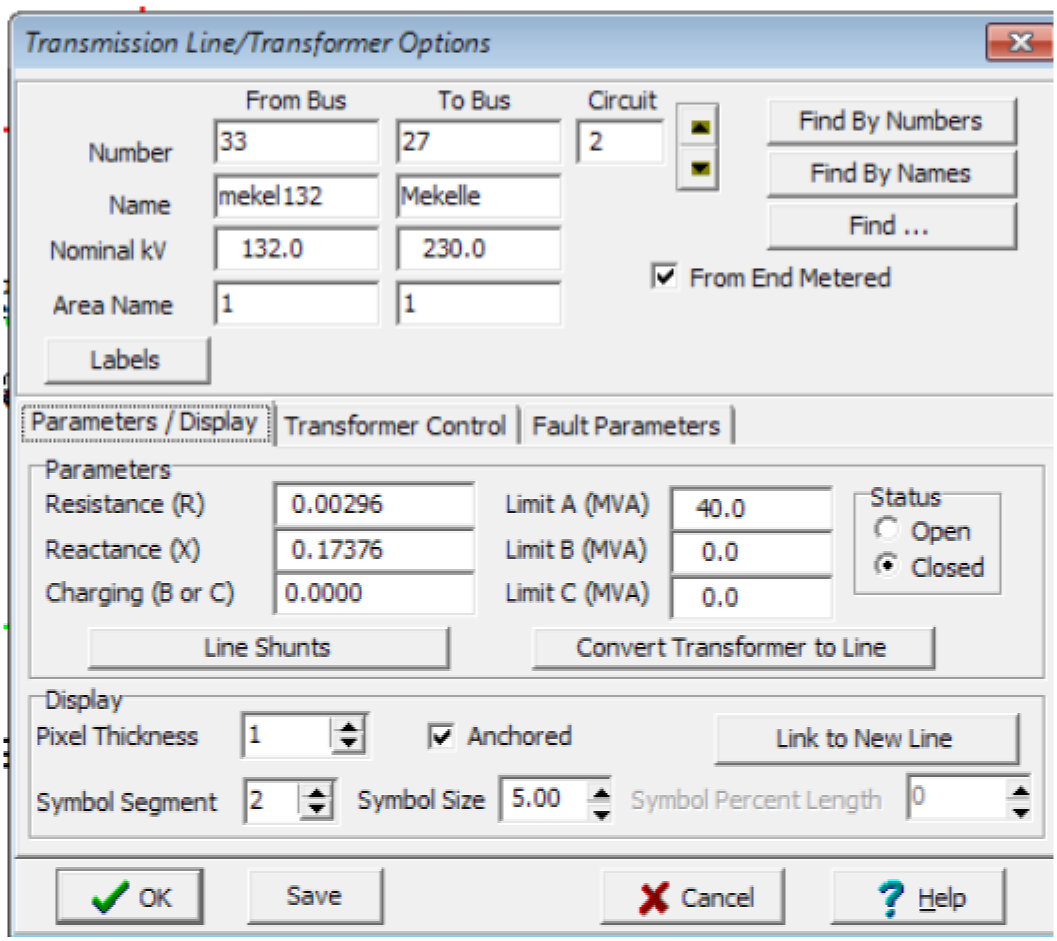


Figure 22 transformer input option of power world simulator

The traction substation is model with a transformer having a turn's ratio k connected to infinite grid

The Thevenin equivalent circuit of substation would be represented by voltage source in series with impedance.

$$Vss = V_{grid}/K$$

$$Zs = Z_T + Z_{grid}/K^2$$

Where,

k is the turns ratio

ZT = equivalent impedance of transformer as refer to secondary

Vss = substation voltage (secondary voltage of the transformer

Table 3 installs capacity of traction substation for multi truck

Traction Sub	Sebeta	Indode		Bishoftu		Mojo	
Location of section post	Labu		DK48		DK82		Adama
Length of feeding section(Km)	14.42	16.10	16	16.5	13	14.48	17.37
Calculated capacity short term(MVA)	6.87	7.03	5.83	5.94	3.2	3.8	6.17
Installed capacity	2*25	2*(25+25)		2*(25+20)		2*(20+25)	

Table 4 installs capacity of traction substation for single truck

Traction Substation	Wachulalu		Chisa		Haro		Ajo Tere		Awashisht		Adele		Meiso
Location of section post	DK144			DK173		DK220		DK253		DK286		DK318	
Length of feeding section(km)	11.6	12.35	14	17.05	17.9	17.09	17	16	16.7	16	16.45	16	16.45
Calculated capacity short term(MVA)	4.41	2.28	4.15	5.98	5.67	4.33	2.4	5.23	6.36	4.39	4.45	6.06	6.45
Installed capacity	2*(10+10)		2*(16+16)		2*(20+16)		2*(10+16)		2*(16+16)		2*(16+20)		2*20

3.5.3 Feeding line parameter

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

The impedance is generally expressed by the following formula:

Z = (R+ X)* L

Where

Z = Line impedance

R = Line resistance

X = Line reactance

L = Length of the cable

Table 5 list of impedance per unit length

Discription \ train		SS_9	HX_{D3B}
Single truck	Impedance traction network(Ω/km)	0.091894+j.342983	
	Power factor	0.85	0.95
	Equivalent impedance traction network(Ω/km)	0.2793	0.1945
Multi track	Impedance traction network(Ω/km)	0.0808668+j0.303805	
	Power factor	0.85	0.95
	Equivalent impedance traction network(Ω/km)	0.2468	0.1715

The per unit value of transmission line impedance:

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

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

$Z_{base} = \frac{V^2{base}}{S_{base}}$

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

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

$V_{base(primery\ side)}$ = 132kV

$V_{base(secondary\ side)}$ = 27.5kV

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

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

The per unit value will be calculated using the above equation and will be inserted in the table below:

Table 6 feeding line equivalent actual and per unit impedance for multi truck

Traction Sub	Sebeta	Indode		Bishoftu		Mojo	
Location of section post	Labu		DK48		DK82		Adama
Length of feeding section(Km)	14.42	16.10	16	16.5	13	14.48	17.37
Impedance (Ω)	1.33+ j4.94	1.49+ j5.52	1.49+ j5.52	1.5+ j5.66	1.2+ j4.46	1.34+ j4.97	1.6+ j5.96
$Z_{pu}=Z_{actual}/Z_{base}$	0.176+ j0.65	0.186+ j0.73	0.186+ j0.73	0.187+ j0.75	0.159+ j0.59	0.177+ j0.657	0.21+ j0.7888

Table 7 feeding line equivalent actual and per unit impedance for single truck

Traction Substation	Wachulalu		Chisa		Haro		Ajo Tere		Awashisht		Adele		Meiso
Location of section post	DK144			DK173		DK220		DK253		DK286		DK318	
Length of feeding section(km)	11.6	12.35	14	17.05	17.9	17.09	17	16	16.7	16	16.45	16	16.45
Impedance in (Ω)	1.07 + j3.98	1.14+ j4.24	1.3+ j4.8	1.57+ j5.85	1.65+ j6.14	1.58+ j5.86	1.57+ j5.58	1.49+ j5.49	1.54+ j5.73	1.49+ j5.73	1.52+ j5.64	1.49+ j5.49	1.52+ j5.64
$Z_{pu} = Z_{actual}/ Z_{base}$	0.14 + j0.53	0.15+ j0.561	.172 +j.635	.208+ j.774	.218+ j.812	.209+ j.775	.208+ j.774	.1979 +j.726	.204+ j.7577	.1979 +j.7577	.2+ j.7458	.1979 +j.726	.2+ j.7458

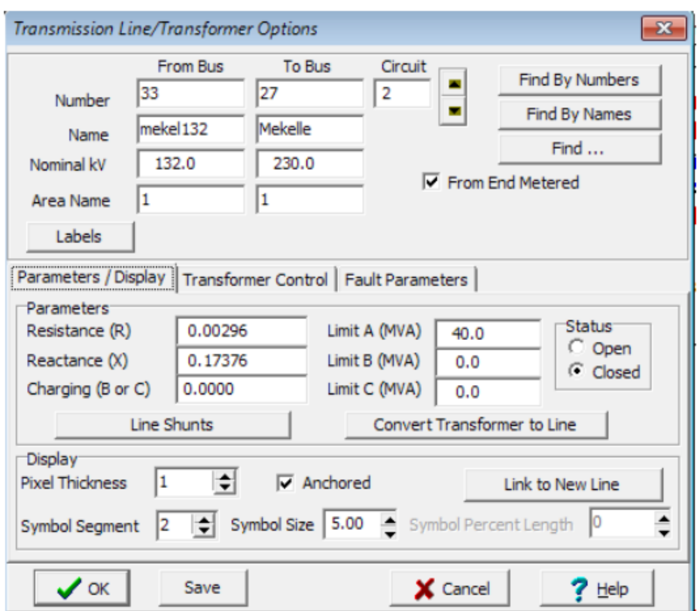


Figure 23 feeder line option of power world simulator

3.5.4 Train modeling

It requires a simple model to reduce problem complexity and overall execution time; directly applying differential equations to obtain a model is not appropriate for steady-state power flow calculations [4].

A train is model by Constant power model. This model is widely used in power flow problems. Also, it is mainly used in this research because powers and power factor are the two quantities that can be measured by the on-board traction controller. Furthermore, applying tractive effort vs speed and train running information with the Newton's second law of motion can alternatively calculate the model parameters [5 6]. Figure below shows the power model.

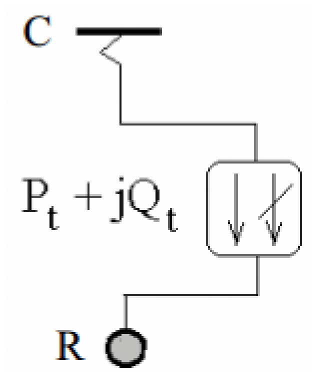


Figure 24 Train model for power flow calculation

Table 8 train model by active and reactive power for double truck

Traction Sub	Sebeta	Indode		Bishoftu		Mojo	
Location of section post	Labu		DK48		DK82		Adama
Aparent power/train MVA	2.9+j1.774	2.98+j1.81	2.478+ j1.5	2.52+j1.53	1.36+ j0.83	1.65+ j.98	2.62+ j1.59

Table 9 train model by active and reactive power for for single truck

Traction Substation	Wachulalu		Chisa		Haro		Ajo Tere		Awashisht		Adele		Meiso
Location of section post	DK144			DK173		DK220		DK253		DK286		DK318	
Apparent power/train MVA	1.874+ j1.14	.969+ j.59	1.76+ j1.07	2.54+ j1.54	2.4+ j1.46	1.84+ j1.12	1.02+ j0.62	2.22+ j1.35	2.703+ j1.64	1.86+ j1.13	1.89+ j1.15	2.57+ j1.56	2.9+ j1.7

When I use Powerworld simulating software to do power flow analysis the train is model by a load (active power P and reactive power Q).

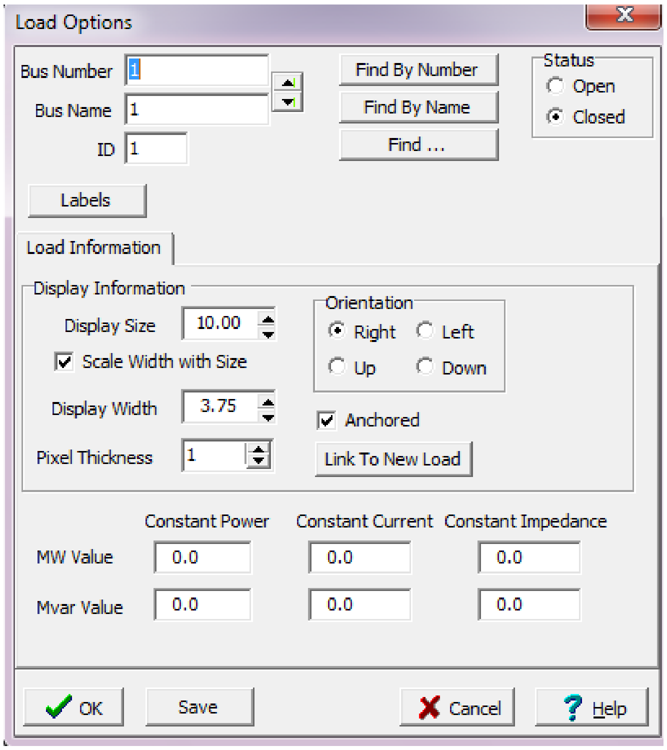


Figure 25 Load option of power world simulator

3.6 Mathematical modeling of static var compensator

The main components of static var compensator are shown in the figure below

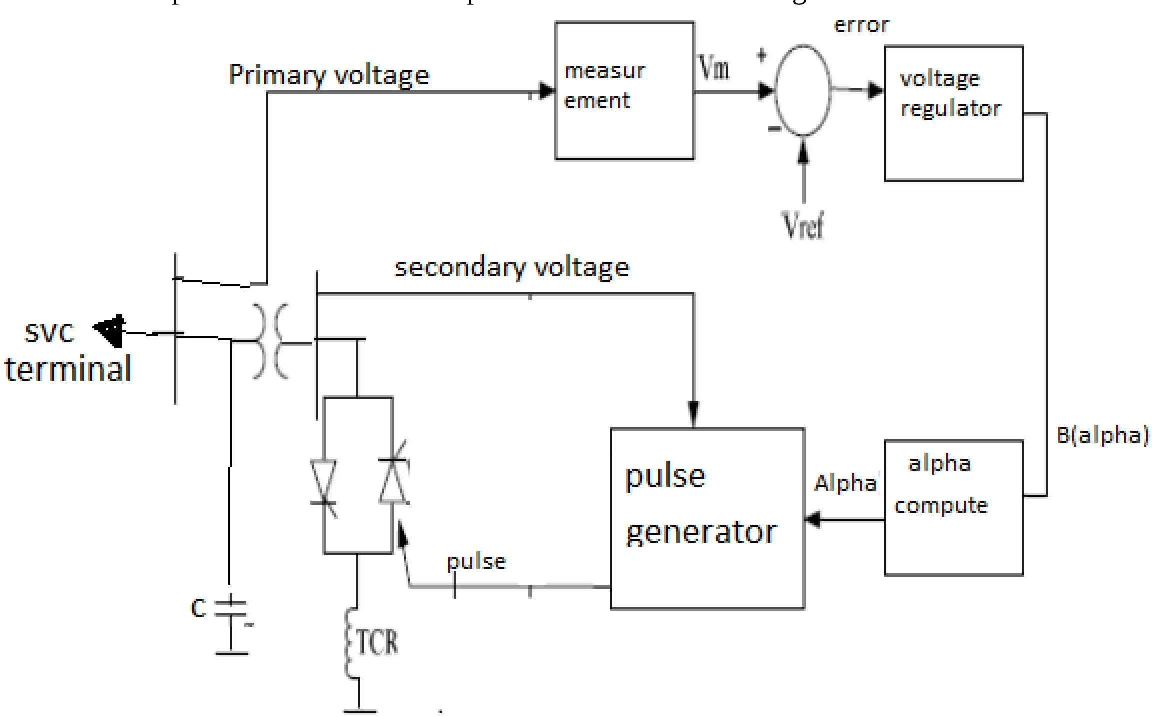


Figure 26 components of static var compensator

a) Thyristor control reactor and capacitor

Consider an inductive load taking a lagging current I at a power factor cosφ_1. In order to improve the power factor of this circuit, the remedy is to connect such equipment in parallel with the load which takes a leading reactive component and partly cancels the lagging reactive component of the load. And if there is a load taking a leading current I should connect equipment in parallel with the load which takes a lagging reactive component and partly cancels the leading reactive component of the load.

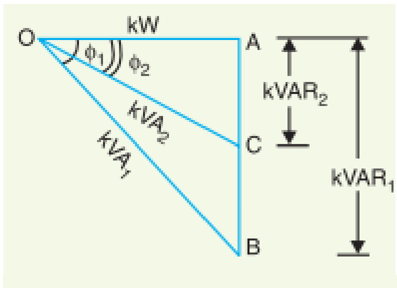


Figure 27 power triangle for power factor correction

It is clear that φ_2 is less than φ_1 so that new p.f. cosφ_2 is more than the previous p.f. cos φ_1.

The power triangle OAB is for the power factor cos φ_1, whereas power triangle OAC is for the improved power factor cos φ_2. It may be seen that active power (OA) does not change with power factor improvement. However, the lagging kVAR of the load is reduced by the p.f. correction equipment, thus improving the p.f. to cos φ_2.**[8]**

Leading kVAR supplied by p.f. correction equipment

=BC = AB − AC

=$kVAR_1 - kVAR_2$

=OA (tan φ_1−tan φ_2)

= kW (tan φ_1−tan φ_2)

The SVC comprises fixed capacitor (FC), thyristor control reactor and transformer. The fixed capacitor is directly connected to the 25kV bus. The thyristor control reactor is connected to the 25kV bus via 20MVA, 25/5kV transformer with X_k =12%. The system voltage varies with in 1 $\pm$ 0.05% pu.the SVC rating is calculated as follows:

- Q_{FC} = 22MVar
- Q_L = 3MVar
- $Q_{TCR} = Q_{FC} + Q_L$ = 25MVar

The reactance of FC and TCR is calculated as follow

- $X_{Lrated} = U^2_{secandary}/Q_{TCR}$ = 30.25Ω
- Xtr = $0.12\frac{5^2}{20}$ = 0.15 Ω
- $X_{TCR} = X_{Lrated} - X_{tr}$ = 30.1 Ω

- L_{TCR} = 30.1/100pi = 95.8mH
- $X_{cap} = U^2_{secandary}/Q_{FC} = 25^2/22 = 28.4\Omega$
- $C_{cap} = \frac{1}{100\pi * 28.4} = 112.1\mu F$

b) Measurement system model: The unit measures the voltage of the network. In the simulation I used a voltmeter with rms measured block and a gain that converts in to per unit value is shown below.

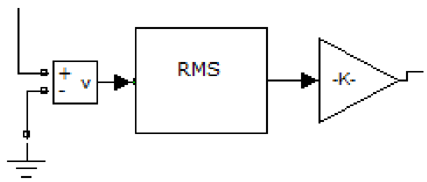


Figure 28 voltage measurement model

The rms block computes the rms value of the input voltage source. A periodic sinusoidal voltage can be defined as $V_{(t)}$ = Vm.cos(ωt) with a period of T. Then we can calculate the **root-mean-square** (rms) value of a sinusoidal voltage ($V_{(t)}$) as:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T V_m^2 cos^2(\dot{\omega} t)dt}$$

Where T is the period of the voltage source

C) Voltage Regulator Unit Model: The Voltage measurement module takes the reference voltage and the measured voltage of the system and calculates the Susceptance of the network. The voltage regulator block uses PI controller. The response speed to a change of system voltage depends on the voltage regulator gains (proportional gains Kp and integral gain Ki), the droop reactance Xs, and the system strength (short circuit level). For an integral type voltage regulator (Kp=0), if the voltage measurement time constant Tm and the average time delay Td due to valve firing are neglected, the closed loop system consisting of the SVC and the power system can be approximated by a first-order system having the following closed-loop time constant:

$$Tc = \frac{1}{Ki(Xs+Xn)}$$

Where,
Tc= Closed loop time constant
Ki =Proportional gain of the voltage regulator
Xn = Equivalent power system reactance
XS= Slope or Current Droop is defined as the ratio of voltage-magnitude change to current-magnitude change over the linear-controlled range of the compensator.
Thus slope X_S is given by $\frac{\Delta V}{\Delta I}$; usually between 0.01 and 0.05

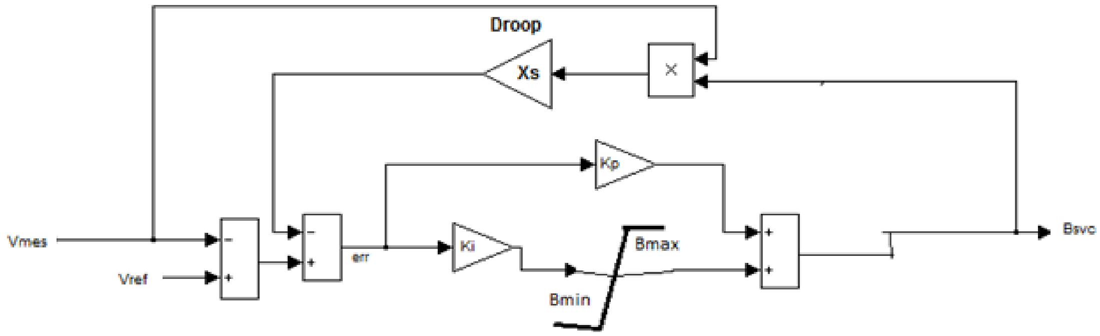


Figure 29 modeling voltage regulator

The smaller the time constant, the faster the system response.[7]
In my simulation I took Xs = 0.03.
Ki = 300;
The equivalent power system reactance is Xn = 0.067; Tc = 0.035 s.

d) Firing angle computing system: this computes the firing angle ''alpha‟ of the TCRs. It uses the primary susceptance (Bsvc) computed by the voltage regulator to determine the TCR firing angle ''alpha‟.
The firing angle „alpha‟ as a function of the TCR susceptance if given by:

$$B_{tcr} = \frac{2(pi - alpha) + \sin(2 * alpha)}{pi}$$

In my simulation firing angle computing is done by look up table and inserting appropriate table date so that it will compute the value of alpha by interpolation and extrapolation until it gets the accurate value that match.

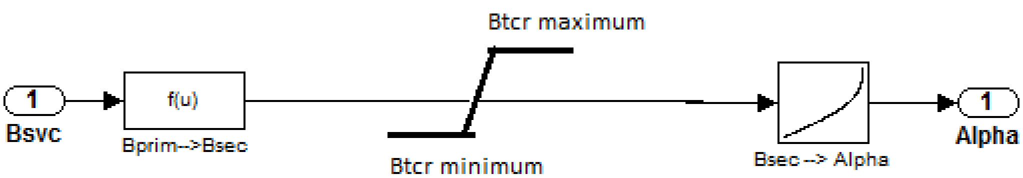


Figure 30 Firing angle computing

e) Pulse generator: A synchronizing system using a Phase Locked Loop (PLL) synchronized on the secondary voltage and a pulse generator that send appropriate pulses to the thyristor. The pulse generator uses the firing angle ''alpha‟. For simulation the phase locked loop available in matlab simulink is used.

Chapter 4
Power Flow Calculation of AC Railway

4.1 Introduction

The main function of AC railway power supply systems is to deliver electric energy to the electric locomotives that are connected to the system, and to do so, effectively and economically. Calculations related to AC railway power supply systems need basic tools such as power flow algorithms for obtaining voltage, current or power flows through each feeder section. As long as the AC railway power systems can be described by the conventional power supply analysis [12], classical power flow methods are applicable. The Newton-Raphson (NR) and the Gauss-Seidel (GS) methods are two well-known iterative techniques for solving power flow problems. With quadratic convergence [14], the NR method has been successfully developed and broadly accepted as the most powerful algorithm for several decades. Although these methods were originally developed for solving industrial power systems, they can be adapted to railway power distribution systems. In this chapter, analysis, modeling and simulation of the Newton Raphson power flow analysis is explained in more detail.

4.2 Newton-Raphson AC Railway Power Flow Method

There are many kinds of the NR power flow method depending upon which circuit analysis echnique is applied, Nodal or Mesh analyses [42]. This leads to the use of either bus admittance or bus impedance matrices. In this thesis, only power flow methods based on the bus admittance matrix is determined. Before describing any power flow algorithm, the bus admittance matrix formulation is vital and needs to be reviewed.

Newton-Raphson method is an iterative technique for solving systems of simultaneous equations in the general form. [25]

$f_1(X_1,..X_n,..X_r) = K_1$

$f_n(X_1,..X_n,..X_r) = K_n$

$f_r(X_1,..X_n,..X_r) = K_r$

Where $f_1,....f_n....f_r$ are differentiable functions of the variables $x_1,....x_n ,....x_r$ and $K_1, ..K_n....K_r$ are constants.

There are many kinds of the NR power flow method depending upon which circuit analysis technique is applied, Nodal or Mesh analyses [42]. This leads to the use of either bus admittance or bus impedance matrices. In this thesis, only power flow methods based on the bus admittance matrix is determined. Before describing any power flow algorithm, the bus admittance matrix formulation is vital and needs to be reviewed.

4.2.1 Formulation of the bus admittance matrix

The bus admittance matrix, [**Y**], depends on the interconnection between bus pairs through a feeder portion. This is the essential characteristic of the power feeding system and it is usually independent from the load unless the train is described by the admittance model. In this thesis, the trains will be modelled by the power model only. This endows a great advantage to the power flow solution and will be discussed later. In addition, many other network components are also modelled by the admittance. Each of them can be either a series admittance connected between two buses or a shunt admittance to ground. Therefore, the bus admittance matrix is built up by the collection of all series and shunt components connected to the system.

Assume that **Y**ij is an admittance of a feeder portion connected between bus i and j while **Y**i0 is an admittance to ground at bus i, e.g. **Y**AT for an AT bus or **Y**SS for the substation. The size of [**Y**] is equal to the total number, NB, of buses in the system. The ith row, jth column of [**Y**] is called an off-diagonal element, [**Y**ij] where i ≠ j, and it represents the admittance value linking between bus i and j. The diagonal element, [**Y**ii], is the collection of all the admittances connected to bus i, including the shunt admittances to ground. Each element of [**Y**] can be calculated by the following formula.

$[\mathbf{Y}ii] = \sum_{h=1}^{N_B} Y_{ih}$ for diagonal element (3.9)

$[\mathbf{Y}ij] = -Y_{ij}$ for diagonal element (3.10)

Applied to the load flow problem, the variables are the nodal voltage magnitudes and phase angles, the functions are the relationships between power, reactive power and node voltages, while the constants are the specified values of power and reactive power at the generator and load nodes. Power and reactive power functions can be derived by starting from the general expression for injected current at node n:

In general, for a system with r nodes, then at node n:

$I_n = Yn1V1 + Yn2V2 + \ldots + YnnVn + \ldots + YnrVr = \sum_{k=1}^{r} Y_{nk} V_k$

Where:

Y_{nn} = sum of all admittances connected to node n

Y_{nk} = -(sum of all admittances connected between node n and k) = Y_{kn}

I_n = current injected at node n

For the complete system of r nodes:

$$\begin{bmatrix} I_1 \\ \vdots \\ I_n \\ \vdots \\ I_r \end{bmatrix} = \begin{bmatrix} Y_{11} & \cdots & Y_{1n} & \cdots & Y_{1r} \\ \vdots & & \vdots & & \vdots \\ Y_{n1} & \cdots & Y_{nn} & \cdots & Y_{nr} \\ \vdots & & \vdots & & \vdots \\ Y_{r1} & \cdots & Y_{rn} & \cdots & Y_{rr} \end{bmatrix} . \begin{bmatrix} V_1 \\ \vdots \\ V_n \\ \vdots \\ V_r \end{bmatrix} \quad \text{or} \quad [I] = [Y].[V]$$

Where, [Y] is the nodal admittance matrix. Formulation of the load flow problem is most conveniently carried out with the terms in the nodal admittance matrix expressed in polar notation:

$Y_{kn} = |Y_{kn}| < \Theta_{kn}$,

So the complex power input to the system at node n is:

$S_n = V_n I_n^*$

Where the subscript * denotes the complex conjugate. Substitute from above equation with all complex variables written in polar form:

$$S_n = V_n \sum_{k=1}^{r} Y^*_{nk} V_k^* = \sum_{k=1}^{r} |V_n||V_k||Y_{nk}| < \{\delta_n - \delta_k - \Theta_{nk}\}$$

The power and reactive power inputs at node n are derived by taking the real and imaginary parts of the complex power:

$$P_n = \text{real } \{\sum_{k=1}^{r} |V_n||V_k||Y_{nk}| < \{\delta_n - \delta_k - \Theta_{nk}\}\}$$

$$Q_n = \text{imaginary } \{\sum_{k=1}^{r} |V_n||V_k||Y_{nk}| < \{\delta_n - \delta_k - \Theta_{nk}\}\}$$

The load flow problem is to find values of voltage magnitude and phase angle, which, when substituted into above equation Pn and Qn, produce values of power and reactive power equal to the specified set values at that node, Pns and Qn s.The first step in the solution is to make initial estimates of all the variables:

$|V^o_n|, \delta_n^o$

Where the superscript ^{0} indicates the number of iterative cycles completed. Using these estimates, the power and reactive power input at each node can be calculated from P_n and Q_n. These values are compared with the specified values P_{ns} and Q_{ns} to give a power and reactive power error. For node n:

$$\Delta P_n^0 = P_{ns} - \sum_{k=1}^{r} |V_n^o||V_k^o||Y_{nk}| \cos \{\delta^0_n - \delta_k^0 - \Theta^0_{nk}\}$$

$$\Delta Q_n^0 = P_{ns} - \sum_{k=1}^{r} |V_n^o||V_k^o||Y_{nk}| \sin \{\delta^0_n - \delta_k^0 - \Theta^0_{nk}\}$$

The power and reactive power errors at each node are related to the errors in the voltage magnitudes and phase angles $\Delta|V_n|^0$, $\Delta\delta_n^o$ by the first order approximations:

$$\begin{bmatrix} \vdots \\ \Delta P_n^0 \\ \vdots \\ --- \\ \vdots \\ \Delta Q_n^0 \\ \vdots \end{bmatrix} = \begin{bmatrix} \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \frac{\partial P_n}{\partial \delta_{n-1}} & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial \delta_{n+1}} & \vdots & \vdots & \vdots & \frac{\partial P_n}{\partial |V_{n-1}|} & \frac{\partial P_n}{\partial |V_n|} & \frac{\partial P_n}{\partial |V_{n+1}|} & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ - & --- & --- & --- & - & -- & -- & --- & --- & --- & - \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \frac{\partial Q_n}{\partial \delta_{n-1}} & \frac{\partial Q_n}{\partial \delta_n} & \frac{\partial Q_n}{\partial \delta_{n+1}} & \vdots & \vdots & \vdots & \frac{\partial Q_n}{\partial |V_{n-1}|} & \frac{\partial Q_n}{\partial |V_n|} & \frac{\partial Q_n}{\partial |V_{n+1}|} & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} \Delta\delta_{n-1}^0 \\ \Delta\delta_n^0 \\ \Delta\delta_{n+1}^0 \\ --- \\ \Delta|V_{n-1}|^0 \\ \Delta|V_n|^0 \\ \Delta|V_{n+1}|^0 \end{bmatrix}$$

(2) Where, the matrix of partial differentials is called the Jacobian, [J]. The elements of the Jacobian are calculated by differentiating the power and reactive power expressions (P_n,Q_n) and substituting the estimated values of voltage magnitude and phase angle. [24]

At the next stage of the Newton-Raphson solution, the Jacobian is inverted. Matrix inversion is a computationally-complex task with the resources of time and storage increasing rapidly with the order of [J]. This requirement for matrix inversion is a major drawback of the Newton-Raphson method of load flow analysis for large-scale power systems. However, with the inversion completed, the approximate errors in voltage magnitudes and phase angles can be calculated by pre-multiplying both sides of Jacobian matrix:

$$\begin{bmatrix} \Delta\delta_{n-1}^0 \\ \Delta\delta_n^0 \\ \Delta\delta_{n+1}^0 \\ --- \\ \Delta|V_{n-1}|^0 \\ \Delta|V_n|^0 \\ \Delta|V_{n+1}|^0 \end{bmatrix} = \begin{bmatrix} & J^0 & \end{bmatrix}^{-1} \begin{bmatrix} \vdots \\ \Delta P_n^0 \\ \vdots \\ --- \\ \vdots \\ \Delta Q_n^0 \\ \vdots \end{bmatrix} \qquad \textbf{(3)}$$

The approximate errors from (3) are added to the initial estimates to produce new estimated values of node voltage magnitude and angle. For node n:

$$|V_n^1| = |V_n^0| + \Delta\,|V_n^0| \qquad (4)$$

$$\delta_n^1 = \delta_n^0 + \Delta\delta_n^0 \qquad (5)$$

Because first-order approximations are used in (2) the new estimates (denoted by the superscript [1]) are not exact solutions to the problem. However, they can be used in another iterative cycle, involving the solution of Equations (1-5). The process is repeated until the differences between successive estimates are within an acceptable tolerance band usually less than 0.0001.

4.3 POWER WORLD SIMULATOR SOFTWARE

Power World Simulator is an interactive power system simulation package designed to simulate high voltage power system operation on a time frame ranging from several minutes to several days. The software contains a highly effective power flow analysis package capable of efficiently solving systems with up to 60,000 buses. Powerful visualization techniques are used on an interactive basis, resulting in an extremely intuitive and easy to use graphical user interface (GUI). The GUI includes animated one-line diagrams with support for panning, zooming and conditional display of objects. Power World Simulator simulates the operation of a control area in an interconnected power system over a given period of time, usually ranging from several hours up to an entire day.

During the course of the simulation, users get to not only see the system operate, but also to easily interact with the system using a number of animated displays. In addition, the loads can be set to change automatically. The user operates the system primarily by using a dynamic one -line diagram to change system controls, including generator megawatt (MW) output, load tap changing (LTC) transformer tap positions, phase-shifter positions, or circuit breaker status.

Other windows allow the user to interchange power with other areas, to monitor various aspects of the system, and to change simulation options. Because of the quick display refresh rate, users get almost immediate feedback concerning the effects of their actions. The displays have been

designed to look good both for group presentations and individual use. A new user can start operating just a two-bus system and then work up to systems of just about any size.

Also available in the PowerWorld product line is Viewer. Viewer allows the user to observe a power system in operation using the PowerWorld interface. However, none of the parameters of the system may be changed.

Electrical Buses

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

Three type of buses:

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

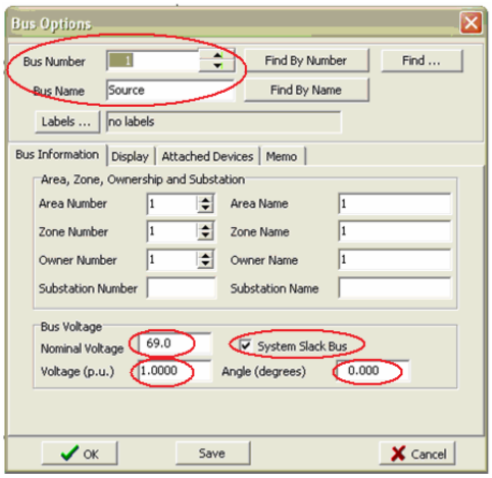


Figure 31 Slack bus option

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

2. **PV bus:** is connected to the generator. No need to input the angle setting box.

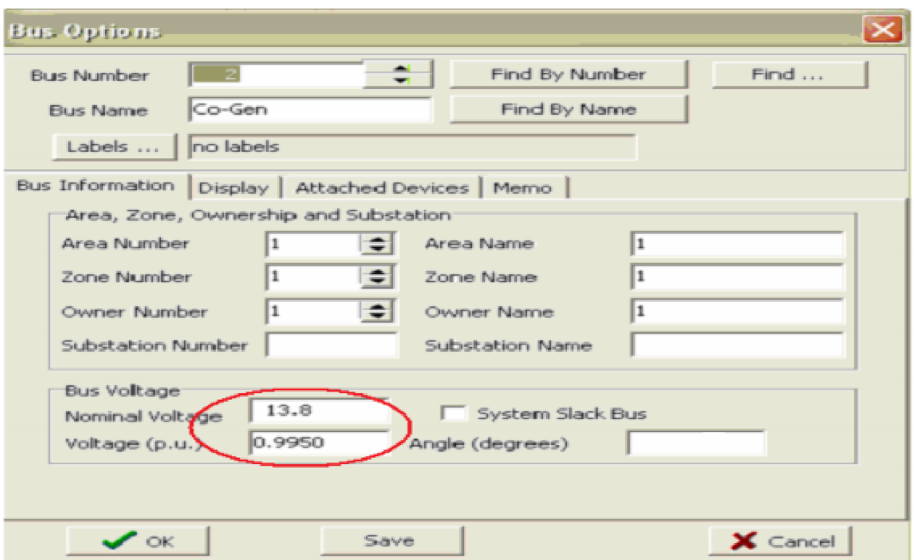


Figure 32 PV bus option

3. **PQ bus:** Neither voltage setting nor angle setting information is needed.

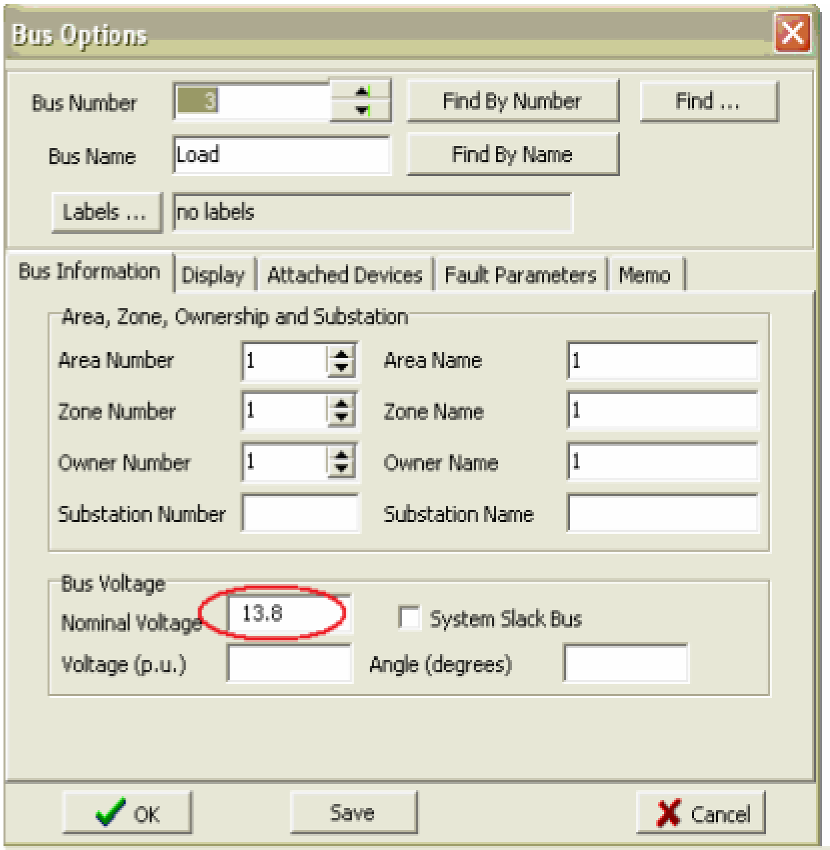


Figure 33 load bus option

4.4. Power flow Solution

Power-flow problem starts with a single line diagram of the power system, from which computer solutions can be obtained. Data for the simulation include bus data, transmission line data, and generator data. Computer simulation was used in this paper to obtain the solutions to the grid

systems power flow based on the Newton-Raphson technique in Power World simulator run mode. This is an iterative numerical method to find power flow solution until the specified convergence.

4.5 One-line Diagram

The starting point of any power-flow problem is the development of a single-line diagram of the power system, from which computer solutions can be obtained. The one line diagram of the case

study network, AC railway electric network, was thus drawn on the POWER WORLD SIMULATOR platform for this study. All the organized data were then fed to the one-line diagram. Partial view of the one-line diagram is given below in both edit and run modes of POWER WORLD.

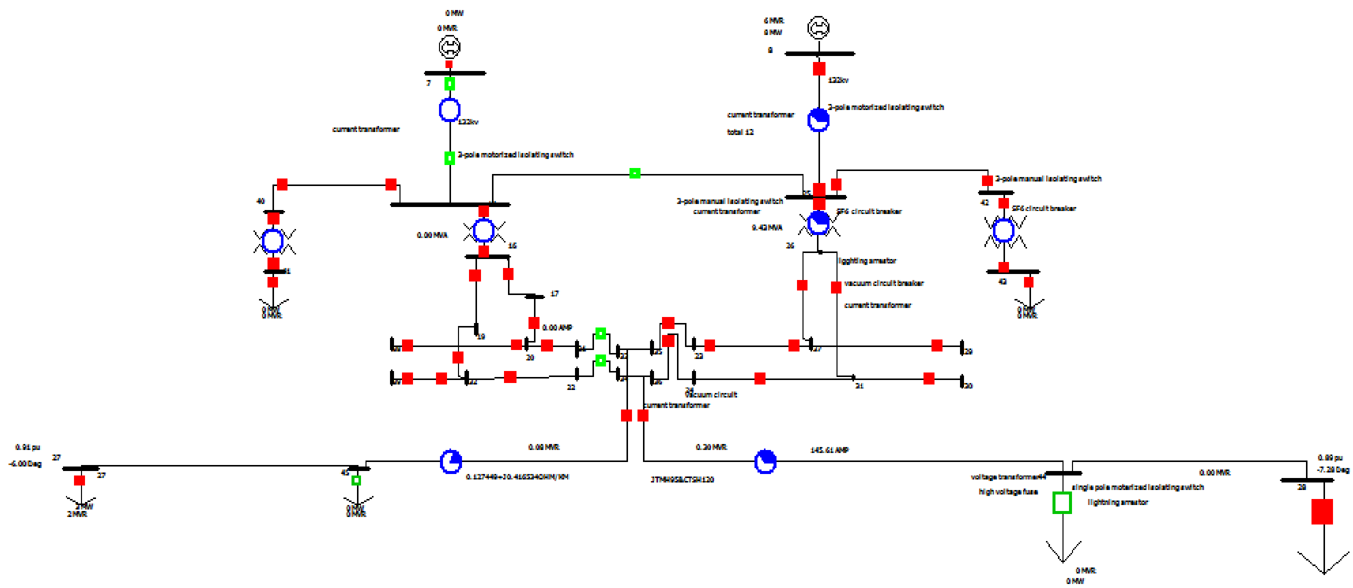


Figure 34 One line diagram of AC electric railway power system

4.6 Load Flow Problem

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

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

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

Chapter 5
Simulation Result and Analysis

5.1 Power flow result of Sebeta-Meiso without using compensator

To identify whether a compensator is required or not, and to determine the place at which the compensator is placed the power flow solution is done by PowerWorld simulating software using Newton Raphson iterative method. The simulation result presents the voltage, angle, losses, active and reactive power at every point of common connection.

Table 10 power flow result of sebeta- meiso ac railway

substation	Reactive power loss(MVar)	active power loss(MW)	Voltage(pu)	angle
sebeta	0.62	.1	0.94	-3.82
Indodo	0.65	.102	0.94	-3.96
Bishoftu	0.7	.11	0.93	-4.39
Mojo	.37	.06	0.95	-3.28
Adama	.59	.1	0.93	-4.46
Walachu	.71	.13	.91	-5.73
Chisa	.42	.07	0.95	-3.27
haro	.85	.141	0.91	-5.85
ajotre	0.23	0.04	0.96	-2.75
Awashit	.68	.11	0.92	-4.83
Adele	.49	.08	0.95	-3.64
Meiso	1.43	.24	0.89	-7.28

The above result shows the power system quantities for different traction substation without compensation. For successful power system operation under normal condition requires, bus voltage magnitude close to rated value (within 5% for HV, within 10% for LV); generator operates with in specified active and reactive power limit.

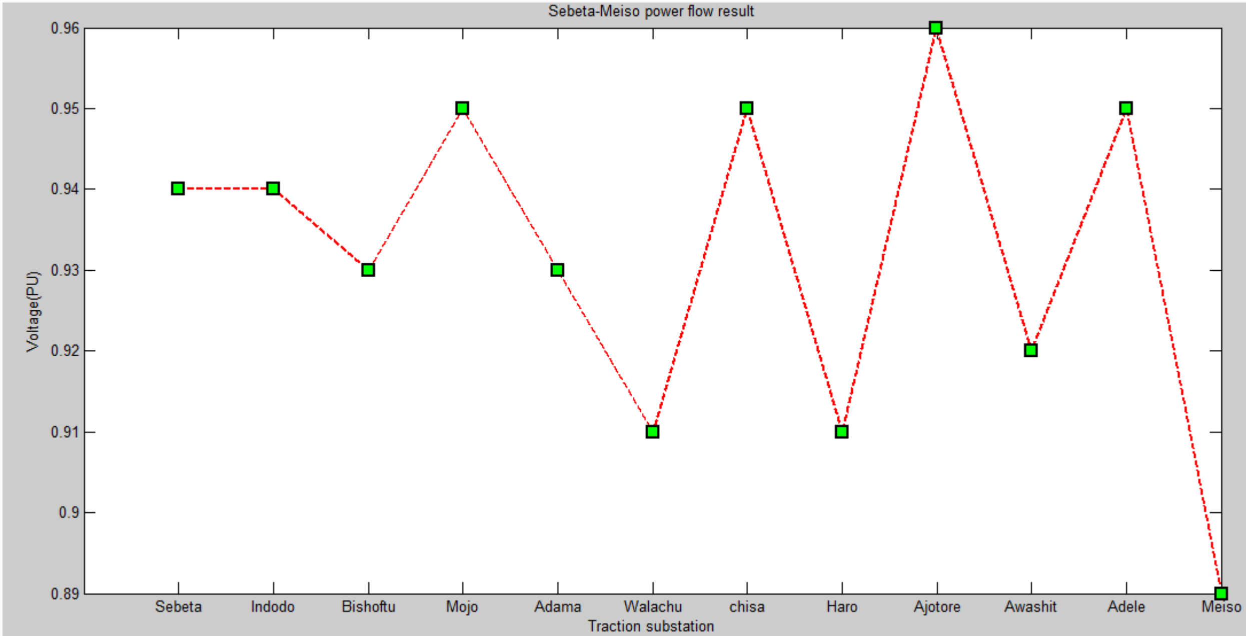


Figure 35 Bus voltage for Sebeta-Meiso Ac raiway network

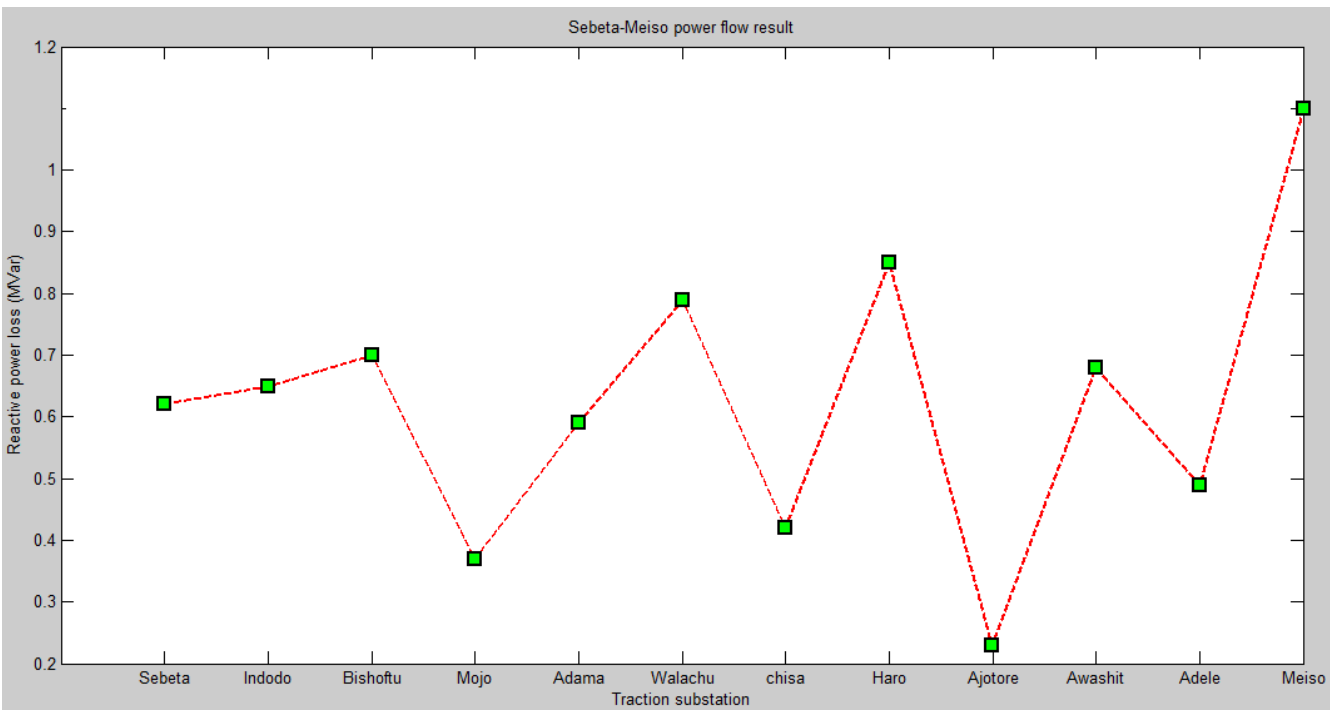


Figure 36 reactive power loss (MVar) for Sebeta-Meiso Ac raiway network

From the above results the voltage at Meiseo, Walachu and Haro is far from rated value. Moreover the reactive power loss is high. A properly designed and operated power system the voltage level would maintain close to rated value, and the reactive power should be minimized as much as possible. This is done by controlling the reactive power in the ac railway network.

The movement of reactive power is controlled by appropriate designing of SVC connected in shunt.

5.2 The SVC simulation result

SVC supply reactive power based the system requirement by controlling the firing angle of TCR.

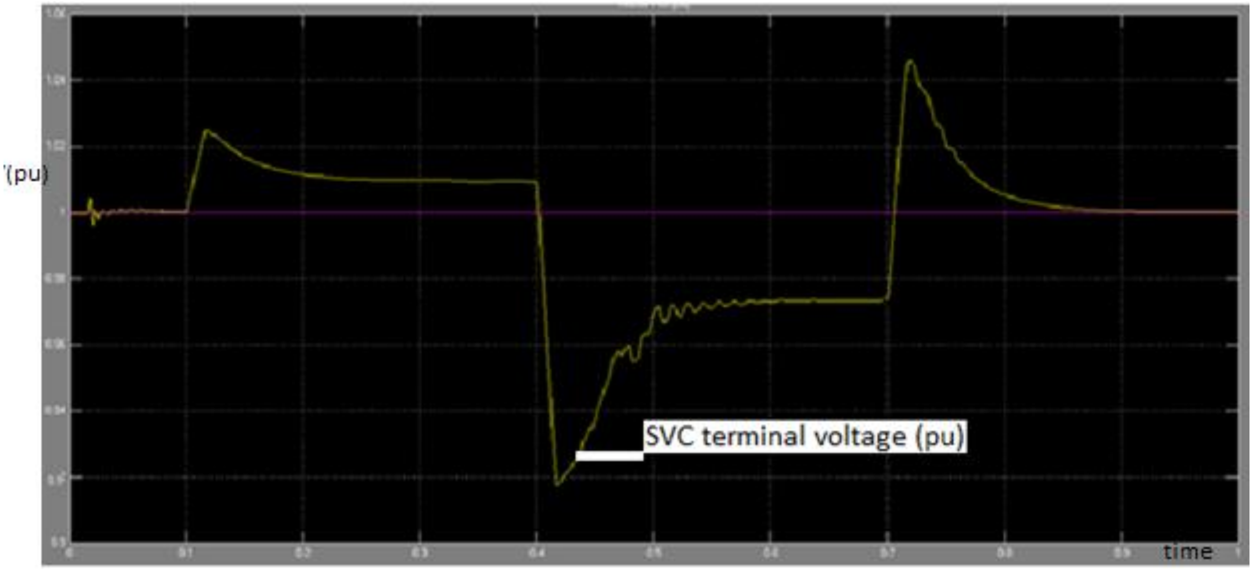


Figure 37 terminal voltage of SVC

To regulate the terminal voltage close to the rated value the firing angle of the TCR is varied between 90^0 and 180^0 as follows:

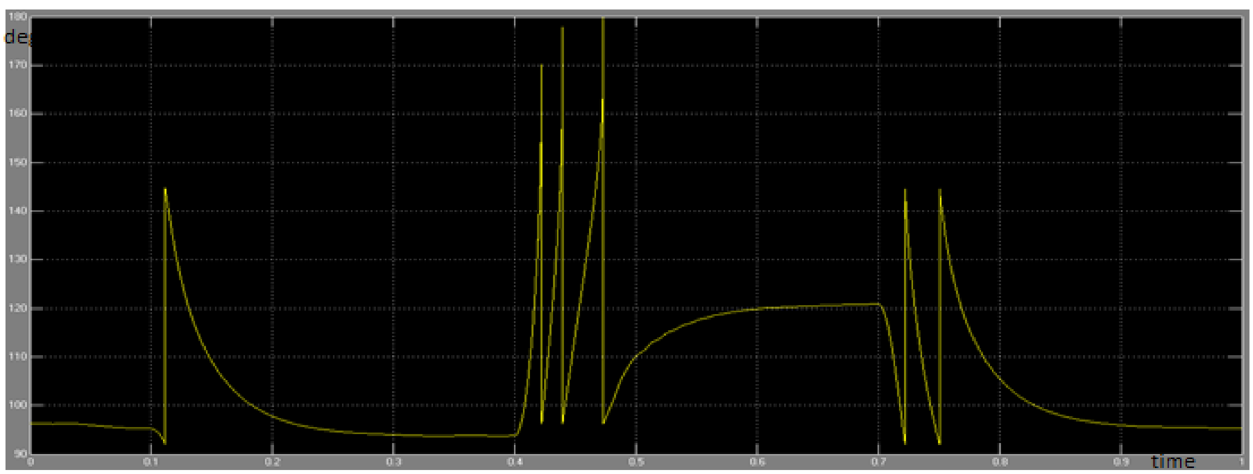


Figure 38 firing angle of TCR

5.3 The power flow result after the compensator

From the power flow result the traction substation Meiseo, Walachu and Haro requires a compensator to make the voltage terminal close to the rated value. Connecting designed compensator to these traction substation results with figure below:

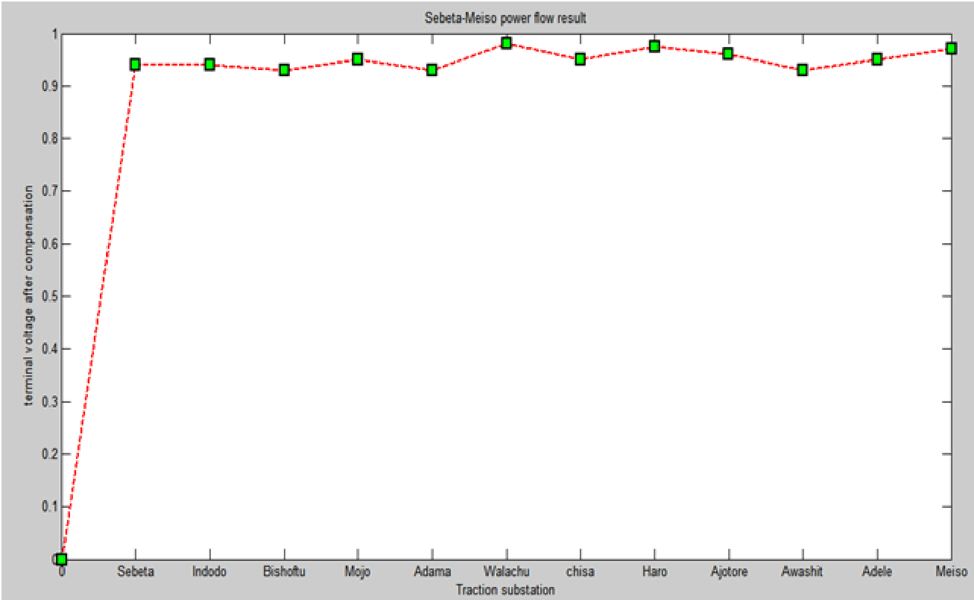


Figure 39 Voltage terminal after compensation

Table 11 power flow result after compensation and before compensation

Traction substation	Reactivepower loss(MVar)		Voltage(pu)	
	Before compensation	After compensation	Before compensation	After compensation
Walachu	0.75	0.41	0.91	0.98
Haro	0.81	0.4	0.91	0.975
Meiseo	1.43	0.90	0.89	0.97

A properly designed and operated ac railway power system meets the quality of power supply with regard to the constancy of voltage and level of reliability.

The three traction substation required a compensator and appropriate SVC is connected in shunt. The rest of traction substation power transfer capability would improve by the compensator connected on the train.

Chapter 6
Conclusion, recommendation and future work

6.1 CONCLUSIONS

The reactive power is compensated in to acceptable standard value by using SVC as compensator. An overview of the technological development of VAR generators and compensators has been presented. Starting from the principles of VAR compensation, controlling of movement of reactive power by controlling the firing angle of TCR have been reviewed. The introduction of semiconductors produced a dramatic improvement in the performance of VAR compensators: they have a faster dynamic behavior and they can control more variables. The introduction of FACT device at even higher voltage levels will increase the impact of VAR compensation in future applications. It can be observed that modern VAR compensators improve power systems performance, helping to increase reliability and the quality of power delivered to the customers.

The modeling of power system components and power flow analysis is done using Newton Rahpson iterative on powerworld simulating software to determine the place at which the compensator is connected.

This thesis presents a reactive power compensation and it can be concluded that the use of PI-controlled SVC (FC-TCR) compensating device with the firing angle control is continuous, effective and it is a simplest way of controlling the reactive power of transmission line. It is observed that SVC device was able to compensate both over and under voltages. With MATLAB simulations and actual testing it is observed that SVC (FC-TCR) provides an effective reactive power control irrespective of load variations.

Furthermore, for an economical operation of the system the losses is kept at a low value taking various constraints into account, and the risk that the system enters into unstable modes of operation is supervised.

6.2 Recommendation and future work

In this research thesis it mainly focus on the design of SVC and identifying suitable place by using power flow analysis to improve power factor by compensating reactive power.

From the result obtained it is better to install a compensator on the train for those traction substations whose pf is not very small. Since SVC is mostly efficient when there is high reactive power loss and voltage variation.

The compensation of reactive is well done by appropriate design and installing of SVC. This compensator would be more suitable where there is high reactive power loss.

From this research thesis it could be continuous detail on design of static var compensator using fuzzy logic controller, compensation using SVC with thyristor switched capacitor. The compensation could be expanding to the rest of new constructed ac railway network so that the movement of reactive power is controlled efficiently.

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Appendix A: Electrical Models for Simulation

Matlab model of SVC for compensation

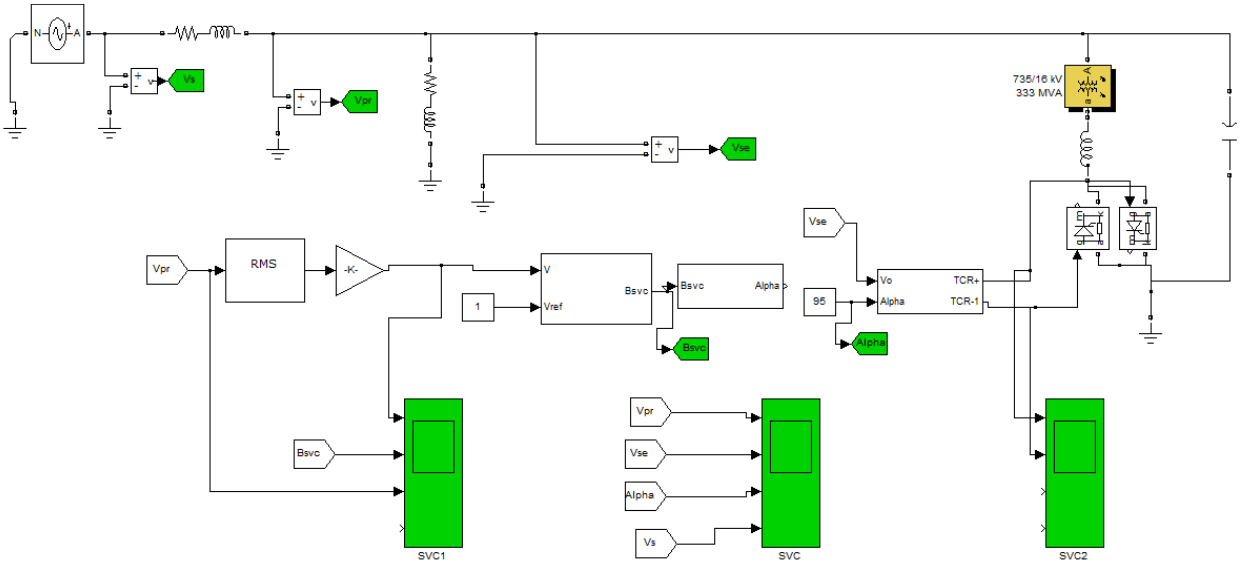

Figure 40 Matlab model of SVC for compensation

Powerworld model of traction substation network

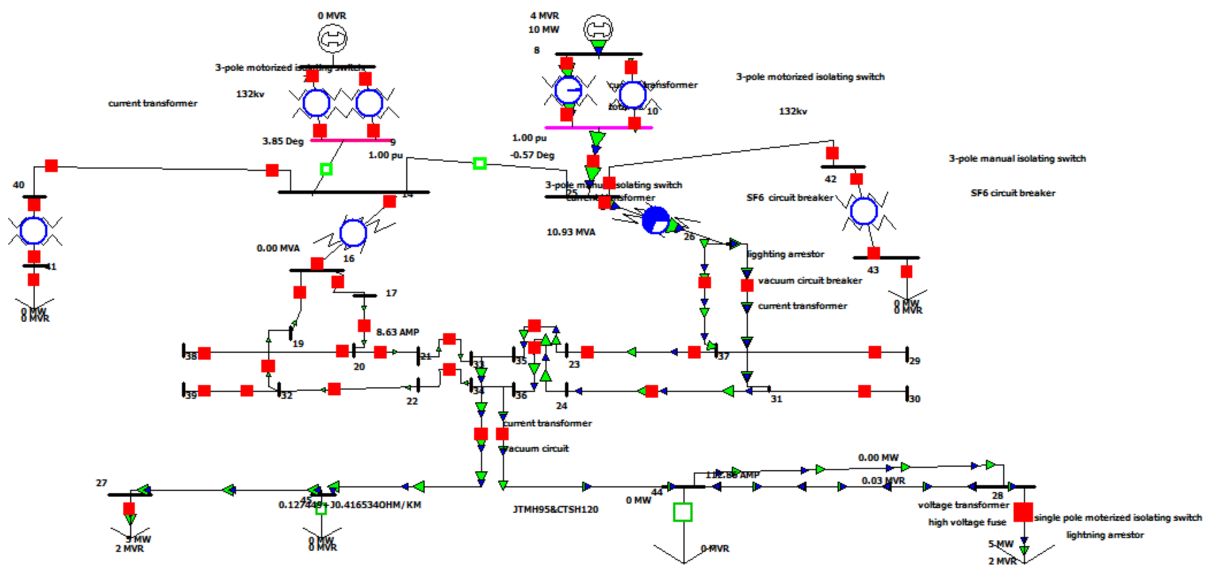

Figure 41 Powerworld model of traction substation network

Matlab code to plot power flow result

```
X =1:1:12
Y= [power flow result]

plot(X,Y,'--rs','LineWidth',2,...
        'MarkerEdgeColor','k',...
        'MarkerFaceColor','g',...
        'MarkerSize',10)
set(gca,'XTick',[1 2 3 4 5 6 7 8 9 10 11 12])
set(gca,'XTickLabel',{'Sebeta','Indodo','Bishoftu','Mojo',   'Adama',   'Walachu','chisa',   'Haro',
'Ajotore', 'Awashit', 'Adele', 'Meiso' })
xlabel('Traction substation')
ylabel('Reactive power loss (MVar)')
 title('Sebeta-Meiso power flow result')
```

Table 12 Installed capacity of traction substation （multiple-track section）

Traction substation		SEBETA	INDODE		BISHOFTU		MOJO	
Location of section post		LABU		DK48		DK82		ADAMA
Length of feeding section （km）		14.42	16.10	16.00	16.50	13.00	14.48	17.37
Calculated capacity （MVA）	Short term	6.87	7.03	5.83	5.94	3.20	3.80	6.17
	Long term	10.13	10.41	8.61	8.80	4.76	5.65	9.15
Verified capacity （MVA）	Short term	24.29	23.76	21.86	21.96	16.86	17.66	21.01
	Long term	24.29	23.76	21.86	21.96	16.86	17.66	21.01
Installed capacity （MVA）		2×25	2×（25+25）		2×（25+20）		2×（20+25）	

Table 13 Installed capacity of traction substation （single-track section）

Traction substation		WACHULALU		CHISA		HARO		AJO TERE		AWASHISHT		ADELE		MIESO
Location of phase splitting		DK144			DK173		DK220		DK253		DK286		DK318	
Length of feeding section （km）		11.60	12.35	14.00	17.05	17.90	17.09	17.00	16.00	16.70	16.00	16.45	16.00	16.45
Calculated capacity （MVA）	Short term	4.41	2.28	4.15	5.98	5.67	4.33	2.40	5.23	6.36	4.39	4.45	6.06	6.64
	Long term	6.33	3.37	6.07	8.73	8.25	6.35	3.67	7.67	9.33	6.39	6.53	8.80	9.75
Verified capacity （MVA）	Short term	9.25	6.42	13.86	9.97	14.93	12.64	8.72	14.71	19.68	15.22	8.62	10.74	18.21
	Long term	9.25	9.34	13.86	14.93	14.93	12.64	8.72	14.71	19.68	15.22	15.62	19.47	18.21
Installed capacity （MVA）		2× （10+10）		2×（16+16）		2×（20+16）		2×（10+16）		2× （20+16）		2×（16+20）		2×20

Table 14 Selection of wires

Purpose of wire material		Specifications of wire material
Contact wire	Main line	CTSH120
	Station track	CTSH-85
Messenger wire	Main line	JTMH-95
	Station track	JTMH-70
Additive wire	Line feeder	LBGLJ-185
	Return wire	LBGLJ-185

Table 15 Calculation of traction energy consumption and electrical energy loss （Unit: 10^4 kW•h）

Traction substation	Traction energy consumption	Short-term electrical energy loss			Traction energy consumption	Long-term electrical energy loss		
		Electrical energy loss of traction network	Electrical energy loss of traction transformer	Total		Electrical energy loss of traction network	Electrical energy loss of traction transformer	Total
SEBETA	1998	64.1	48.2	112.3	3596	115.1	86.3	201.4
INDODE	3827	122.7	92.3	215.0	6889	220.4	165.3	385.7
BISHOFTU	2765	88.8	66.4	155.2	4976	159.2	119.4	278.6
MOJO	2900	93.1	69.6	162.7	5606	179.4	134.5	313.9
WACHULALU	1881	86.8	67.0	153.8	3628	159.6	129.2	288.8
CHISA	3035	139.6	108.0	247.6	5854	257.6	208.4	466.0
HARO	2963	136.3	105.5	241.8	5714	251.4	203.4	454.8
AJO TERE	2512	115.6	89.4	205.0	4843	213.1	172.4	385.5
AWASHISHT	3223	148.3	114.7	263.0	6217	273.5	221.3	494.8
ADELE	3094	142.3	110.1	252.4	5968	262.6	212.5	475.1
MIESO	2061	94.8	73.4	168.2	3976	175.0	141.5	316.5