Addis Ababa University

Addis Ababa Institute of Technology (AAiT)

School of Electrical and Computer Engineering

Power Flow Analysis of Sebeta to Adama Railway Electrification power Line with Thyristor Controlled Series Compensator (TCSC)

By

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APPROVAL BY BOARD OF EXAMINERS

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I would thank my wife **Tigist Alemayehu** for her constant encouragement, and my four year old son ***Natinael Samuel*** who suffered some alienation and negligence during the course of this work.

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ABSTRACT

The Ethiopian Railway Corporation (ERC) is working hard to have modern railway system that uses the AC power supply system. Voltage drop in the feeding circuit differs substantially depending up on the train position, train current, number of train in the same power feeding section, track impendence etc. The minimum pantograph voltage for the train expected is to be 20kV, which is within the tolerable voltage fluctuation range of the overhead contact line. On the other hand, power transfer problems have occurred frequently within large variation of loads. These issues are important in traction power supply system to ensure normal operation of the electric locomotives.

Considering these two problems this thesis work propose integration of Thyristor Control Series Compensator transmission system for improving traction network voltage and enhancing power transfer capability for double-track Sebeta-to-Adama section of Ethiopian Railway line.

The necessary data and Electrical parameters are collected from the double-track Sebeta-to-Adama section of Ethiopian Railway line.

Modeling and simulation of traction system have been performed using MATHLAB/SIMULINK. The plots after simulation of networks both with and without Thyristor control series capacitor has helped to analyze the power flow and traction voltage level. The overall power transfer capacity of the catenary line of the system is increased. This thesis work shows that the real power is enhanced from 11.9MW to 14.33MW (measured at the load side), which is 16.34% enhancement by using TCSC controlling of catenary line. Integration of TCSC has also advantages of improving the substation power factor, In this thesis it is shown that the power factor is improved from 0.94 to 0.99, at the same time it can be used as the load voltage improving device, As shown from result part of this thesis the load voltages of train one and train two are improved from 21.69kV to 25kV and 21.61kV to 25kV respectively. Based on these results it is recommended that Ethiopian Railway Corporation to consider integrating TCSC device for Sebeta to Adama railway line.

Keywords- Direct fed , Power flow , Power control ,Traction system, and Voltage drop

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LIST OF ABBREVIATIONS AND SYMBOLS

a	Substation's transformer ratio
AC	Alternate Current
AT	Autotransformer
BT	Booster Transformer
C	Overhead Catenary Contact Wire
C-bank	Capacitor bank
CC	Capital cost
DC	Direct Current
EEPCO	Ethiopian Electric Power Corporation
EMI	Electromagnetic Interference
Et	Voltage source of the train model
f	Operating frequency, normally 50 Hz
F	Feeder wire
FACTS	Flexible Alternating Current Transmission Systems
FD	Feeding distance (Between SS and sp
Fdrag	Drag force or train resistance
Fgrad	Gradient force
FS	Feeder Substation
g	Acceleration due to gravity (9.81 m/s2)
G	Generation or Generator
HVAC	High Voltage Alternate Current
HVDC	High Voltage Direct Current
Hz	Hertz
IC, *VC*	Current and voltage of the overhead catenary contact wire
IF, *VF*	Current and voltage of the feeder wire
kV	kilo Volt
MVA	Mega Volt Ampere
STATCOM	Static Synchronous Compensator
IR, *VR*	Current and voltage of the rails
iS	Source current
km	Kilometre
kph	Kilometre Per Hour
Meff	Effective mass
Mfrgt	Freight load
Mpsg	Passenger mass
MPTSC	Mid-Point Track-Sectioning Cabin
Mtare	Tare mass
MVA	Mega Volt-Ampere
MVar	Mega Volt-Ampere Reactive
p.u.	Per-unit
PAC	Phase-angle Compensator
pf	Power Factor

PS	Constant real power demand
RC	Return conductor
SD	Complex power drawn by load or powering train
SG	Complex power supplied by generator or re-generative
SS	Substation
STATCOM	Static Synchronous Compensator
SVC + UPF	Compensation with the SVC together with PWM
SVC	Static Var Compensator
TCR	Thyristor-controlled Reactor
TCSC	Thyristor-controlled Series Compensator
TE	Tractive Effort (N)
Vgrid	Nominal voltage of the utility supply grid
Vi	Voltage vector at bus i
Vi	Magnitude of the voltage *Vi*
VS	Thevenin voltage of the substation
VSI	Voltage Source Inverter
VSS	Substation terminal voltage
YSS	Admittance matrix representing the substation
z1	Primary leakage impedance of the substation's transformer
z2	secondary leakage impedance of the substation's transformer
zCC	Self-impedance of the overhead catenary contact wire
ze	Earthing impedance
zFF	Self-impedance of the feeder wire
zgrid	Short-circuit impedance of the utility supply grid
zS	Thevenin impedance
zt, yt	Impedance/admittance of the train model
α	Firing angle
β	Diagonal bandwidth
δ	Phase angle
ΔELoss	Energy loss reduction

CHAPTER ONE

INTRODUCTION

1.1. Back ground

Electrified railway systems (RES) are used widely around the world as a significant means of mass and public transportation. They are expanding at great speed throughout the world. Like many other nations, Ethiopia is also working to have the modern railway lines that use the AC power supply system.

Electric traction networks will be interconnected to different substations and load centers according to the existing plan. But load demands on the railway system will not constant. With the increase of traction load, more power is consumed. To fulfill the load demand, either electrical system network to be re-evaluated or the power carrying capability the transmission line to be increased. Economic point of view, modification or alteration of electric network is costly. Thus aim is to increase the power carrying capability of transmission line.

Nowadays power system are undergoing changes and becoming more complex from operation, control and stability maintenance standpoints when they meet ever-increasing load demand [1]. Voltage stability is concerned with the ability of a power system to maintain acceptable voltage at all buses in the system under normal conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance, increase in load demand or change in system condition causes a progressive and uncontrollable decline in voltage [2]. Power flow in Electrical Power System can be improved by adjusting reactance parameter of the transmission line. It can also be enhanced by adding a new transmission line in parallel with the existing one [2]. The main factor causing voltage instability is the inability of the power system to meet the demand for reactive power [3]. In power system applications the equivalent impedance control that maintains the equivalent impedance of the transmission line may be the preferred method from the operating stand point.

The various parameters involved in power flow are:

a) Load angle

b) Transmission line impedance

c) Operating variables such as voltage and current

To enhance the power flow from one bus to another bus, either of three parameters to be controlled. To maintain both dynamic and steady state operation, the new technology i.e. FACTS (Flexible AC Transmission System) is used which is a power electronics based system. Its main role is to enhance controllability and power transfer capability in AC systems. FACTS technology uses switching power electronics to control power flow in the range of few tens to a few hundreds of Megawatts.

1.2. Statements of the problem

In rail way power transmission lines should not be overloaded, the catenary voltage should be within specifications, and the train power requirements should met. Voltage drop in the feeding circuit differs substantially depending up on the train position, train current, number of train in the same power feeding section, track impendence etc. The minimum pantograph voltage for the train is expected to be 22.25kV (reference is ne)[7-8], which is within the tolerable voltage fluctuation range of the overhead contact line. On the other hand, power transfer problems have occurred frequently within large variation of loads. These issues are important in traction power supply system to ensure normal operation of the electric locomotives. There for the two problems which will be addressed on this thesis are how can be enhance the power transfer capability of Sebeta- to-Adama railway power supply line ? and how can be improve its network voltage at the same time ? this thesis work propose integration of Thyristor Control Series Compensator transmission system for improving traction network voltage and enhancing power transfer capability for double-track Sebeta-to-Adama section of Ethiopian Railway line.

1.3. Objectives

General objective

The main objective of this thesis work is to analyze the power flow of Sebeta_to-Adama railway electrification power line and investigating the advantages of inserting TCSC to the transmission line for enhance power transfer capability and improve traction network voltage drop.

Specific objectives

The specific objectives of this thesis are:

- to improve power transfer capability of Sebeta- to- Adama traction line
- To enhance traction voltage level
- To improve the feeding section power factor
- Reduce traction line voltage

1.4. Scope of the thesis work

The performance analysis in this thesis work has been carried out based on simulation of the proposed techniques using MATLAB software. In this thesis only the railway line from Sebeta-to-Adama is considered for simplification. It also discussed some aspects of railway electrification system (RES) and in particular electric distribution system of direct feeding with return conductor railway power system.

With the objective of enhancing the power flow and improving traction network voltage level in the transmission line using TCSC, it is essential to know the power flow between two buses and the various parameters involved in the power flow equation. Thus use of Flexible AC transmission System (FACTS) controller has strong impact on power flow enhancement.

1.5. Methodology of the study

The methodology that has been employed to achieve the objectives of this thesis work includes:

- Literature Reviewing: This includes reading books, articles, and simulation tools.
- System modeling: it involves formulating the mathematical relationship governing the railway electric load flow system parameter for each component.
- Collecting data which are essential for the thesis work from different company's and standards
- Simulation: involves simulating the modeled component using MATLAB/SIMULINK software.

1.6. Organization of the thesis

The thesis work is organized into six chapters which are briefly summarized below.

Chapter one presents the introduction, background, motivation and statement of the problem, objectives of the study and methodology followed in the thesis work. In addition, it provides the outline of the thesis.

The second chapter discusses about the theoretical background and literature review of the study topic, mainly on train movement and performance calculation, power consumed by the train, speed and position update, AC and DC traction power supply system and FACT devices.

Active and Reactive power flow analysis is included in third chapter of this thesis work. In this chapter, principle of Active and Reactive power flow, principle of AC power control and methods of series compensation are discussed.

The fourth chapter outlines the modeling of subsystems. In this chapter the substation, transmission line, train, and TCSC are modeled.

Simulation results and discussions are put in the fifth chapter of this thesis work. Proposed solutions to the power transfer enhancement and traction network voltage improvement problems and the appropriate simulations are discussed in detail in this chapter.

Conclusions, recommendations and future works are incorporated under chapter six.

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1. Train movement and performance calculation

Suppose that a train of mass M_{eff} is on a slope making an angle θ to the horizontal as shown in Fig. bellow, where M_{eff} is the effective mass [24]. The train motion is opposed by various forces, e.g. aerodynamic drag, track gradient force, etc. By applying Newton's second law, the train movement equation is expressed in equation 2.1, where α is the train acceleration.

$$TE - F_{grad} - F_{drag} = M_{eff}\alpha \qquad 2.1$$

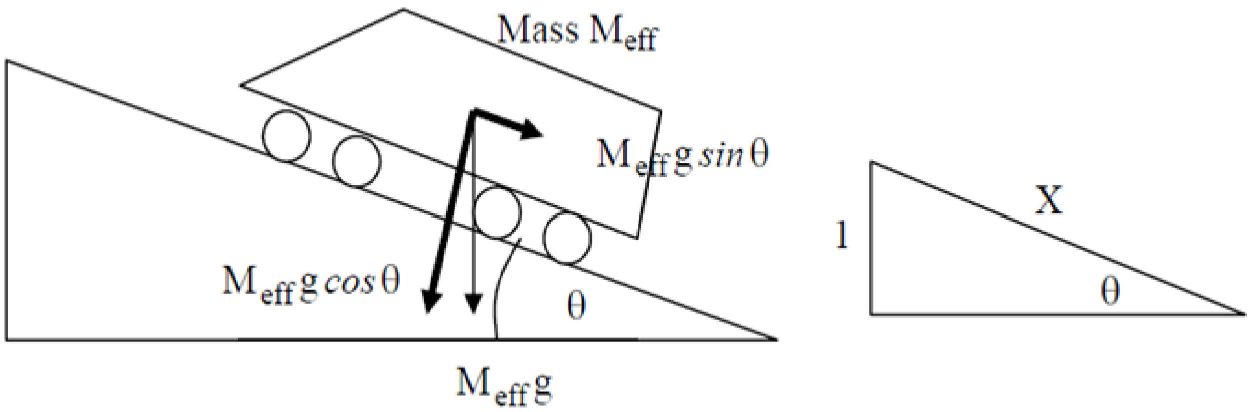


Fig. 2.1 Resolution of Mass force on gradient [8]

The aerodynamic drag is difficult to predict from calculations, however based on measurements from run-down tests where the natural deceleration of a train on straight, level track on a windless day is measured the drag force can be characterized [8]. Different operators have their own favorite equation to fit the train resistance. The Davis equation [2] as equation 2.2 is commonly used.

$$F_{drag} = a + by + cy^2 \qquad 2.2$$

Where a, b and c are drag-force coefficients and v is the train speed. It is common to use different values for open or tunnel situations [8]. To push a heavy train up slopes requires substantial force. Gradients on railways are small and usually expressed in the form of 1 in X, where X is the horizontal distance moved to rise 1 unit, see Fig2.1.

With a small arbitrary angle θ the gradient force can be approximated by using equation bellow.

$$F_{grad} = M_{eff}\, g \sin\theta = \frac{M_{eff}\, g}{X} \qquad 2.3$$

When accelerating a train, there are both linear and rotational movements. The total mass (tare mass plus passenger or freight mass) is accelerated in linear sense while the wheel sets, gears and motors are involved rotationally. It is usual to express this rotational effect as an increase in the effective linear mass of the train called the "rotary allowance" and expressed as a fraction of the tare weight of the train as equation bellow.

$$M_{eff} = M_{tare}(1+\tau) + M_{PSG} + M_{frgt} \qquad 2.4$$

where

Mtare is the tare mass

Mpsg is the passenger mass

Mfrgt is the freight mass

τ is the rotary allowance

Traction drive equipment provides the tractive effort. The power being developed is the product of the tractive effort and speed. There are some key factors that result in variations of train performance. In the most country system, during train running, the pantograph voltage can vary from 16.5 kV to 27.5 kV with a maximum fault level at the pantograph of 330 MVA, 25 kV [8]. This variation causes a change of the tractive effort as a function of the line voltage applied to traction motors, especially in DC railways. The tractive effort curves resulting from line voltage variation are shown in Fig. 2.2, where three traction control regions [8]: i) Constant tractive effort, ii) Constant power and iii) Reduced power are evident. In AC railways where traction motors are fed through an AC/DC power converter with DC link voltage regulation, the train performance is less dependent on the pantograph voltage. Thus, in the present study, tractive effort variation with line voltage has not been included in the modeling. This is reasonable as one of the main objectives of the central controller is precisely to maintain a good voltage profile. However, if it became apparent that voltages lower than 19.5 kV, say, were present, it would be necessary to refine the simulation to include voltage dependent tractive effort models as shown in Fig. 2.2.

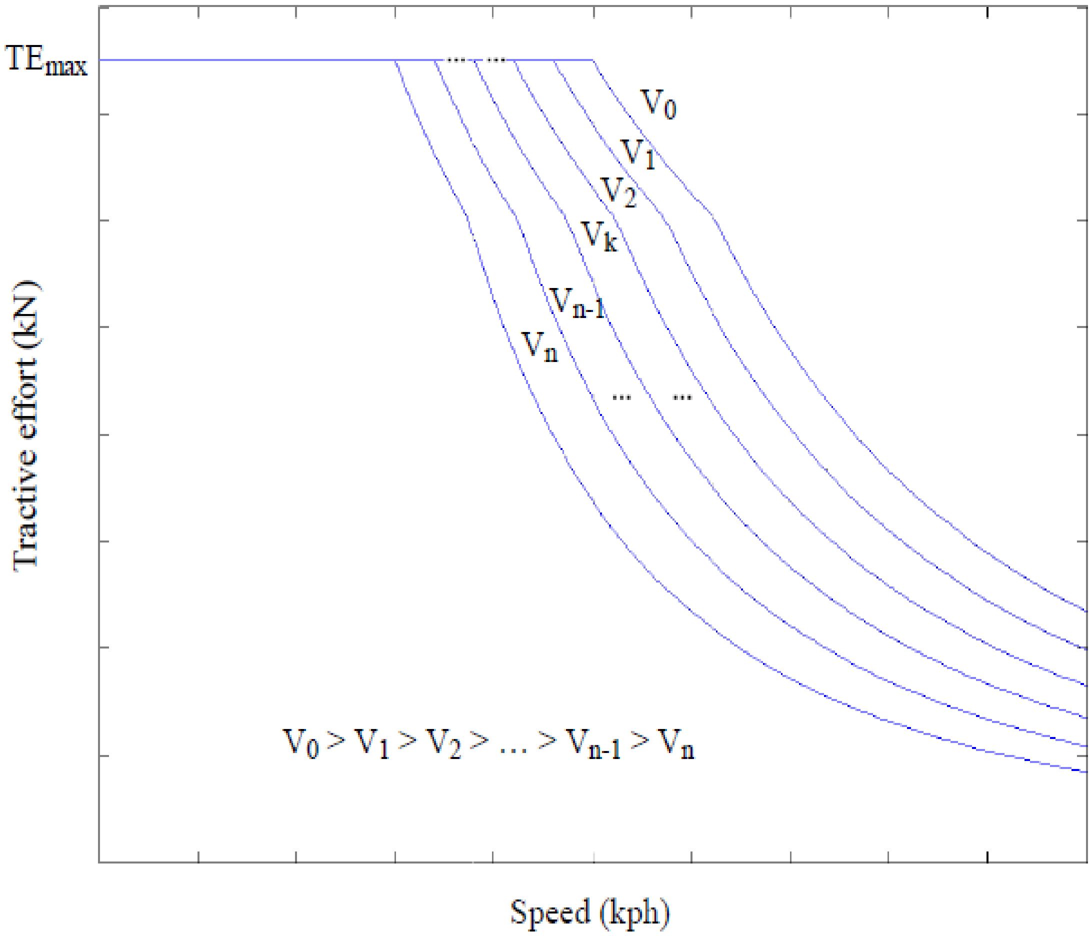


Fig. 2.2 Tractive efforts resulting from the line voltage variation [8]

2.2. Power consumed by a train

Power consumed by a train corresponding to tractive effort TE and instantaneous speed v is given by the following expression:

$$P = \frac{TE * V}{\eta} \qquad 2.5$$

Where

η denotes the efficiency of conversion of electrical input power to the mechanical output power at the wheels.

The power consumed by a train depends on:

- The train speed
- The line gradient
- Transportation density
- Train operation (start, stop, etc…)

The higher train's speed means the larger air resistance. Air resistance is geometric growth with speed. At the same traction weight and line gradient situation, traction power and energy will raise rapidly with the increased speed. Especially in the high speed, air resistance is the main factor. [China document]

Train's running needs to overcome gravity when climbing. At low speed, air resistance is small. Line gradient is the main factor influencing traction power. While at high speed, air resistance is the main factor. Line gradient has less influence.

Train tracing interval is the minimum departure interval between adjacent two trains. This interval needs to meet the requirement of transportation and safety operation. Train operation organization is determined according to traffic volume and transportation plan.

2.3. Speed and position update

Once the train acceleration is obtained, the speed and position of the train is calculated by the following equations,

$$V_t = V_i + \alpha \Delta t \qquad 2.6$$

$$d_t = d_i + V_i + \frac{1}{2}\alpha \Delta t^2 \qquad 2.7$$

Where,

v_i and v_t are the initial and terminal speed

Δt is the time step, 0.5 s in this thesis

d_i and d_t are the position before and after updated

2.4. Traction power supply system

A traction power supply or traction power network is an electricity grid for the supply of electrified railway networks. Rail transit power supply system converts electrical energy in to mechanical energy to drive electric trains, electric multiple units and urban trains.

The evolution in electrical traction systems has produced a variety of electrification systems inspired to very different principles [23]. At the moment several kinds of Railway Traction Electric Power Systems exist in different countries:

- DC systems (750/1500/3000 V)
- Medium voltage AC systems (15/25 kV, 50/60 Hz)
- High voltage AC systems (50/2x25 kV, 50 Hz)
- Low frequency systems (15 kV, 15-16$^{2/3}$ Hz)

The low voltage DC system is used for light rails usually supplied at 750 Volts (metro transit) and for commuter and intercity trains usually supplied at 3000 Volts .The medium voltage AC system was adopted in order to reduce voltage losses. The 25 kV system has the various advantages such as the simplicity of substations and of single contact wires. It is typically used for commuter trains or freight trains. The high voltage AC systems are the 50 kV and 2x25 kV (or ±25kV) ones. The 50 kV system has been used where the traction load is high and the traction distances are large. Typically it can however; medium and high voltage single-phase alternating current supply of the typical AC electrified railway has always involved several problems owing to the relevant power of intrinsically single-phase traction loads, which produce unbalanced in the three-phase section and the subsequent generation of voltage unbalances within the primary grid.

. The electrical substations play the role of handling the electrical energy supplied by AC transmission network (transforming, sharing out and converting sections).

The substation schemes differ according to the kind of traction line they feed, the train load, the number of tracks being fed by the substation, etc. The distance between the various substations depends on the train electrification system and on the traction load power. Generally there are two incoming tracks and two outgoing tracks to be fed at each substation unless it is a junction substation. The substation scheme is different according to whether it is an AC substation or a DC one.

As far as concerns the *catenary functioning***,** an electric railway takes its power for the electric motors, lights, air conditioning, etc., from the overhead line using the pantograph on the roof. The pantograph is in constant contact with the overhead line (contact wire) located about 5 m above the rails, whether the train is moving or not. Therefore, the overhead line must always be located within the pantograph range, and the pantograph must always maintain contact with the overhead line in order to supply uninterrupted, good-quality power at all times.

If most of an existing rail network is already electrified, there are benefits to extend electrified lines to allow through running. The main disadvantage is the capital cost of the electrification equipment, most significant for long distance lines that do not have heavy traffic. Suburban railways with closely spaced stations and high traffic density are the most likely to be electrified, and main lines carrying heavy and frequent traffic are also electrified in many countries. Basically the major advantage and disadvantages of electrification can be listed as in below.

Advantages:

- Lower running cost of locomotives and multiple unit
- Higher power-to-weight ratio , resulting in
- Fewer locomotives
- Faster acceleration
- Higher practical limit of power
- Higher limit of speed
- Less noise pollution
- Lower power loss at higher altitudes

Disadvantages:

- Upgrading brings significant cost ,
    - Especially where tunnels and bridges and other obstruction have to be altered for clear an
    - Alteration or upgrades will be needed on the railway signaling to take advantage of the new traffic characteristics.

- Increased maintenance cost of the lines (although reduced maintenance cost and multiple units)

Power is transmitted to electric railway locomotives and vehicles using DC or AC networks. The parallel development of traction technology in the industrialized countries has led to a plethora of different electrification systems, Table 1 exemplifying the geographical extent of the various voltages and frequencies in use in Europe. For new railways, the type of network is influenced by technical considerations such as:

- operational requirements (for urban metro, high-speed passenger or heavy haul freight)
- physical route characteristics (such as gradients, and bridge and tunnel clearances)
- proximity of generating plant and utility or railway-owned power networks
- Available traction technology (converters, traction motors and regenerative capability).

2.4.1. DC Railway Electrification Supply System

A DC substation derives AC High Voltage energy from one or more supply nodes. Then it converts the voltage to a suitable level for feeding the contact wires. There are rectifying units to convert the AC to DC and delivery systems to the different fed lines. The feeding voltage of the DC substations can be 66, 132 or 150 kV. A direct-current feeding system features a three-phase bridged silicon rectifier for conversion from alternating to direct current. In order to reduce the harmonics, a more-modern rectifier design using a 12-pulse system featuring two sets of 6-pulse rectifying circuits is used. [7]

2.4.2. AC Traction Power Supply System

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 Ethiopian's overhead catenary feeding system [8]. Each feeder substation 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 [9] as shown in fig 2.3

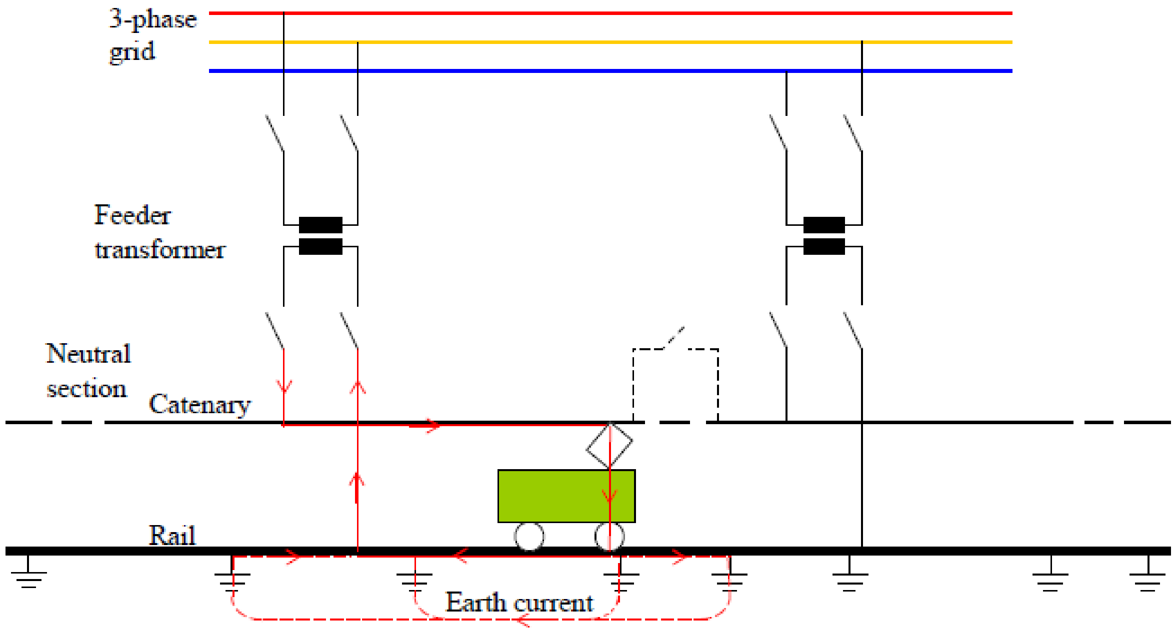


Fig 2.3 Typical feeding arrangement of 25 kV traction system [7]

The feeding arrangement of the single-phase AC railway power supply requires neutral sections to separate two adjacent feeding networks at the feeder substation under normal operation.

The function of an AC traction system is to deliver power to the locomotives as efficiently and economically as possible. Problems involved in providing protection to traction systems are different from those faced in protecting other transmission lines or distribution systems working at the same voltage level. This is due to the continuous movement of locomotive load, change in the length of the line during operation, nature of loading, voltage drop due to the flow of the lagging reactive current in inductive components of the overhead system and the high levels of harmonic distortion [1]. Fig.2.3 shows the typical feeding arrangement of a 25 kV electrified railway system. The adjacent traction substations are fed from different phases of the three-phase supply in rotation having phase difference of 120^0. The supply to the OHE can be switched ON/OFF through interrupters. Normally power supply from the traction substation extends up to the sectioning post (SP) on either side of the substation, but in case of an emergency necessitating total shut down of the substation, it can be extended up to the failed substation by closing the bridging interrupters at the two SPs. Fault on the OHE can be of two types (i) Earth faults (ii) Phase-to-phase faults. The second fault can occur by accidental closure of the bridging interrupter at the SP during normal feeding condition or by a short circuit at the insulated overlap opposite a traction substation at times of emergency feed conditions. This is termed as Wrong phase coupling (WPC) fault. The excessive voltage drop due to the flow of lagging reactive current makes the performance of the system even worse. Voltage regulation with shunt compensation allows overcoming these drawbacks. Static VAR Compensators (SVCs), Thyristor controlled reactors (TCRs) and Thyristor Switched Capacitors (TSCs) can be used to provide such compensation.

The typical AC feeding systems on the traction side that are widely used for feeding electric energy to electric trains in mainline AC railway are [7, 8]:

a) Direct feeding system

b) Booster transformer feeding system, and

c) Auto transformer feeding system

A) 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]. Fig. 2.2a shows the diagrams of the direct feeding configuration

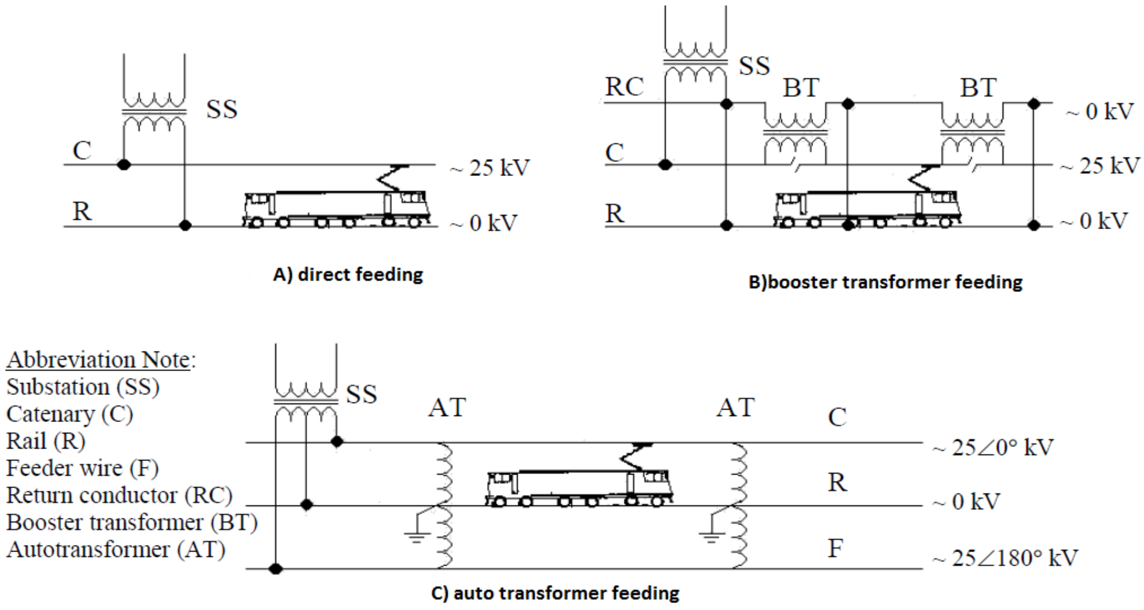


Fig 2.4 Overhead catenary feeding systems for AC railways[8]

B) Booster transformer feeding configuration

This method employs booster transformers (BT) added along the catenary at every specified 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, 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. Fig. 2.2b shows the configuration of the BT feeding system.

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.

C) Autotransformer feeding configuration

Adding autotransformer (AT) at specified intervals can increase substation distance. 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. Fig. 2.2c shows the configuration of the AT feeding system.

2.5 Flexible AC Transmission System (FACTS)

FACTS is defined by the IEEE as a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability [8]. There are two groups of FACTS devices. The first group employs conventional Thyristor switched capacitors and reactors, and quadrature tap-changing transformers. This includes the Static Var Compensator (SVC), the Thyristor- Controlled Series Capacitor (TCSC), and the Thyristor-Controlled Phase Shifter (TCPS). The second group utilizes gate turn-off (GTO) hyristor-switched converters as voltage source converters (VSCs). This group contains Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), the Unified Power Flow Controller (UPFC), and the Interline Power Flow Controller (IPFC) [7].

FACTS devices have been mainly used for solving various power system steady state control problems such as voltage regulation, power flow control, and transfer capability enhancement [9]. As supplementary functions, damping the interred modes and enhancing power system stability using FACTS controllers have been extensively studied and investigated [10]. These regulatory tasks are accomplished trough appropriate reactive power compensation, or by series capacitive compensation of line inductances, or by phase angle shifting.

However it is not found to be cost-effective to install FACTS devices for the sole purpose of power system stability enhancement [7].

The basic applications and advantages of FACTS devices are [15]:

1. Power flow control.
2. Increase of transmission capability.
3. Voltage control.
4. Reactive power compensation.
5. Stability improvement.
6. Power quality improvement.
7. Power conditioning.

8. Flicker mitigation.
9. Interconnection of renewable and distributed generation and storages [15].
10. Rapid, continuous control of the transmission line reactance [17].

2.6 Related works

Fuerte-Esquivel. C.R.; Acha, E.; Ambriz-Perez, H. presented a paper on TCSC model for the power flow solution of practical power networks in which power flow from one bus to another bus is determined. In this paper he discussed how TCSC can be incorporated into electrical network having large number of buses. Also he found

load flow solution using Newton-Raphson method within the specified tolerance.

R. Mohan Mathur, Rajiv K Verma, IEEE Press Series on Power Engineering, 2002, discussed the various applications of TCSC such as improvement in system stability, the damping of power oscillations, the alleviation of sub-synchronous resonance (SSR) and the prevention of voltage collapse. In addition, he described about two TCSC's installation : one in Sweden, the other in Brazil. P.H. Ashmole described in IEEE publication about the FACTS controllers andits utility. In his discussion in "Introduction to FACTS" he described that FACTS controller are mainly aim to control three parameters such as voltage, phase angle and impedance.

Narain G. Hingorani, Laszlo Gyugyi, [3] has described about all FACTS controller in his book 'Understanding FACTS". Out of many FACTS controller TCSC is one of the important FACTS controller about which he described in details how its range of reactance varies from inductive to capacitive region. Persson, J.; Rouco, L.; Soder, L, [18] presented a related topic on Linear analysis with two linear models of a thyristor controlled series capacitor at Power Tech Conference Proceedings, 2003 IEEE Bologna. Abdel-Moamen, M.A.; Padhy, N.P,

Billinton, M. Fotuhi-Firuzaba and S.O. Faried describe the impact of a Thyristor Controller Series Capacitor (TCSC) on power system reliability [24]. In this application the TCSC is employed to adjust the natural power sharing of two different parallel transmission lines and therefore enable the maximum transmission capacity to be utilized. A reliability model of a multi-module TCSC has been developed and incorporated in the transmission system. The result of the investigation shows a significant improvement in the system reliability when the TCSC is utilized.

A review of earlier paper published on the FACTS controller shows that a lot of work done on different FACTS controller. Also several papers published on Thyristor Controlled Series Capacitor (TCSC) which is used for different application as mentioned above. Still a lot of work to be done to improve the power flow control in industrial transmission line.

This thesis work propose integration of Thyristor Control Series Compensator transmission system for improving traction network voltage and enhancing power transfer capability for double-track Sebeta-to-Adama section of Ethiopian Railway line as one part of transmission system.

CHAPTER THREE

ACTIVE AND REACTIVE POWER FLOW

3.1. Introduction

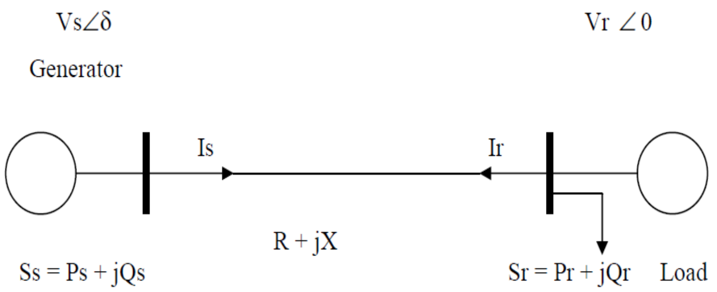


Fig 3.1 Two bus system

From fig 3.1 which is a two bus system connected two generators and one load

Let

I_s = Sending end current

I_r = Receiving end current

E_s = Sending end voltage = $Vs\angle\delta$

E_r = Receiving end voltage = $Vr\angle 0$

R=Transmission line resistance

X= Transmission line reactance

Transmission line impedance Z = R + jX = $|Z|\angle\alpha$

Sending end current

$$Is = \frac{Vs\angle\delta - Vr\angle 0}{|Z|\angle\alpha} \qquad 3.1$$

$$Is = \frac{Vs\ \angle\delta - \alpha}{|Z|} - \frac{Vs\angle - \alpha}{|Z|} \qquad 3.2$$

Ss = Sending end complex power = Vs Is*

$$Ss = Vs\angle\delta\left[\frac{Vs\ \angle\alpha - \delta}{|Z|} - \frac{Vs\angle\alpha}{|Z|}\right] \qquad 3.3$$

$$Ss = \left[\frac{Vs^2 \angle \alpha}{|Z|} - \frac{VsVr \angle \alpha + \delta}{|Z|} \right] \quad 3.4$$

Real power or active power flow from sending end is

P_s = Real (S_s)

$$Ps = \frac{Vs^2 \cos \alpha}{|Z|} - \frac{VsVr \cos(\alpha + \delta)}{|Z|} \quad 3.5$$

Reactive power at sending end is

Qs = Imaginary (Ss)

$$Qs = \frac{Vs^2 \sin \alpha}{|Z|} - \frac{VsVr \sin(\alpha + \delta)}{|Z|} \quad 3.6$$

Power system transmission lines have small resistance compared to the reactance i.e. R/X ratio is very small. Also power loss in the transmission line is negligible. Thus with this assumption

R = 0, $Z = |X| \angle 90$

i.e $\alpha = 90^0$

So equations (3.2) and (3.3) becomes

$$Ps = \frac{VsVr}{|X|} \sin \delta \quad 3.7$$

$$Qs = \frac{Vs}{|X|} [Vs - Vr \cos \delta] \quad 3.8$$

From the equations (3.7) and (3.8), it is clear that for a typical power system with small R/X ratio, the following important observations are made:

Equ (3.7) shows that flow of real power from sending end is proportional to sin δ. That is with small change in phase angle between sending end and receiving end voltage has significant effect on the real power flow. But small changes in voltage magnitude will not have appreciable effect on the real power flow.

If E_s leads E_r, then load angle δ is positive and real power flows from sending end to receiving end.

If E_s lags Er, then load angle δ is negative and power flows from receiving end to sending end.

2. If resistance R = 0, then maximum real power flow from sending end occurs at δ = 90^0

The maximum power flow is given by $P_{max} = \frac{VsVr}{|X|}$

3. For maintaining transient stability, the power system is usually operated with small load angle δ. Thu s cos δ≈ 1 for δ is very small. Thus reactive power flow from sending end for small δ is given by:

Fig3.2. show how both the active and reactive power changes with load angle.

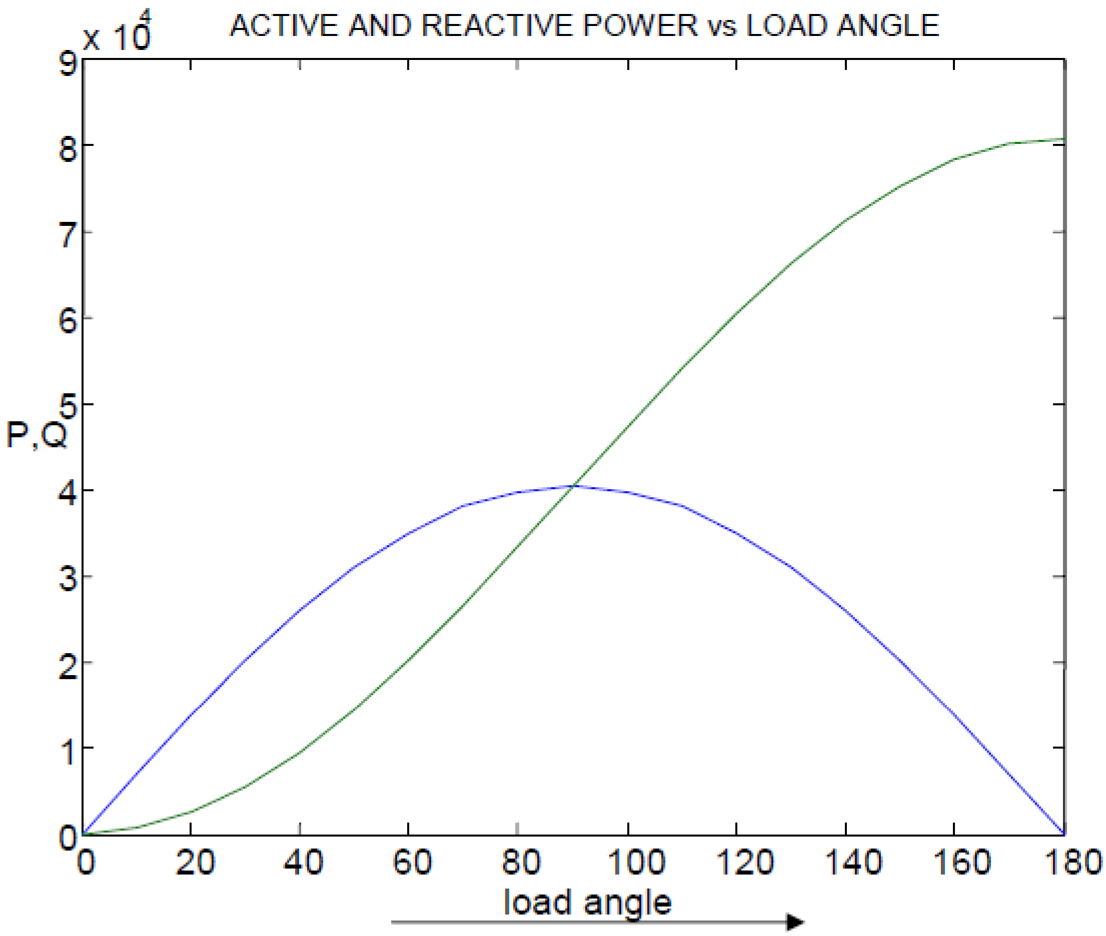


Fig 3.2 Ative and Reactive power VS Load angle [Reference]

3.2. Principles of AC Power Control

From the above discussion it is clear that the power and current in the transmission line can be controlled by the following means **[2][3]** :

- Applying a voltage in the midpoint can increase an decrease the magnitude of power.
- Applying a voltage in series with the line, and in phase quadrature with the current flow, can increase or decrease the magnitude of current flow. As the current flow lags the voltage by 90^0, there is injection of reactive power in series.
- If a voltage with variable magnitude and a phase is applied in series, then varying the amplitude and phase angle can control both active and reactive power. This requires injection of both active power and reactive power in series.
- Increasing and decreasing the value of the reactance X can also decrease and increase the power height of both active and reactive power
- Power flow can also be controlled by regulating the magnitude of sending and receiving end voltages V_s and V_r. This type of control has much influence on reactive power flow than active power flow.

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

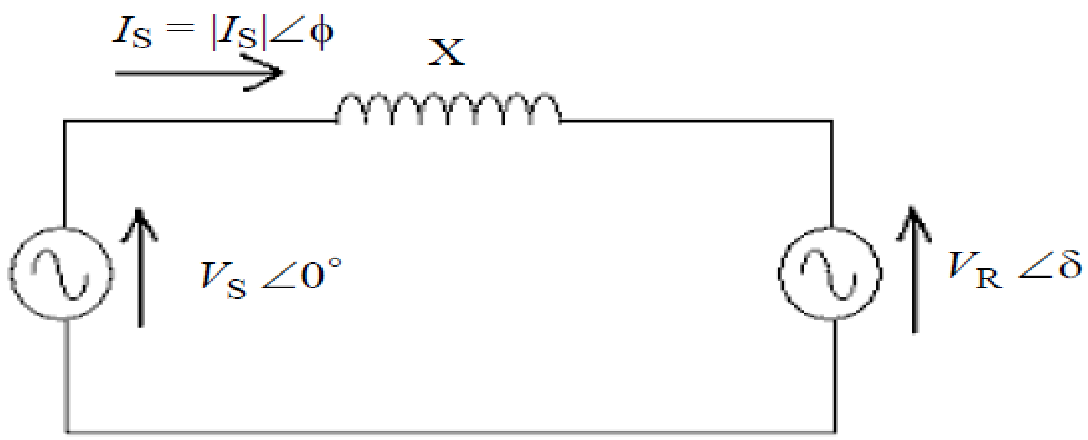


Fig 3.3 A two-machine model for an AC transmission system [8]

Neglecting line resistance, the power flow through the line can be expressed by the following equations [19].

$$Ps = \left(\frac{|Vs||Vr|}{X}\right)\sin\delta \qquad 3.9$$

$$Qs = \left(\frac{|Vs|^2}{X}\right) - \frac{|Vs||Vr|}{X}\sin\delta \qquad 3.10$$

According to the above two equations 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 Fig. bellow. The power flow equations are thus modified to equations 3.11 to 3.13 for shunt, series and phase-angle compensation, respectively.

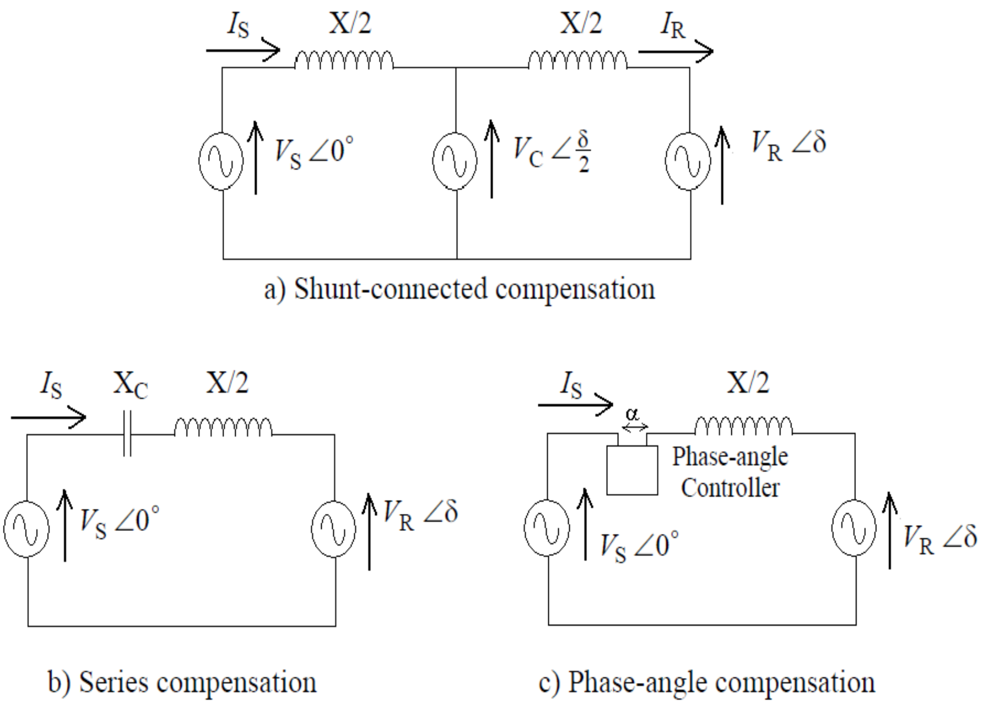


Fig 3.5 Three basic compensation methods[8]

$$P_S + jQ_S = 2\frac{|V_S||V_C|}{X}\sin\delta + j\left(2\frac{|V_C^{\,2}|}{X} - 2\frac{|V_S||V_C|}{X}\cos\delta\right) \qquad 3.11$$

$$P_S + jQ_S = 2\frac{|V_S||V_R|}{X - X_C}\sin\delta + j\left(\frac{|V_C^{\,2}|}{X - X_C} - \frac{|V_S||V_C|}{X - X_C}\cos\delta\right) \qquad 3.12$$

$$P_S + jQ_S = 2\frac{|V_S||V_R|}{X}\sin(\delta-\alpha) + j(\frac{|V_S^2|}{X} - 2\frac{|V_S||V_R|}{X}\cos(\delta-\alpha)) \quad 3.13$$

3.3. Series compensation

3.3.1. Principle of series compensation

Let consider the circuit in figure 3.6, that represents a typical series compensated radial circuit, where R_L, X_L and X_C are respectively the line resistance, the line reactance and the reactance of the series capacitor. The approximated voltage drop per phase from source to load obtained from phasor diagram is given by [24]:

$$\Delta V = R_L.I_L\cos(\phi_R) + (X_L - X_C).I_L\sin(\phi) \quad 3.14$$

$$P_R = E_R.I_L\cos(\phi_R) \quad 3.15$$

$$Q_R = E_R I_L\sin(\phi_R) \quad 3.16$$

There for:

$$\Delta V = \frac{P_R R_R + Q_R(X_L - X_C)}{E_R} \quad 3.17$$

Equation 3.17 shows that the voltage regulation provided by the series capacitor is continuous and instantaneous. In case of voltage fluctuations due to large variations of the load, a series capacitor will improve the quality voltage at the loads downstream from the series capacitor. Figure 3.6 shows the influence of the series capacitor on the voltage profile for a radial power distribution line with inductive loads.

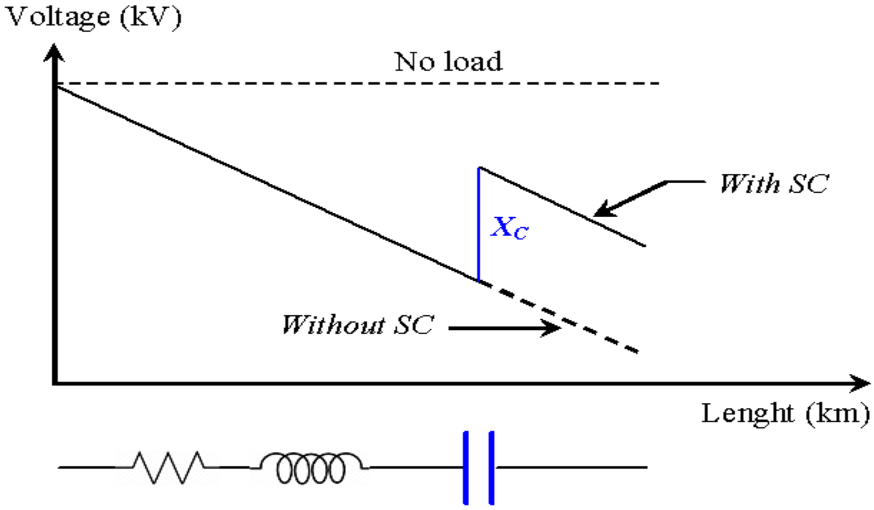


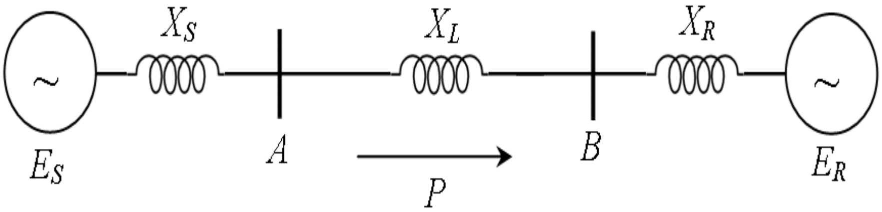
Fig 3.6 Voltage profile for a radial circuit with series capacitor[27]

1 Power Transfer

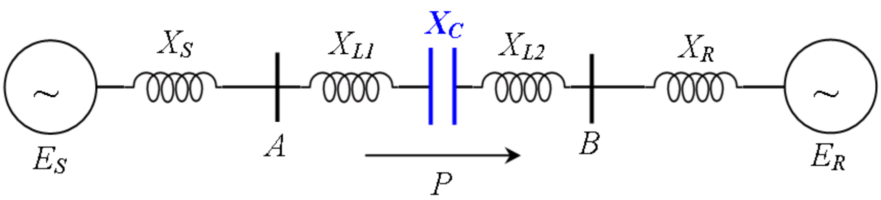
SC transmission lines utilize series capacitors to reduce the net series inductive reactance of the line in order to enhance the power transfer capability of the line. The power transfer along a transmission line is often explained in terms of the simple two-source power system shown in figure.3.7.a without series capacitor and figure.3.7.b with series capacitor. The active power P transferred by the uncompensated and compensated transmission lines are computed using equations (3.18) and (3.19) respectively

$$P = \frac{E_S E_R}{X_T} \sin(\delta) \quad 3.18$$

$$p = \frac{E_S E_R}{X_{T-} X_C} \sin(\delta) \quad 3.19$$



(a)



(b)

Fig 3.7 Voltage profile for a radial circuit a) Without SC b) With SC [27]

In addition, series compensating capacitors allow power transfer at the same voltage level over longer transmission lines than uncompensated lines. This better utilizes the existing transmission network, which is cost effective and quicker rather than building new or additional parallel lines. Modern HV and EHV transmission lines are series compensated to improve power system performance, enhance power transfer capacity, enhance power flow control and voltage control; decrease transmission losses, environmental impact reduction, decreased capital investment [7]. SC of transmission lines is widely used for very long transmission lines. The literature reveals that heavily-loaded, short transmission lines are also typically series compensated to gain the aforementioned benefits. However, these benefits also bring with them significant transmission line protection challenges, particularly in heavily SC networks.

2 Series Capacitor Protection

The introduction of series capacitors presents a number of technical challenges when setting distance protection relays, because of the combined effects of the series capacitor's compensating reactance and the series capacitor's own protective equipment, on the measured impedance to a short-circuit fault. During a short-circuit fault, the fault current through the capacitor produces over voltages across the terminals of the series capacitor. Therefore, protection is provided to limit voltage across the series capacitor [7- 9]. The MOV is a nonlinear resistive device, which starts to conduct at specific instantaneous voltage and ceases to conduct when the voltage falls below the same voltage at each half cycle of the power frequency. The result is that there is a nonlinearly time-varying degree of SC during a fault, due to the non-linear impedance characteristics of the parallel MOV-series capacitor combination [9]. The MOV itself is protected against excessive absorption of energy by a bypass switch. As the MOV conducts current, energy accumulates within the MOV itself. The MOV has a maximum amount of energy that it can absorb before it breaks down. Hence, the MOV is bypassed at a preset energy level to avoid break down. The bypass breaker operates when the energy absorbed by the MOV is greater than the preset value. This bypasses both the MOV and series capacitors and re-inserts them when the energy falls below the pre-set value.

The impedance seen by the relay transits rapidly from compensated impedance to uncompensated impedance during severe short-circuits faults. Goldsworthy [10] has introduced an equivalent series capacitive reactance and resistance of a MOV protected series capacitor as a function of normalized line current based on the capacitor's protective level current (Fig. 3.8).

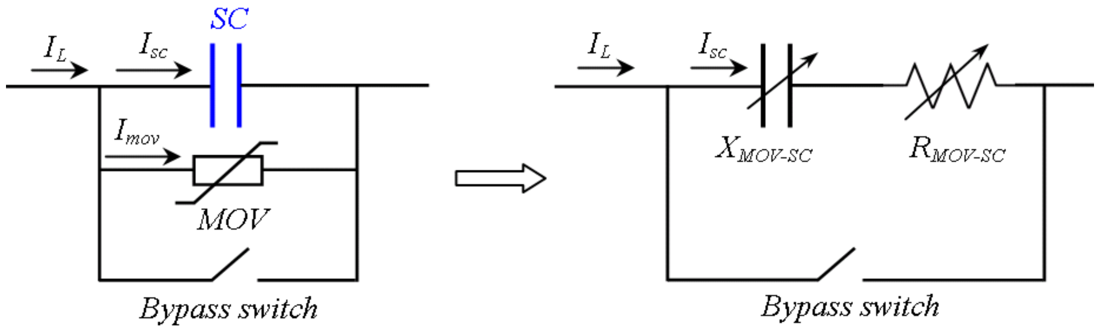


Fig 3.8 MOV equivalent model[27]

3.3.2. Types of Series Compensator

- Thyristor-switched series capacitor
- Thyristor-controlled series capacitor
- Forced-commutation-controlled series capacitor
- Series static VAR compensator
- Advanced SSVC

Out of these series compensator, Thyristor-controlled series capacitor (TCSC) is discussed in this thesis and a MATLAB program is used for it to analyze, how it control the power flow.

3.4. Thyristor-controlled series capacitor (TCSC)

3.4.1 Introduction

Several power electronics equipments have been proposed for improving power system behavior in recent decades. These equipments are in series and shunt, active and passive, controlled and switched categories. Each of them is used for one or some purposes like reactive power compensation, voltage control, dynamic stability improvement and power oscillation damping [24].

Thyristor Controlled Series Capacitor (TCSC) consists of a series compensating capacitor shunted by a Thyristor controlled reactor (TCR). TCSC is one of the Flexible AC Transmission Systems (FACTS) devices which is used for all mentioned purposed. TCSC has shown good capabilities in researches [23-25]. TCSC has advantages of using Thyristor (with natural commutation) and low frequency switching. Therefore its cost, complexity and power loss have reduced.

TCSC requirements are less considered and studied in aspect of design view like capacitor and inductor sizing and switching conditions. Thyristor and Gate-Controlled Series Capacitors are compared in [24]. The reactance characteristic and resonance condition of TCSC are discussed in [24]. A prototype, laboratory scale TCSC design is described in [24]. Proper Thyristor triggering base on inductor and capacitor size is presented in [23].

Impedance of transmission line for compensation, switching time, capacitive and inductor mode switching, minimum voltage necessary for switching, harmonics and components ratings, Thyristor ratings and other factors are considered in this paper.

Considering ideal switching angle may lead to unsuccessful switching or instability. Therefore practical limits of switching angle, capacitor and inductor reactance are discussed in details here.

At the first, main structure and operation of TCSC is brought up. Then, the capacitive and inductive operation mode of TCSC is analyzed in details. The requirements of L and C and practical limits of firing angle are mentioned in the third section. Validation of those conditions is satisfied by simulation in the last section and checking with practical installed three TCSC's.

3.4.2. Principle Operation of TCSC

TCSC is consisted as a series compensating capacitor (C) shunted by a Thyristor controlled reactor (TCR) as shown in Figure 1 which is placed series in transmission line [24].

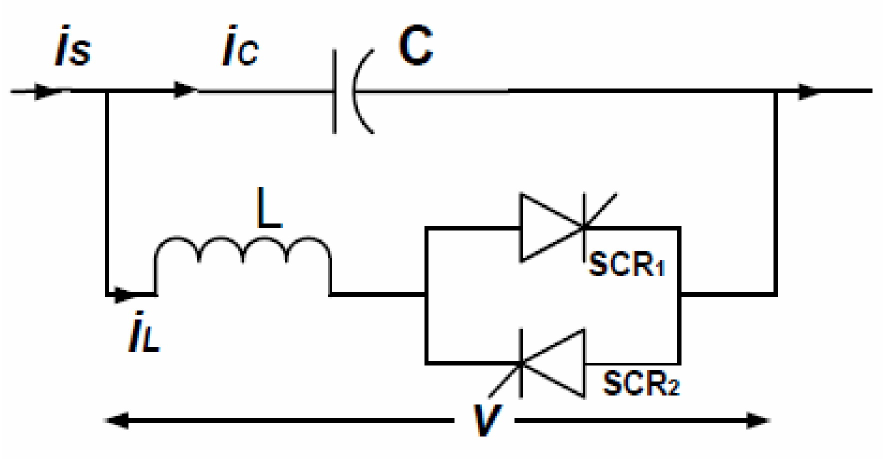


Fig 3.9 Schematic Diagram of TCSC [27]

TCSC has four operation modes: Blocking, Bypass, Capacitive and Inductive mode. TCSC impedance consists of capacitor and inductor reactance as equation (3.20) where reactance of the inductive branch is and depends on the firing angle (α) of Thyristors. The four mode operations are made by this angle.

$$jX_{TCSC}(\alpha) = \frac{jX_L(\alpha) * (-jX_C)}{jX_L(\alpha) + (-jX_C)} \qquad 3.20$$

Blocking Mode Operation

If Thyristors are off during the each period, The TCSC impedance will be equal to capacitance reactance XC. It is obvious that TCSC will be like a series capacitor and will have all effects of series capacitor in the transmission line. The firing angle of the Thyristors is 90 degree in this mode [5].

Bypass Mode Operation

When two anti-parallel Thyristors are on in all time that they have turning on condition, TCSC will operate in Bypass mode. Thyristors conduct 180 degree in each cycle. The inductance of TCR branch is in circuit always and TCSC impedance is equal to equation (21) in this case [5].

$$X_{TCSC} = \frac{X_L X_C)}{X_L - X_C} \qquad 21$$

It is recommended to consider negative sign in equation (21) because the negative value of X_{TCSC} will mean capacitive reactance and the positive value will be equal inductive reactance. This is demonstrated in equation (22).

$$jX_{TCSC} = \frac{jX_L * (-jX_C)}{jX_L + (-jX_C)} = -j\frac{X_L X_C}{X_L - X_C} \qquad 22$$

TCSC impedance will be inductive because XL is smaller than XC.

Capacitive and Inductive Mode Operation

If the firing angle of the Thyristors is greater than zero and smaller than 90 degree, The Impedance of TCR branch in fundamental frequency will be equal to equation (23) that α is firing delay angle respect to zero crossing of the line current. δ is conducting angle and is equal to $\delta = 2\pi - \alpha$.

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin 2\alpha}, X_L \le X_L(\alpha) \le \infty \qquad 23$$

In an angle, named resonance angle, $X_L(\alpha_{resonance})$ will be equal to XC and equation (3.20) will be infinite. Therefore TCSC impedance characteristics gains as shown in Figure 3.20. TCSC will be in inductive mode for firing angle smaller than resonance angle and will be in capacitive mode for firing angle greater than resonance angle.

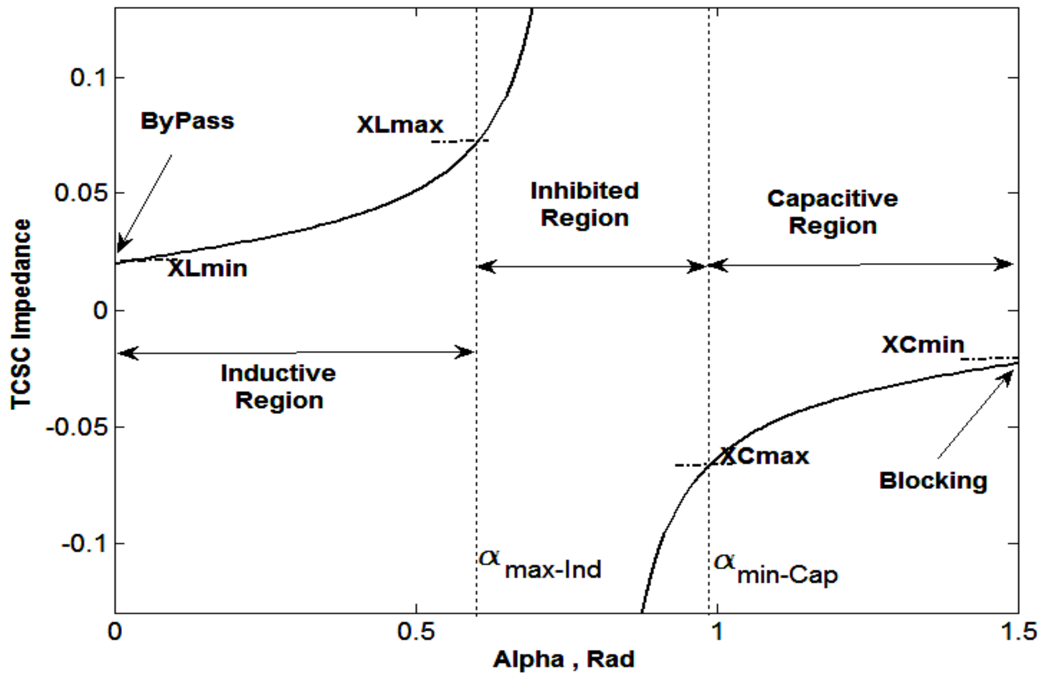


Fig 3.10 Mode of Operations of TCSC [27]

Changing of TCSC impedance is very fast near the $\alpha_{resonance}$ and sensitivity to the firing angle is high. Therefore, an inhibited region is defined between capacitive and inductive area. This area is shown in Figure 2 between $\alpha_{\min-cap}$ and $\alpha_{\max-ind}$.

3.4.3. Physical Model of TCSC

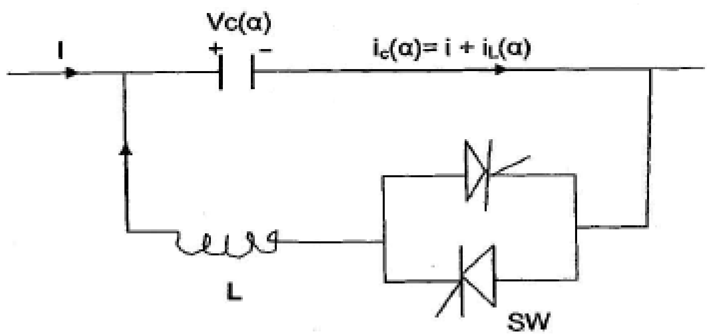


Fig 3.11 Physical model of TCSC [27]

The TCSC consists of the series-compensating capacitor shunted by a Thyristor-controlled reactor (TCR) as shown in fig. 3.21 [2-3]. The impedance of the reactor X_L is sufficiently smaller than that of the capacitor impedance X_C is taken. By varying the delay angle or firing angle (α) of TCR, the inductive impedance of TCR can be varied. Thus TCSC can provide variable capacitance by means of canceling the effective capacitance by the TCR. Therefore, the steady state impedance of TCSC is simply that of the parallel LC circuit, consisting of fixed capacitive impedance X_C and variable inductive impedance XL.

The effective impedance of the TCSC is given by

$$X_T(\alpha) = \frac{X_c X_L(\alpha)}{X_L(\alpha) - Xc} \qquad 3.24$$

Where $X_L(\alpha)$ is the variable impedance of TCR which can be taken from Equ.(3.25) ,that is

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin 2\alpha} \text{ for } X_L \le X_L(\alpha) \le \infty \qquad 3.25$$

Where $X_L=\omega L$ and α is the delay angle measured from the crest of the capacitor voltage or the zero crossing of the line current.

The TCSC behaves as a tunable parallel LC-circuit to the line current. As the impedance of the controlled reactor $X_L(\alpha)$ is varied from its maximum (infinity) toward its minimum (ωL) i.e. when α varies from 90^0 to 0^0, then TCSC increases its minimum capacitive impedance $X_{T(\min)} = X_c = 1/\omega C$, until parallel resonance occurs at $X_c = X_L(\alpha)$ and $X_T(\alpha)$ approaches to it maximum value $X_{T(max)}$=infinite. If we decrease $X_L(\alpha)$ further, the $X_T(\alpha)$ becomes inductive and approaches to its minimum value of $X_{T(min)}=XcX_L/(X_L-Xc)$ at $\alpha=0^0$. i.e. the effect of capacitor is bypassed by TCR.

Angle α has two limiting values (1) one for inductive $\alpha_{L(lim)}$ and

(2) One for capacitive $\alpha_{C(lim)}$.

The TCSC has two operating ranges around its internal circuit resonance:

(1) One is the $\alpha_{C(\lim)} \le \alpha \le \pi/2$ range, where $X_T(\alpha)$ is capacitive

(2) The other is the $0 \le \alpha \le \alpha_{L(\lim)}$ range, where $X_T(\alpha)$ is inductive.

3.4.4 Analysis of the TCSC equivalent circuit

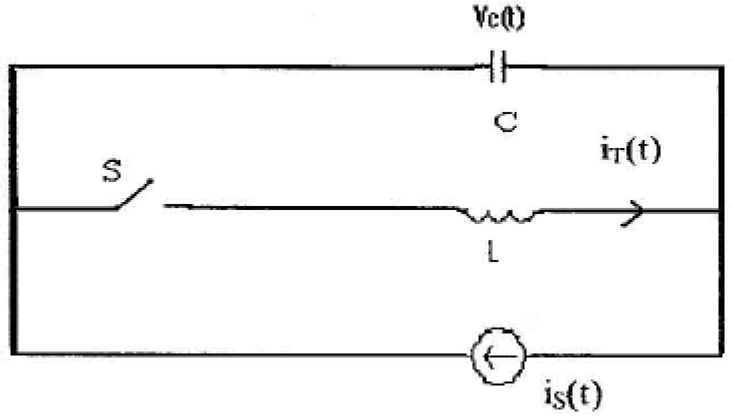


Fig 3.12 Simplified TCSC circuit [26]

The analysis of TCSC operation is performed based on the simplified TCSC circuit as shown in Fig 3.12 above.

Where:

i_S (t) = Transmission line current which is modeled as an external current source and assumed to be sinusoidal current.

i_T(t) = Thyristor-valve current

u = switching variable

When u = 1, Thyristor is conducting i.e. switch S is closed

When u = 0, Thyristor is blocked i.e. switch S is open

C = Fixed capacitor used in parallel with TCR circuit

L = Inductance used in series with Thyristor bidirectional switch

V_c(t) = voltage across the capacitor C

The current through the fixed capacitor C is expressed as

$$C\frac{dv_c}{dt} = i_S(t) - i_T(t)\cdot u \qquad 3.26$$

The current through Thyristor is given by

$$L\frac{di_T}{dt} = v_C \cdot u \qquad 3.27$$

Let the line current $i_S(t)$ be represented by

$$i_S(t) = I_m \cos wt \qquad 3.28$$

In equidistant firing-pulse control, for balanced TCSC operation, the Thyristors are switched on twice in each cycle of the line current at instants t_1 and t_3 and these are given by

$$t_1 = -\frac{\beta}{w}$$

$$t_3 = \frac{\pi - \beta}{w}$$

Where

β is the angle of advance (before the forward voltage becomes zero) or,

Where

α is the firing angle of the Thyristor. This angle is generated using a reference signal that can be in phase with the capacitor voltage. The Thyristor switch S turns off at the instants t_2 and t_4, defined as

$$\beta = \pi - \alpha ; \qquad 0 < \beta < \beta_{\max}$$

Where α is the firing angle of the Thyristor. This angle is generated using a reference signal that can be in phase with the capacitor voltage. The Thyristor switch S turns off at the instants t_2 and t_4 , defined as

$$t_2 = t_1 + \frac{\sigma}{w} \text{ s}$$

$$t_4 = t_3 + \frac{\sigma}{w}$$

Where σ is the conduction angle, which is assumed to be the same in both the positive and the negative cycle of conduction,

$$\sigma = 2\beta$$

Solving the TCSC equations (3.27)-(3.28) results in the steady state Thyristor current $i_{T,}$ as

$$i_T(t) = \frac{\varpi^2}{\varpi^2 - 2} I_m \left[\cos wt - \frac{\cos\beta}{\cos\varpi\beta} \cos w_r t \right] \; ; -\beta \le wt \le \beta \qquad 3.29$$

Where w_r is called resonance frequency and is given by

$$w_r = \frac{1}{\sqrt{LC}}$$ and

$$\varpi = \frac{w_r}{w} = \left(\frac{X_C}{X_L} \right)^{1/2}$$

Where X_C and X_L are capacitive reactance and inductive reactance respectively.

The steady state capacitor voltage at the instant $wt = -\beta$ is expressed as

$$v_{C1} = \frac{\operatorname{Im} X_C}{\varpi^2 - 1} (\sin\beta - \varpi\cos\beta\tan\varpi\beta) \qquad 3.30$$

At $wt = \beta, i_T = 0$, the capacitor voltage is given by

$$v_C(wt = \beta) = v_{C2} = -v_{C1} \qquad 3.31$$

Finally the capacitor voltage is given by

$$v_C(t) = \frac{\operatorname{Im} X_C}{\varpi^2 - 1} \left(-\sin wt + \varpi \frac{\cos\beta}{\cos\varpi\beta} \sin w_r t \right); \; -\beta \le wt \le \beta \qquad 3.32$$

$$v_C(t) = v_{C2} + \operatorname{Im} X_C (\sin wt - \sin\beta); \qquad \beta < wt < \pi - \beta \qquad 3.33$$

Because the non-sinusoidal capacitor voltage, $v_{c,}$ has odd symmetry about the axis $w_t = 0$, the fundamental component, $V_{CF,}$ is obtained as

$$V_{CF} = \frac{4}{\pi} \int_0^{\pi/2} v_C(t) \sin wt \; d(wt) \qquad 3.34$$

The equivalent TCSC reactance is computed as the ratio of V_{CF} to I_m:

$$X_{TCSC} = \frac{V_{CF}}{I_m} = X_C - \frac{X_C^2}{(X_C - X_L)} \frac{2\beta + \sin 2\beta}{\pi} + \frac{4X_C^2}{(X_C - X_L)} \frac{\cos^2\beta}{(\varpi^2 - 1)} \frac{(\varpi\tan\varpi\beta - \tan\beta)}{\pi} \qquad 3.35$$

If we apply $\beta = \pi - \alpha$, in equation (3.43) the reactance of TCSC becomes as:

$$X_{TCSC} = -X_C + C_1\{2(\pi-\alpha)+\sin[2(\pi-\alpha)]\} \\ -C_2\cos^2(\pi-\alpha)\{\varpi\tan[\varpi(\pi-\alpha)]-\tan(\pi-\alpha)\} \quad 3.36$$

Where

$$C_1 = \frac{X_C + X_{LC}}{\pi},$$

$$C_2 = \frac{4X_{LC}^2}{X_L\pi},$$

$$X_{LC} = \frac{X_C X_L}{X_C - X_L},$$

$$\varpi = \left(\frac{X_C}{X_L}\right)^{1/2}$$

From the equation (3.36) it is clear that the reactance of TCSC is dependent on the firing angle of Thyristor and this reactance varies from inductive region to capacitive region between firing angle 90^0 to 180^0 and at around 140^0 there is a condition of resonance.

The compensating coefficient 'r' is having both inductive and capacitive compensation value this varies according to the firing angle. From the analysis it is clear that height of load angle curve increases with the more capacitive reactance of TCSC. But the height of the load angle curve decrease with more inductive reactance of TCSC.

Similarly the reactive power curve for capacitive compensation is positive and reactive power curve for inductive compensation is negative

Also both active and reactive power decreases with the increase of firing angle up to certain value where the reactance of TCSC is inductive. At 90^0 of firing angle the reactance of TCSC becomes capacitive and both active and reactive power increases as shown in fig 3.13.

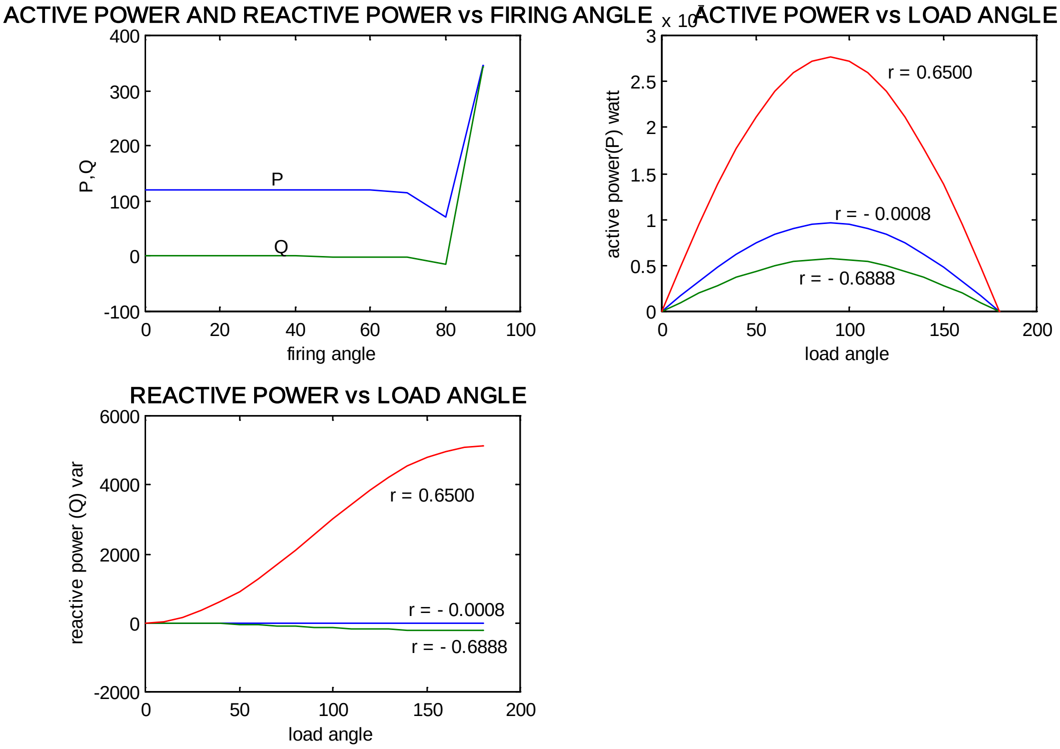


Fig 3.13 Actice power and reactive power Vs firing angle [26]

3.4.5 Requirements of L, C and Firing Angle

Practical requirements and limits of X_L, X_C and the firing angle are discussed in this section. At the first, selection of TCSC parameters and their results have been described and next precision limits of firing angle for stable and successful switching have been analyzed.

Requirements and Notes in Selection of C & L

(Requirement-1) to (Requirement-4) must be considered in the selection of L and C.

(Requirment-1): X_L must be smaller than X_C. Proportion of the inductor impedance to the capacitor impedance, K_{LC} must be smaller than unit as equation (3.37).

$$K_{LC} = \frac{X_L}{X_C} < 1 \qquad 3.37$$

(Requirement-2): The resonance frequency $\omega_r = \frac{1}{\sqrt{LC}}$, must be away enough from power frequency

($\omega 1 = 2\pi * 50 \frac{rad}{\sec}$). It means that reversing polarity of the capacitor voltage must be fast as it longs smaller than half cycle of power frequency period.

$$\omega_r = \omega_1 \sqrt{\frac{XC}{XL}} = \frac{1}{\sqrt{LC}}, \omega_r >> \omega_1 \qquad 3.38$$

(Requirement-3): The resonance frequency ω_r must be far enough from the harmonics of the power frequency, where ω_n is the n^{th} harmonics of the power frequency.

$$\omega_n \neq n\omega_r \text{, n=1, 2, 3…} \qquad 3.39$$

(Requirement-4): The value of XC must be sufficient to have proper line series compensation (typically until 70% compensation). As shown in Fig3.25, the TCSC impedance never is equal to zero. The TCSC impedance is between $X_{L\min}$ and $X_{L\max}$ in the inductive mode and between $-X_{C\min}$ and $-X_{C\max}$ in the capacitive mode.

This boundary must be coordinated with practical requirements like the transmission line impedance and its thermal capacity.

$$X_{TCSC} = -K_{se} X_{Line} \qquad 3.40$$

Where X_{Line} is the transmission line impedance and K_{se} is percentage of the series compensation. The upper limit of the series compensation is also determined by the stability margin of the sub synchronous resonance [24].

Consideration of the above-mentioned requirements is necessary. In addition to these requirements, some notes are useful in TCSC designing.

(Note-1): If XL is very smaller than X_C then TCSC acts as Thyristor series switched capacitor (TSSC).

(Note-2): The small value for X_L has this benefit that duration of the hale cycle resonance will be short and reversing process of capacitor voltage will be fast and good.

(Note-3): The big value for XL has this advantage that maximum current of inductor will be smaller and the overall cost will be lower due to decreasing the components ratings [24].

(Note-4): In Some protection schemes, the Thyristors of TCR branch will be fired to operate in fully conducted mode to perform the bypass operation. In this case, the inductive impedance of TCSC will partly limit the fault current. Therefore, small value for XL is an advantage [24].

(Note-5): If XL is small then the current harmonics will have bigger components. These harmonics affect the capacitor and power system.

(Note-6): Whatever XL/XC selects smaller, capacitor area operation will be shorter and whatever XL/XC is closer to 1.0, the resonance angle will happen in smaller angle and therefore the capacitive operation area will be wider See requiremen-1 also

(Note-7): If XL/XC is smaller than 1/9, then more than one resonance area will exist. Therefore, the available operating area of TCSC will be restricted [24].

(Note-8): As TCSC impedance depends on the firing angle, the controllability and precision of TCSC compensation depends on the resolution of the firing angle controller [24].

(Note-9): The maximum current of LC circuit, $I_{L\max}$, depends on the capacitor voltage on switching instant, V_{C0} , L and C according to equation (3.41). Therefore, a large value for L and small value for C causes larger components rating and larger harmonics.

$$I_{L\max} = V_{C0}\sqrt{\frac{C}{L}} \qquad 3.41$$

Following relations are used for detailed analysis.

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin 2\alpha} = K_{LC} K_\alpha X_C \qquad 3.42$$

$$K\alpha = \frac{\pi}{\pi - 2\alpha - \sin\alpha} \qquad 3.43$$

$$X_C = \frac{K_{LC}K_\alpha - 1}{K_{LC}K_\alpha} K_{se} X_{Line} \qquad 3\ .44$$

$$X_L(\alpha) = (K_{LC}K_\alpha - 1) K_{se} X_{Line} \qquad 3.45$$

The firing angle is formulated in K_α factor. The percentage of series compensation is defined between two boundary on the (Requirement-4) and (Note-4) as (3.45).

$$\alpha_{\min-cap} < \alpha < \frac{\pi}{2} \qquad 3.46$$

The Precision Details of Stable Firing Angle

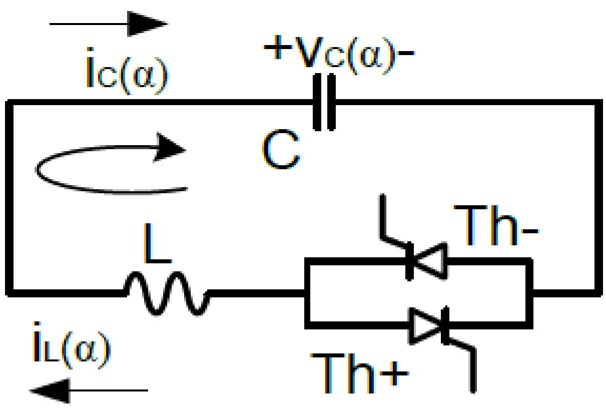
The firing angle for TCSC is defined as equation (2) theoretically, for the capacitive operation $\alpha_{\min-cap} < \alpha < \frac{\pi}{2}$ and for the inductive operation $0 < \alpha < \alpha_{\max-ind}$. But some practical limitation must be considered.

At first, it is necessary that LC resonance circuit must be analyzed in detail. Internal equations of TCSC can be considering as a LC resonance at each switching start with equations (15).

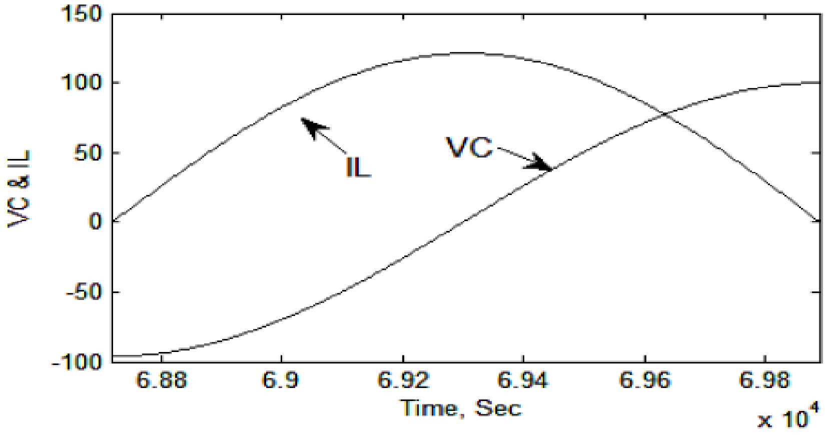
$$0 = V_C + LC\frac{dv_c}{dt}$$
$$V_C(0) = V_{C0}, \frac{dvc}{dt}|_{t=0} = 0 \qquad 3.47$$

As shown in Figure 3.25, the LC resonance will work for half cycle because of conduction Thyristors in one direction as a semiconductor. The resonance frequency is

$$\frac{1}{(2\pi\sqrt{LC})}HZ.$$
$$v_c(t) = V_{C0}\cos(\omega_r t)$$
$$i_L(t) = V_{C0}\sqrt{\frac{C}{L}}.\sin(\omega rt), \omega_r = \frac{1}{\sqrt{LC}} \qquad 3.48$$



(a) LC Circuit



b) Capacitor voltage and Inductor Current in half cycle

Fig 3.14 The LC Resonance Circuit and Capacitor Voltage Change [27]

The result of this resonance is inversing of capacitor voltage according to equation (3.47) in both capacitive an inductive operation mode.

(Lemma-1): the capacitor must have a minimum voltage at switching instant for success switching.

As capacitor voltage and line current are orthogonal to each other (90 degree difference phase), and the capacitor current is equal to the line current before firing thyristors, the initial capacitor voltage can be written as:

$$V_C(t) = jX_C i_{Line}(t) \qquad 3.49$$

The minimum capacitor voltage must be equal to minimum voltage for turning on ($V_{ON-\min}$)for Thyristors. For this calculation, it is necessary to observe the condition that worth case may happen in near zero crossing of line currents.

$$\alpha_{C\max} = \sin^{-1}\left(\frac{V_{on-\min}}{V_{C\max}}\right) \qquad 3.50$$

The VCmax depends on transmission line current, firing angle operation of TCSC and Capacitor capacity. Therefore, maximum firing angle in capacitive mode is not 900. The angle $\alpha_{c\max}$ must be considered as shown in Figure 3.26.

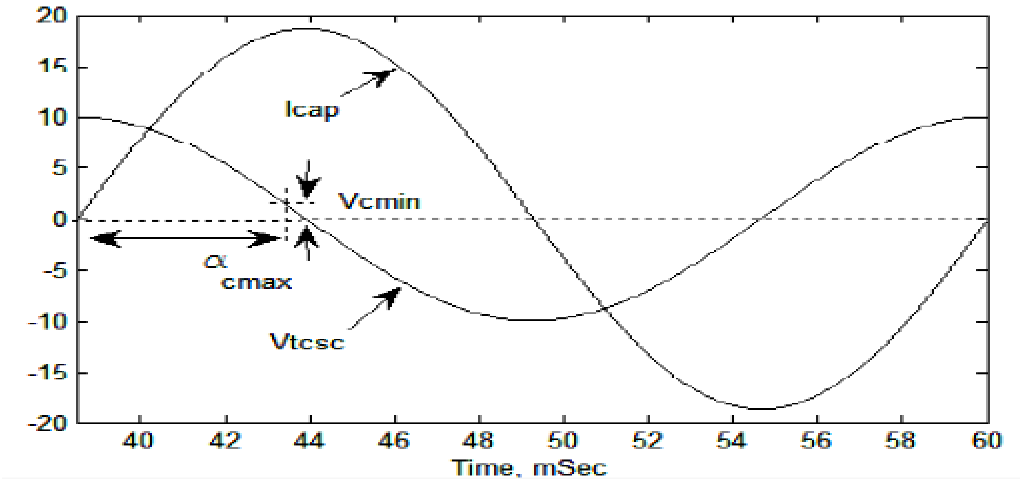


Fig 3.15 The Maximum Firing Angle in the Capacitive Mode [27]

(Lemma-2): The resonance circuit operates for $\pi.\sqrt{LC}$ seconds.

The required time for half cycle resonance is $t_2 - t_1 = \pi.\sqrt{LC}$. This time must be less than half period of power frequency ($t3 = \frac{1}{2f}$). These two time duration are shown in Figure 3.16.

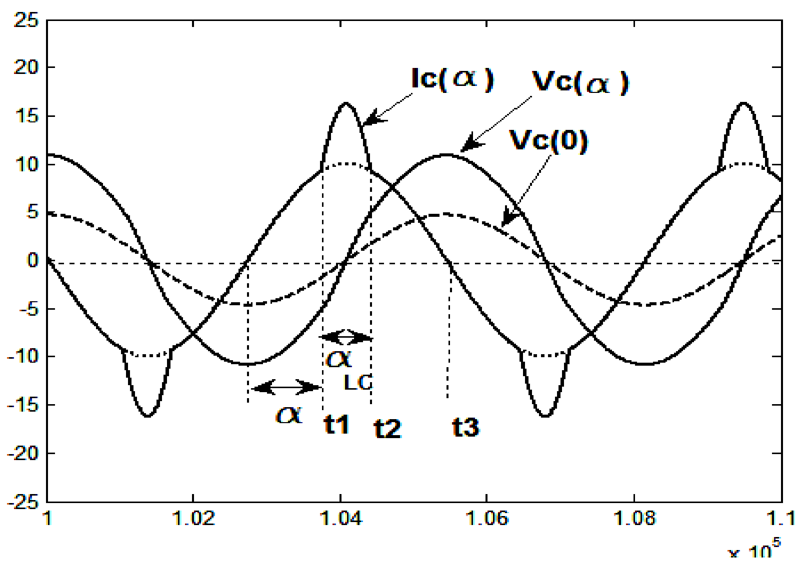


Fig 3.16 Power Frequency Period and Resonance Frequency Period [27]

Therefore, the switching must be done and finished at the amount of α_{LC} degree before the termination of half power frequency cycle.

$$\alpha_{LC} = \omega.\Delta t = (2\pi f)(t_2 - t_1) = 2\pi f\sqrt{LC}$$
$$\alpha_{\max} + \frac{\alpha_{LC}}{2} < \frac{\pi}{2m}, t_1 = \frac{1}{2f} - \alpha_{LC} \qquad 3.51$$

This lemma limits the firing angles that are shown in Figure 3.27.

Obviously these two lemmas are different; the first lemma clearly shows dependency of circuit to the capacitor and line current but second lemma is independent of current and voltage and only depends on L and C value.

3.5 Power supply system voltage

3.5.1 Introduction

Voltage drop in the feeder circuit differs substantially depending up on the train passion, train current, number of trains in the same power feeding section, track impendence and etc. The minimum pantograph voltage for the train is expected to be 22.5kV; which is within the tolerable voltage fluctuation range of the over head contact line.

TB10009-2005 Railway Traction Power Supply design specifications

The rated voltage of traction substation traction side bus is 27.5kV, and AT power supply is 55kV.The rated voltage of Electric locomotives and EMUs pantograph and catenary is 25kV, the maximum voltage is 29kV, the minimum operating voltage is 20kV, and not less than 19kV under abnormal situation.

Traction network voltage is limited by three factors: power grid voltage drop, traction transformer voltage drop and traction network voltage drop.

The following table shows the standardized voltage for AC 25kV, 50HZ traction feeder:

Table 3.1 Voltage specification specified by international standards such as BS EN 50163 and IEC 60850 for AC 25kV, 50HZ traction feeder:

classification	Volts[kV]
Lowest non-permanent voltage	17.5
Lowest permanent voltage	19
Normal voltage	25
Highest permanent voltage	27.5
Highest non-permanent voltage	29

3.5.2 The improvement of the traction network voltage

Traction network voltage is given as

$$U' = E - \Delta U_S - \Delta U_T - \Delta U_C \qquad 3.52$$

Where:

E is the traction bus no-load voltage

ΔU is voltage drop

So traction network voltage can be improved by:

- Increase E-Traction transformer’s voltage regulator (by using Voltage tapping device)
- Reduce ΔU, by using the following mechanisms
- Reducing the impedance of the traction network.
- Reducing the transformer impedance.
- Choosing traction power supply mode and feeding section length
- Using series connected or parallel connected compensator compensate voltage

Traction transformer tapping voltage regulation has the following limitations:

- According to regulations, the transformer does not allow long-term operation under overvoltage.
- Narrow voltage regulation range.
- Can’t apply under voltage frequent fluctuations situation.

Series capacitor compensation method is considered in this thesis to reduce voltage drop for the improvement of the traction network voltage.

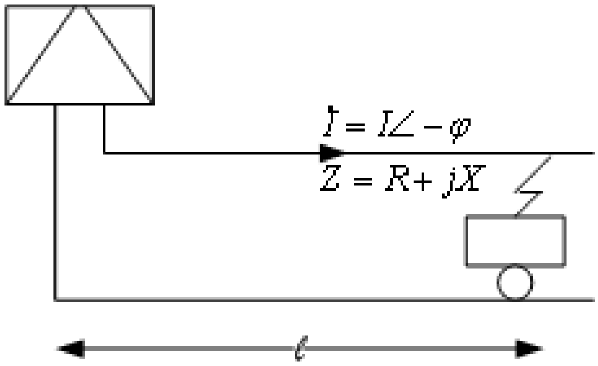


Fig 3.17 traction power supply system [Reference]

Before compensation, the voltage loss of traction network is

$$\Delta U = (r\cos\phi + x\sin\phi)lI \qquad 3.53$$

After compensation, the voltage loss of traction network is

$$\Delta U' = rlI\cos\phi + (xl - X_C)I\sin\phi \qquad 3.54$$

It can be seen the voltage loss caused by series capacitor is

$$\Delta U_C = -X_C I\sin\varphi \qquad 3.55$$

The advantages and disadvantages of series capacitor compensation

- Advantages
    a. The ΔU_C is proportional to the train current I
    b. Can improve the feeding section's power factor;
    c. Reduce unbalanced factor

$$\delta U_C = X_C I\sin\varphi \qquad 3.56$$

- Disadvantages
    a. May result in the opening of catenary;
    b. Need large capacity for traction current go through it.
    c. May cause resonance current

3.5.3 Voltage drop of Single-phase transformer

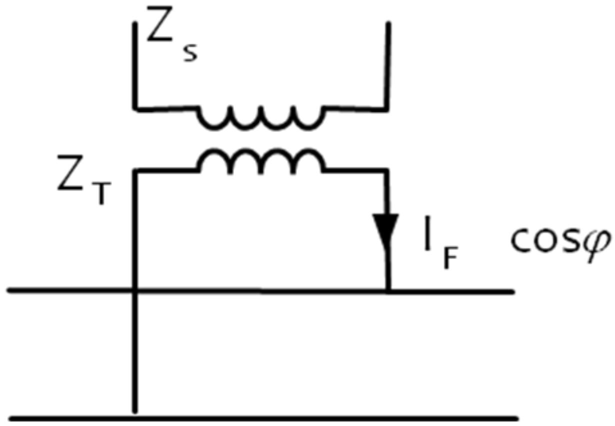


Fig 3.18 Single phase transformer

By considering:

- Feeder load as I_F
- Power factor as $\cos\phi$
- leakage reactance of Traction transformer $Z = R_T + jX_T$

The substation voltage loss is calculated as:

$$\Delta U = I_F (R_T \cos\phi + X_T \sin\phi) \qquad 3.57$$

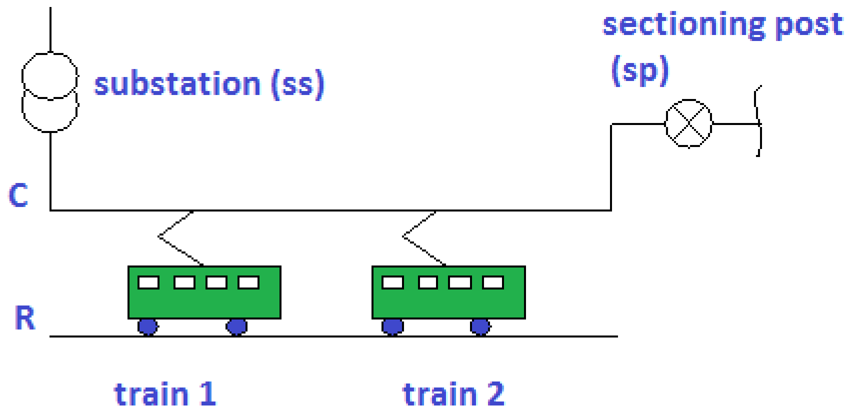
Where $\Delta U =$ transformer voltages drop

CHAPTER FOUR

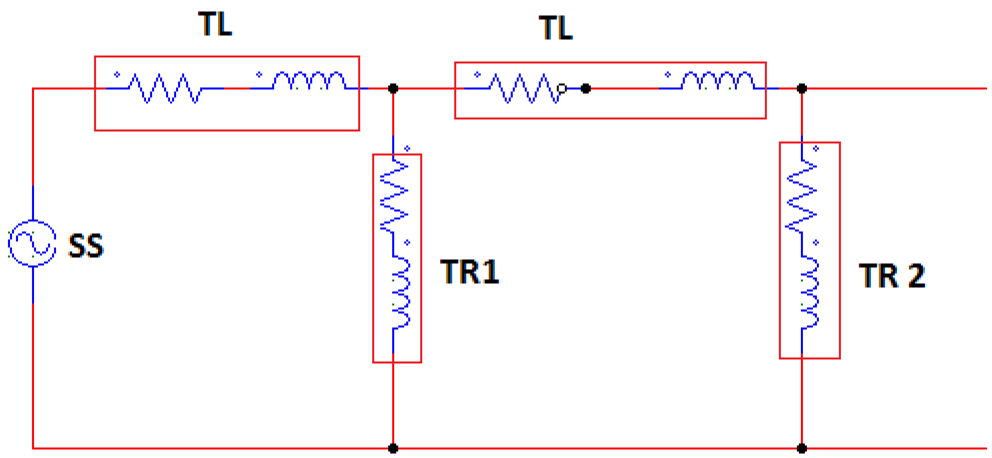
MODELING OF COMPONENTS

4.1. Introduction

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. 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[8]. 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. 4.1. 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.



a) Schematic diagram



b) Equivalent model

Fig 4.1Single-phase AC railway power feeding model

4.2. Substation Model

4.2.1. Description

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. 4.2a.

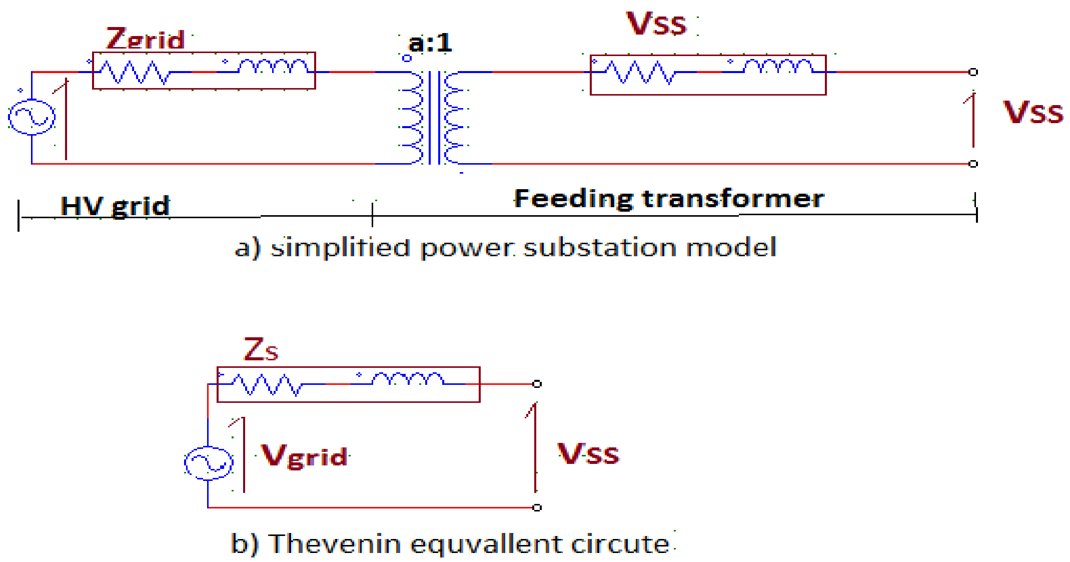


Fig.4.2: Power substation model [8]

This circuit is then simplified to either Thevenin circuits as shown in Fig4.2b.The parameters of these circuits can be easily computed by the following relations [8].

$$V_S = \frac{V_{grid}}{a}, \qquad Z_s = Z_T + \frac{Z_{grid}}{a^2}, \qquad Y_s = \frac{1}{Z_S}$$

The electrical parameters which are usually known and which characterized the machine are:

i. Rated apparent power [S_n]
ii. Primary rated voltage [V_{1n}]
iii. Secondary rated voltage [V_{2n}]
iv. Short circuit voltage in percent [V_k%]; typical values are 4% and 6 %.

With these data it is possible to determine the primary and secondary rated current and the current under short circuit conditions. The typical values of short circuit voltage V_k % in relation to the rated power of the transformer are reported in Table 4.1

Table 4.1 Typical values of short circuit voltage [standard IES60076-5]

Rated apparent power S_n [kVA]	Short - circuit voltage V_K %
$\leq$ 630	4
630 < S_n $\leq$ 1250	5
1250 < S_n $\leq$ 2500	6
2500 < S_n $\leq$ 6300	7
6300< S_n $\leq$ 25000	8

Table 4.2 Traction substation data collected from Sebeta to Adama design guide line document [22]

Nominal voltage of primary side (V_{PO})	132kV
Nominal voltage of secondary side(V_{SO})	27.5kV
Secondary voltage at rated output(V_S)	25kV
Rated output (V_{SO}*I_S)	20MVA
minimum short circuit capacity	400MVA
X/R ratio	20
Transformer short circuit voltage percentage , V_K%	8
Rated copper loss of transformer , ΔP_C	3
Transformer impendence, Z%	10

Rated secondary current $I_S = \frac{20MVA}{\sqrt{3} * 27.5KV} = 419.89A$

Primary short circuit current $I_{PSC} = \frac{I_P}{Z\%} = 4198.900A$

Short circuit $MVA = \sqrt{3} * 25KV * 4198.900 = 181.779MVA$

On the basis of these data and of the correction factor for change of voltage caused by short circuit is possible to calculate the short circuit impendence of the network through the following formula:

There fore $Z_{grid} = \frac{V^2}{MVA_{SC}} = 4.160\Omega$

The impedance of the transformer (Z_T) can be calculated with the nominal parameters of the machine itself (rated voltage $V_{2n,}$ apparent power S_n of transformer, percentage of voltage drop %) by using the formula:

The transformer impendence $Z_T = \frac{V_{SO}{}^2 * V_K\%}{100 * S_N} = \frac{(27.75KV)^2 * 8\%}{100 * 20 * 10^6} = 3.025\Omega$

There for the substation impendence $Z_S = Z_T + \frac{Z_{grid}}{a^2} = 3.025 + \frac{4.160}{(\frac{132}{27.5})^2} = 3.206\Omega$

The resistive and reactive component of Z_S can be determined with the value of the X/R ratio taken from standard on Appendix and the equation $Z_S = \sqrt{R^2 + X^2}$. These resistive and reactive components with X/R ratio 20 are [Reference]:

$$R = 0.160\Omega$$
$$X = 3.20\Omega$$

4.3. Catenary line model

Electric trains takes power from conductor named contact wire using a device named pantograph .The catenary system have different types of geometry due to system design , speed of train , environmental conditions , voltage level , substation distance ,voltage drop, impedance etc…

An overhead line system behaves as a transmission line and has certain values of capacitance, inductance and resistance per unit length that are determined by physical characteristics such as the diameter of the copper conductor and its height above the ground. As a result the overhead has characteristic impedance which by transmission line theory can be shown to alternate between capacitive and inductive values in the form of a hyperbolic curve. The supply from the grid to the feeder station is essentially inductive and resonant conditions exist between the supply and the overhead, i.e. the system has a set of characteristic resonant frequencies. Parameters for catenary system conductor will be taken from ERC design guide line. .The traction system considered in this investigation consists of a 29-km Mojo –to-Adama single-phase contact feeder section with a longitudinal impedance of (0.13008 + i0.39238) Ω/km at 50 Hz and a shunt capacitance of 0.011 μF/km, fed from a substation step-down. Short transmission lines of length 100km or less, the total 50HZ, shunt admittance ($j\omega cL$) small enough to be negligible resulting in a single equivalent circuit.

There for 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. 4.1. This approach is adequate to calculate voltages across trains and phase-to-ground substation and SP voltages. However, rail potential, rail-to-earth leakage current, EMI effect, etc cannot be determined using this simplified 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 [8].

$Z_1 = Z_{OH} * FD$, FD = Feeding distance

The parameters of the each transmission line are calculated according to traction network impendence value determined from [22]. For Mojo -to- Adama traction section which is taken to show the simulation result in this thesis work is modeled as fig 4.2. On this double track section the worst case scenario one train per single line section is considered. There for the line impedance of this model is determined as follows by taking Z = (0.13008 + j0.392381) Ω /km , [].

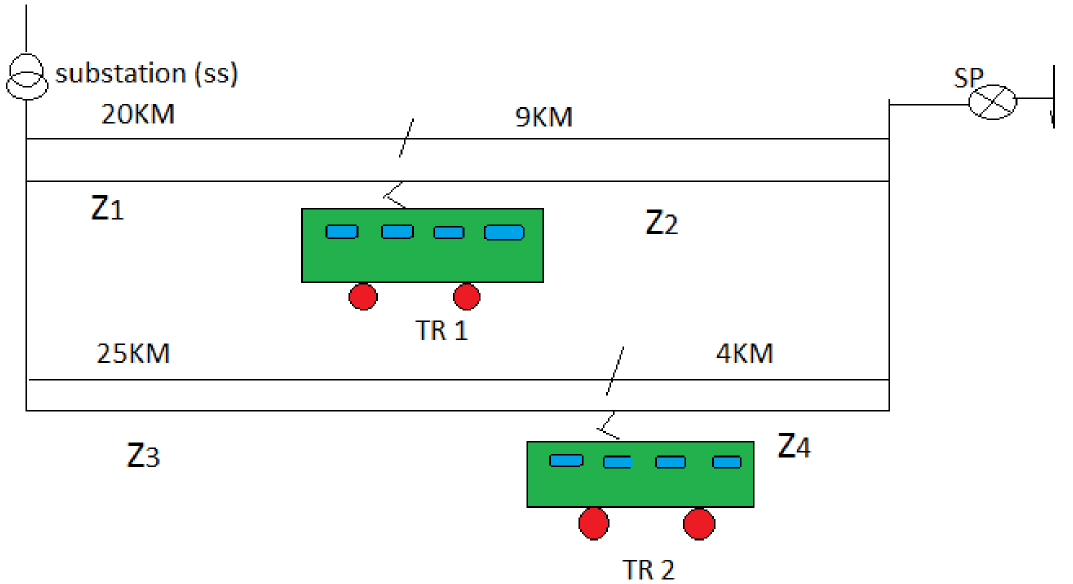


Fig 4.3 Single-phase AC railway power feeding model for Mojo-to-Adama traction line

The parameters of each transmission lines Z_1, Z_2, Z_3, Z_4, Z_5 and Z_6 are:

Z_1 = (0.13008 + j 0.39238) * 20 km = (2.6016 + j7.8476) Ω

Z_2= (0 .13008 + j 0.39238) * 9km = (1.17072 + j3.531429) Ω

$Z_3 = (0.13008 + j\ 0.39238) * 25\ km\ = (3.25 + j\ 9.8095)\ \Omega$

$Z_{4} = (0\ .13008 + j\ 0.39238) * 4km = (0.52032 +j\ 1.569524)\ \Omega$

4.4. The train model

The other key power system component is the electric train. It requires a simple model to reduce problem complexity and overall execution time; directly applying differential equations to obtain a model like that used in traction drive analysis is not appropriate for steady-state power flow calculations [8].

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

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

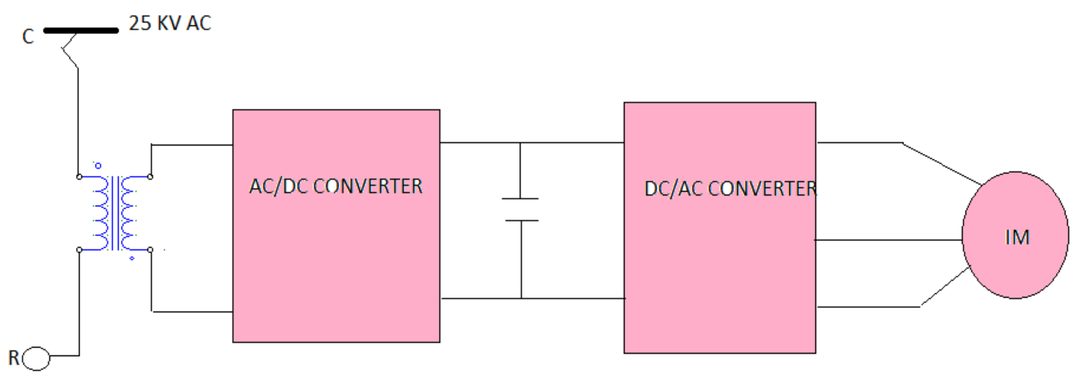


Fig 4.4 AC electric locomotive [8]

The train represents the load in the RES. Usually the MVA requirement of the train is determined for a specific speed, acceleration, and position of the train as explained earlier. The type of motor and drive on the train is usually considered also. Having a fixed MVA at a certain node or nodes, renders the problem nonlinear, according to [8] four methods are used to model a train:

1. Linear model
2. Impedance model
3. Current model and
4. Power model

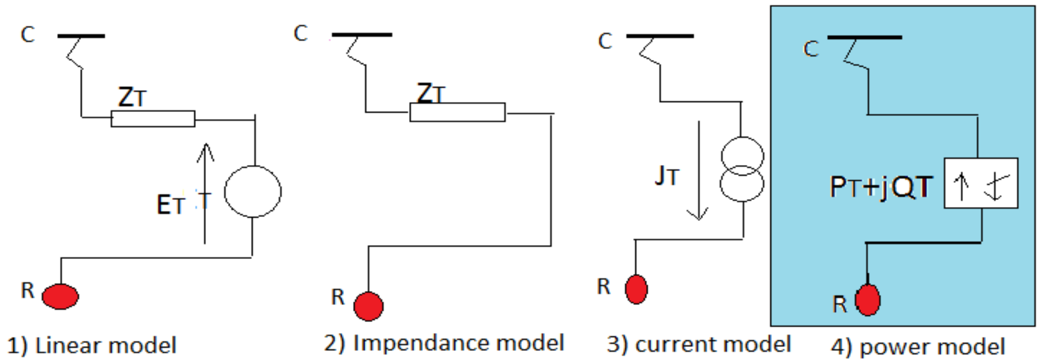


Fig. 4.5 Train model

4.4.1. Linear model

The voltage source E_t and the series impedance Z_t representing this model can be determined as a function of speed, pantograph voltage and tractive effort over the whole range of operation. The direct calculation cannot be done because of the phase angle of the internal voltage source, which must be referenced to the substation. Thus, a look-up table is used to define the model parameters at any instance according to train speed, voltage and tractive effort. When the locomotive model is needed, the relevant values can be loaded and used in the power flow program. The inevitable disadvantage of this model is that a substantial database for each locomotive must be prepared for the simulation program. The linear model is shown in Fig. 4.5(1).

4.4.2. Impedance or admittance model

The effective model is the one that uses only the four measured quantities. The impedance magnitude is calculated by the ratio between the voltage and current magnitudes whereas the phase angle is simply determined from the power factor interpretation. The impedance model is given in Fig. 4.5 (2).

4.4.3. The current model

The current model is not appropriate due to the unknown phase angle, a numerical database stored for this model with respect to train speed, pantograph voltage and tractive effort like the linear model is another effective way. The lookup table is required to obtain its parameters at any simulated time step. During simulation, the pantograph voltage is an unknown and needs to be solved for by a power flow program. The phase angle of the locomotive current must be specified with respect to the phase angle of the substation voltage. It cannot be specified unless the power flow solution has been successfully obtained. In practice, only four electrical quantities (Pantograph voltage-magnitude, input current-magnitude, power and power factor) can be measured on-board a train. The current model is given in Fig. 4.5 (3).

4.4.4. Constant power model

This model is widely used in three-phase power flow problems. Also, it is mainly used in this research because powers and power factor are the two quantities that can be measured by the on-board traction controller. Furthermore, applying tractive effort vs speed and train running information with the Newton’s second law of motion can alternatively calculate the model parameters [8]. Fig. 4.5 (4) shows the power model. The train is modeled with a resistance and inductance and the motor size will be 7.2MW. It is possible to control the firing angle of the TCSC. Finally simulation will be done in several load conditions like different number of loads, different firing angles to investigate the performance of proposed system as much as possible.

Calculating the equivalent train impendence:

Train voltage $V_{tr} = 25kV$

Train power $P_{tr} = 7.2MW$

Power factor $pf = 0.95$

The train current $Itr = \frac{P_{tr}}{V_{tr}\cos\phi} = \frac{7.2*10^6}{25*10^3*0.95} = 303.158A$

Reactive power $Q_{tr} = P_{tr} * \tan(\cos^{-1}(0.95)) = 2.3665MVAR$

4.5. The TCSC Model

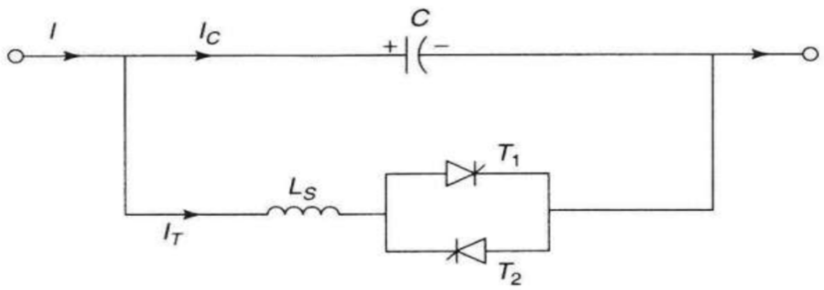


Fig 4.6 the TCSC model

The parameters of TCSC model were designed so that the percentage of compensation of TCSC is between 20 % and 70% when switching Thyristor angle α = 90^0 according to the following calculation.

Line 1 series impendence:

$Z_{L1} = Z_1 + Z_2$

= (3.77232 + j10.379038) Ω

$Z_{L2} = Z_3 + Z_4$

= (3.77232 + j10.379038) Ω

$Z_{LINE} = ZL1 // Z_{L2}$

= (3.77232 + j10.379038)

These the line series reactance is $X_L = 10.379038$

There for base on 50% series compensation, the impendence of the series compensator is:

$$Z_{CAP} = -jX_{CAP} = -j*0.50*10.379038 = -j5.1896\Omega$$

$$Z_{CAP} = -jX_{CAP} = -j*0.50*10.379038 = -j5.1896\Omega$$

The capacitor value $C = \frac{1}{2\pi f X_C} = 613.67\mu F \approx 650\mu F$

Since the compensation is between 20% and 60%:

$$Q_{MIN} = 0.2*Q_C$$
$$Q_{MAX} = Q_C = 0.6*Q$$
$$Q_{TCR} = Q_C - Q_{MIN}$$

But $Q_C = \frac{V_C^{\,2}}{X_C} = \frac{(25KV)^2}{1.707} = 366.354MVAR$

From:

$$Q_{MAX} = Q_C = 0.6*Q$$

$$Q = 610.58MVAR$$

$$Q_{MIN} = 0.2*Q_C = 73.2MVAR$$

There for, $Q_{TCR} = Q_C - Q_{MIN} = 293.15MVAR$

Using the equation $Q_{TCR} = \frac{(25KV)^2}{X_L}$, $X_L = 2.133\Omega$, that means $L = 6.79mH \approx 7mH$

The complete model

The complete model by considering all components described above is given in the figure 4.7.

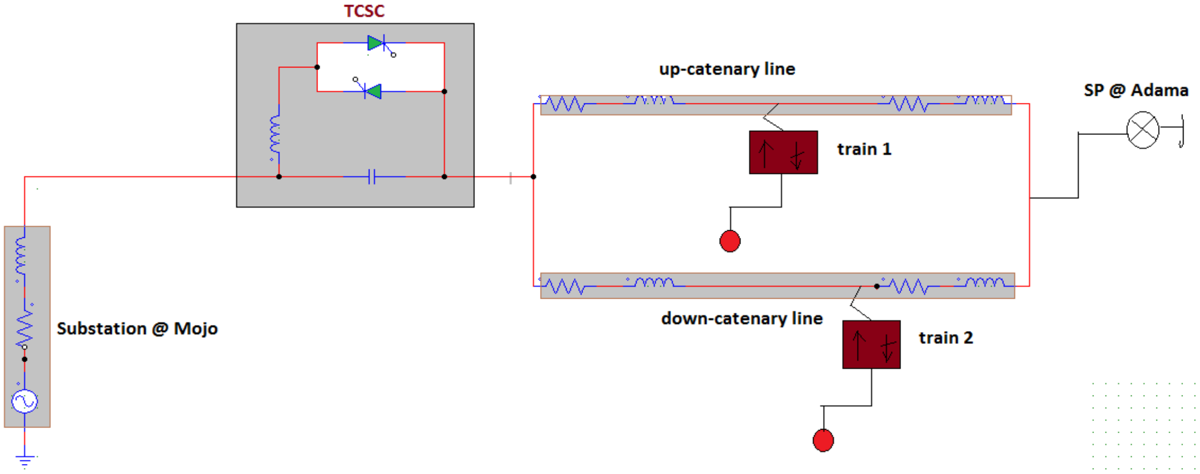


Fig 4.7 the complete system model

CHAPTER FIVE

SIMULATION RESULTS AND DISCUSSIONS

The Mojo-to-Adama secion of Sebeta-to-Adama traction line is selected and modeled for the simulation tests as shown in Figure.5.1. The trains were all assumed to be identical. The properties of the trains and the power supply used in this simulation are shown in **AppendixA**.

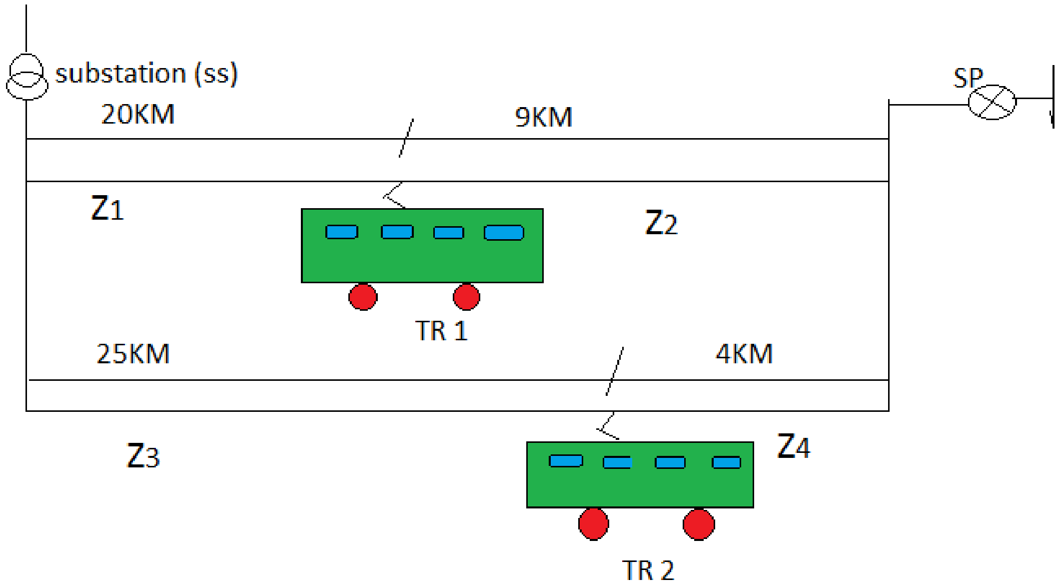


Fig 5.1 Two-train AC railway test system

This system consists of a substation, a line section 20km , a train at 20km and 9km line section on up track and a line section at 25km , a train at 25km , 4km line section on down track to take the worst case .

The model of electrical network with and without TCSC device was prepared and simulated in Simulink / SimPowerSystem of program MATLAB version (R2009b). For demonstration of action TCSC device, from the viewpoint of active power flow control and traction network voltage improvement has been created a simple model of electrical network, in which was subsequently implemented TCSC device. The model of simple electrical network consists of a voltage source, load, two parallel lines and units for measuring and displaying measured electric variables.

PARAMETERS OF THE MODEL

Voltage source:

Line to-line voltage primary voltage *UN = 132 kV*,

Secondary voltage (catenary voltage) = 25KV

Series impendence Zs =0.16+j3.2

Phase angle L_1 = *0°*,

Frequency *f = 50 Hz,*

- *Single phase R_L Load (train):*

Active power *P = 7.2 MW,*

Reactive power *Q = 2.365 MVAr,*

- *Line:*

Line resistance *R = 0.13008Ω /km,*

Line inductance *L = 0.39238 mH/km,*

Line capacity *C = 0.011µF/km,*

Line length *l = 29km,*

5.1. Simulation Result of transmission line without TCSC controller device

Simulation result is performed in MATHLAB Simulink/Simpower system software. Simulation diagram of existing system without TCSC schematic simulation diagram and its output wave form is shown from figure 5.2 to figure 5.5.

Figure 5.2 shows Simulation diagram of existing system without TCSC. This includes the substation model, the catenary line model and load (train model).

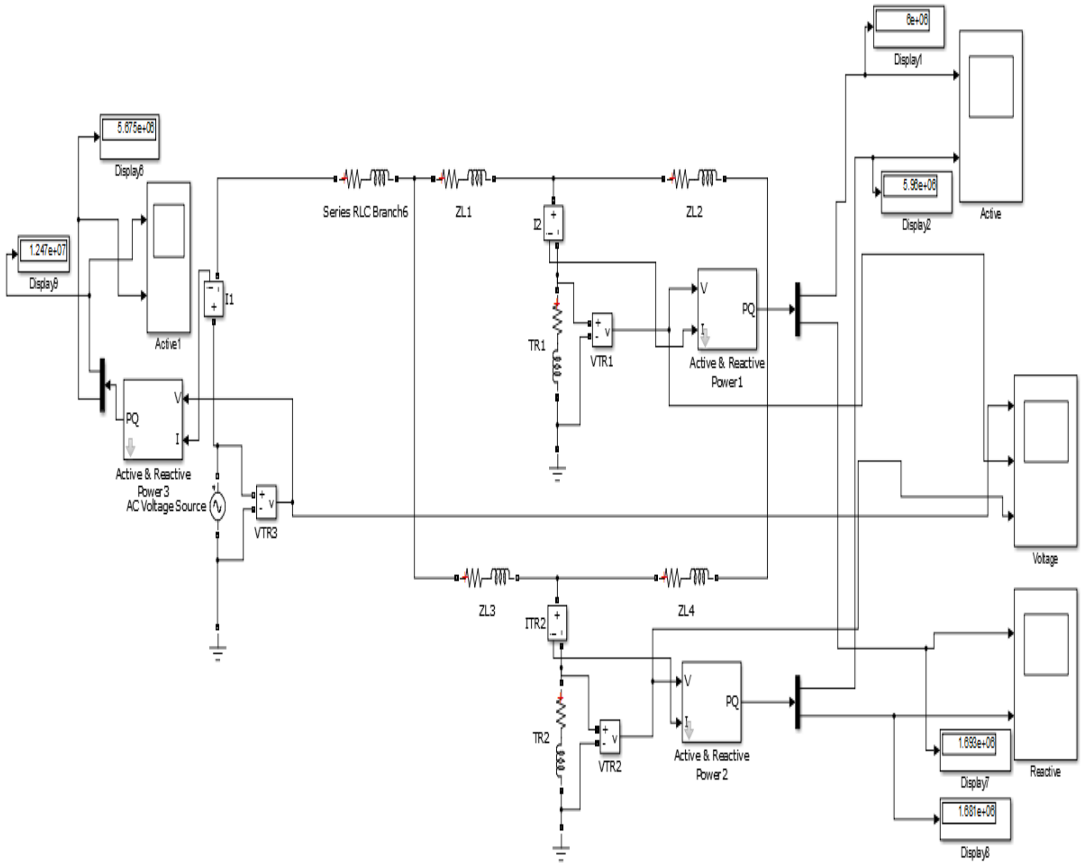


Fig 5.2 Block diagram of the model of electrical network without TCSC

The out puts of source voltage and voltage across one and train two Simulation diagram of the model of electrical network without TCSC are shown in figure 5.3. This figure shown the source voltage, voltage across train one and train two are 24.41kv, 21.69kv and 21.61kv respectively.

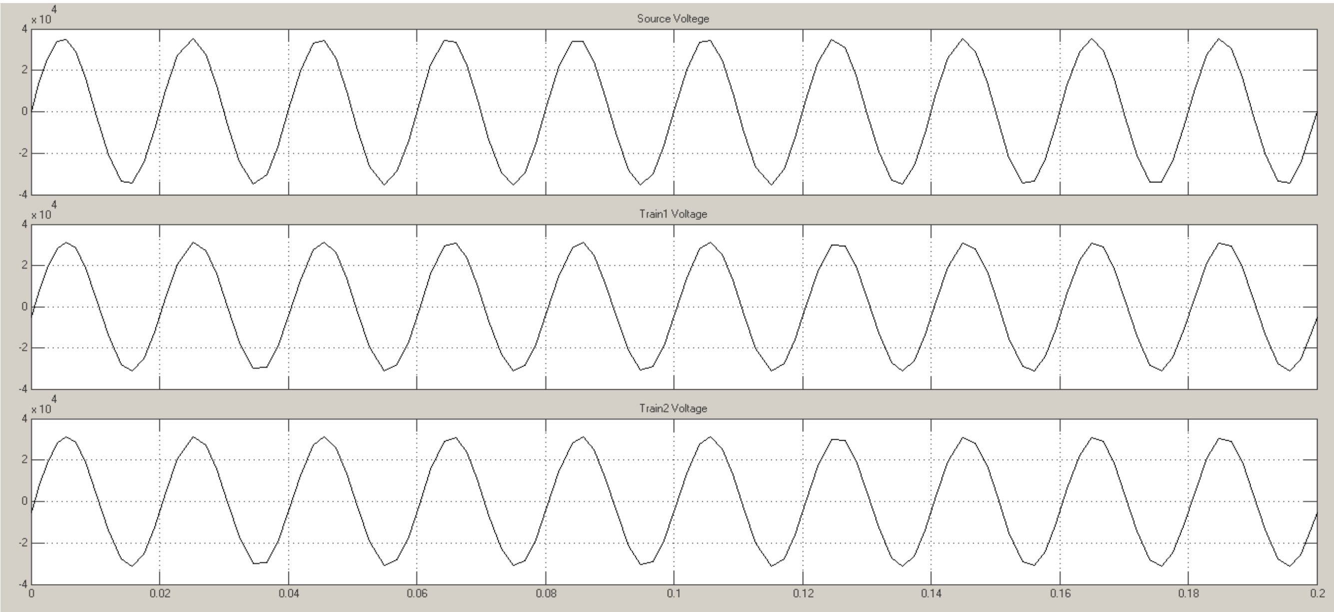


Fig 5.3 Result of voltages without TCSC

Figure 5.3 the out puts of source voltage and voltage across trains without TCSC

Similarly simulation result of real powers of train one and train two for the model of electrical network without TCSC are shown in figure 5.4.

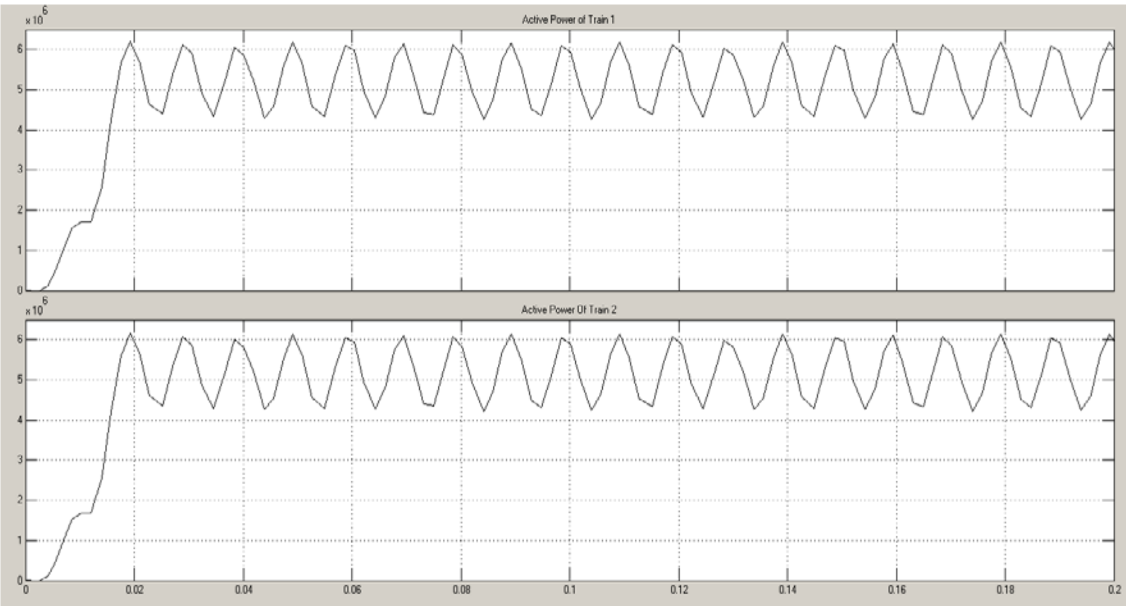


Fig 5.4 Result of powers without TCSC

It shows that the real powers of train one and two are 6.013MW and 5.973MW respectively.

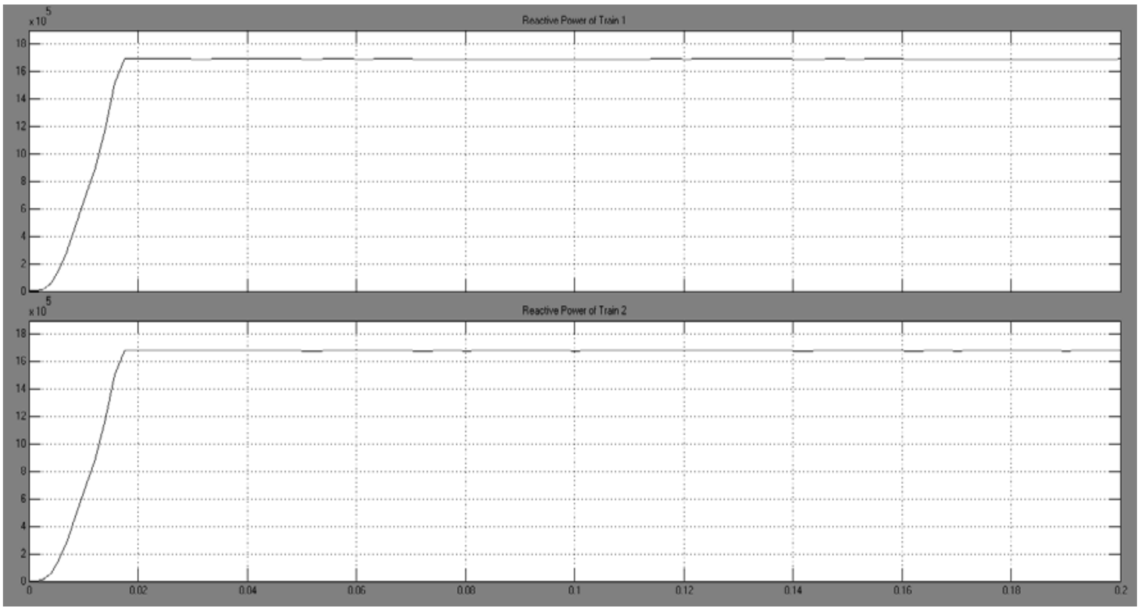


Fig 5.5 Result of reactive power without TCSC

Figure 5.5 Shows simulation result of reactive powers of train one and train two for the model of electrical network without TCSC.

From the figure it is shown that the reactive powers of train one and train are 1.693MVAR and 1.693MVAR respectively.

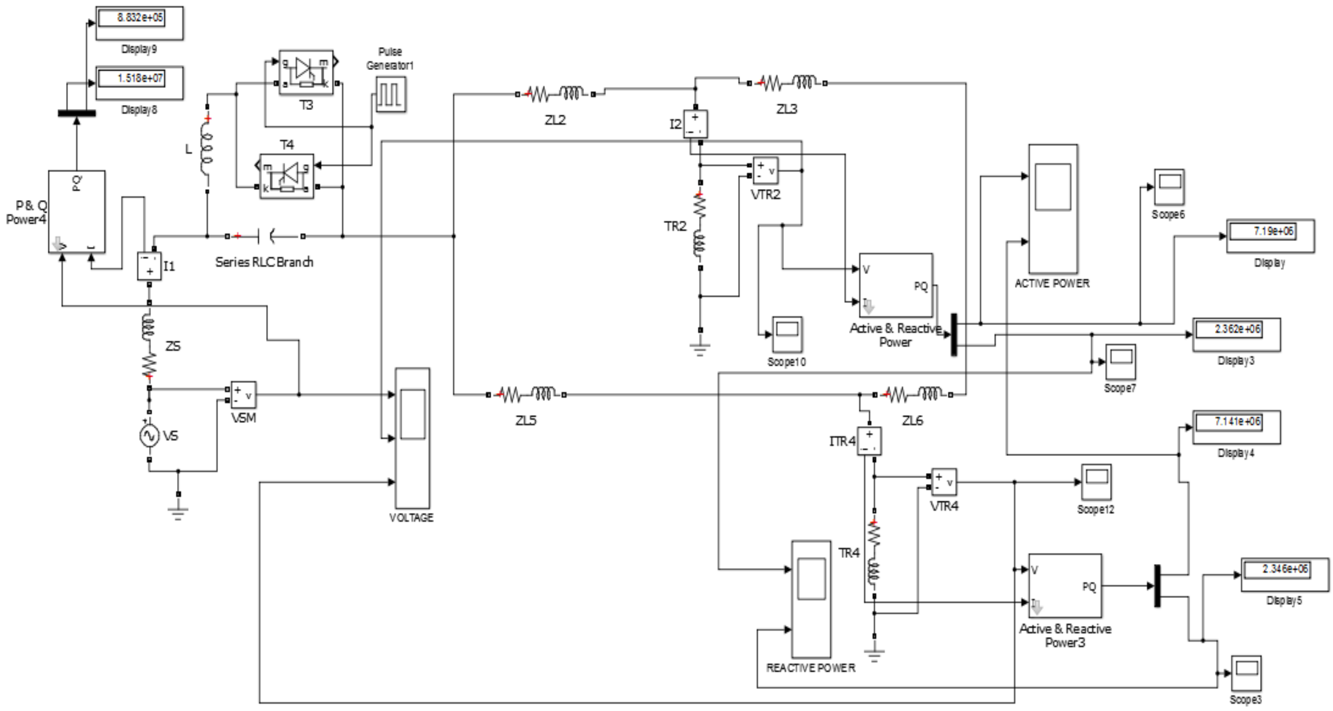


Fig 5.6 the system model with TCSC

5.2. Simulation result of transmission line with TCSC controller

The simulation diagram of purposed TCSC system and its out put wave form is shown from figure 5.6 to figure 5.7.

Figure 5.6 shows Simulation diagram of the system with TCSC. This includes the substation model, the TCSC model, the catenary line model and load (train model).

The out puts of source voltage and voltage across one and train two Simulation diagram of the model of electrical network with TCSC are shown in figure 5.7.

Voltage with TCSC

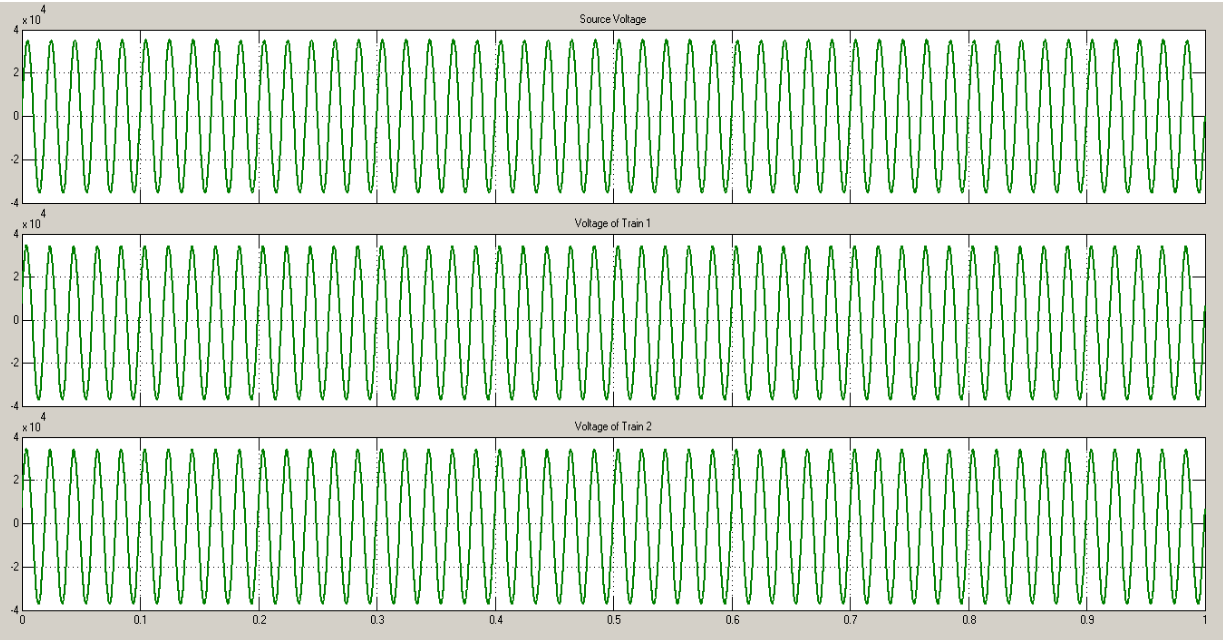


Fig 5.7 Result of voltages with TCSC [Reference]

This figure shown the source voltage, voltage across train one and train two are 24.94kv, 25.08kv and 25.00kv respectively.

Simulation result of real powers of train one and train two for the model of electrical network with TCSC are shown in figure 5.8.

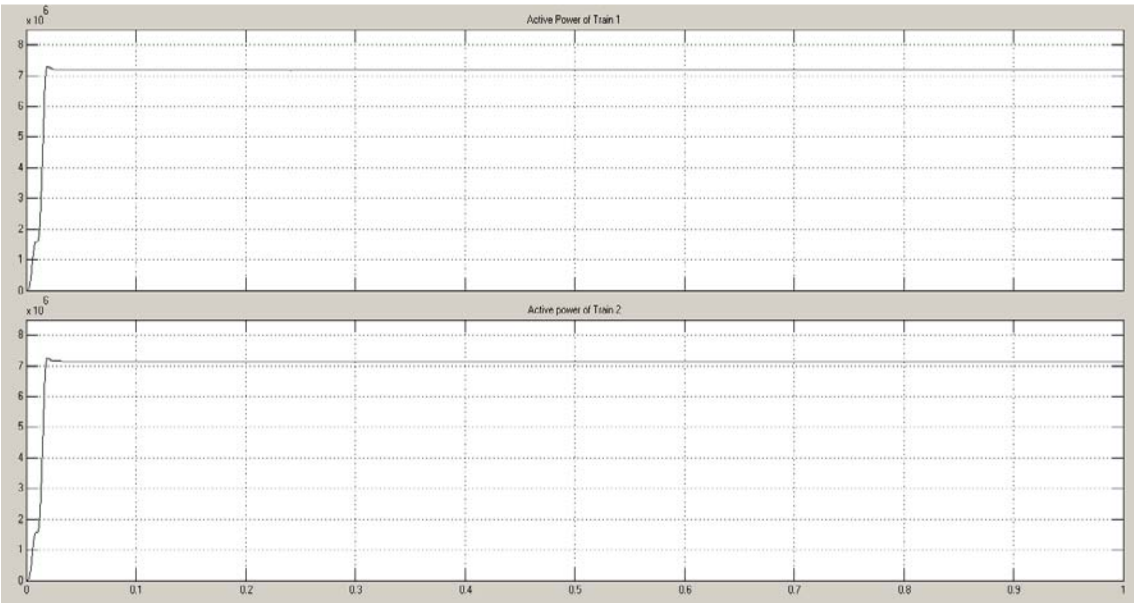


Fig 5.8 Result of Active power with TCSC [Reference]

It shows that the real powers of train one and two are 7.19MW and 7.141MW respectively.

Figure 5.9 Shows simulation result of reactive powers of train one and train two for the model of electrical network with TCSC.

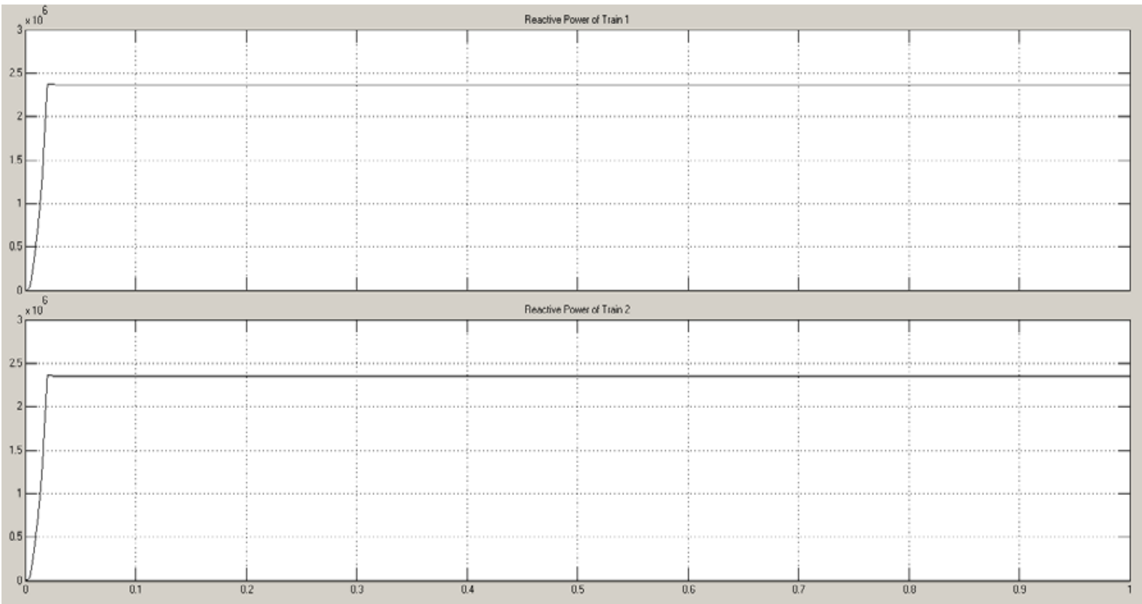


Fig 5.9 Result of reactive power with TCSC

It shows that the reactive powers of train one and two are 7.19MVAR and 7.141MVAR respectively.

The Power flows on lines, losses in the system , voltage across the trains, voltage drop on the line, substation MVA and power factor during operation of TCSC is summarized by the table 5.1.

On table 5.1 is shown change of power in catenary line, depending on set firing angle α of Thyristors of TCSC in inductive or capacitive regime. By change of firing angle α can be seen different impact of TCSC on impedance of line. This thesis is described just capacitive operation of TCSC for analysis case at $\alpha = 60^0$. In this case of capacitive operation of TCSC some calculations are taken to compare the result with the uncompensated line.

Table 5.1 power and voltage of simulation result (Detail calculation is found at Appendix B)

		$\alpha[]^0$									
	With out TCSC	0	15	30	40	60	70	90	120	140	180
P_{TR1}[MW]	6.01	5.382	5.76	6.519	6.83	7.19	7.25	8.17	4.67	4.58	5.38
P_{TR2}[MW]	5.97	5.346	5.721	6.475	6.78	7.141	7.19	8.16	4.64	4.47	5.34
P_{SUM}[MW]	11.98	10.728	11.48	12.99	13.6	14.33	14.44	16.3	9.31	9.05	10.7
Q_{TR1}[MVAR]	1.693	1.768	1.892	2.243	2.24	2.362	2.38	2.48	1.53	1.5	1.76
Q_{TR2}[MVAR]	1.681	1.756	1.879	2.228	2.23	2.346	2.37	2.47	1.53	1.5	1.76
Q_{SUM}[MVAR]	3.374	3.524	3.771	4.471	4.47	4.708	4.75	4.95	3.06	3.0	3.52
P_{LOSS}[MW]	0.14	2.612	1.86	1.17	1.0	0.85	0.87	0.4	2.79	2.85	2.4
V_{SOURSE}[KV]	24.41	25	25	25	25	24.94	25	25	25	25	25
V_{TR1}[KV]	21.69	25.07	25.07	25.07	25.0	25.08	25	25	25	25	25
V_{TR2}[KV]	21.61	24.98	24.98	25.99	25.9	25.00	25	25	25	25	25
V_{DROP}[KV]	2.72	0	0	0	0	0	0	0	0	0	0
P_{SEND} [MW]	12.12	13.34	13.34	14.16	14.6	15.18	15.31	15.9	12.1	11.9	13.1
Q_{SEND}[MVAR]	4.047	0.2792	0.279	0.2632	0.39	0.883	1.171	1.39	1.55	0.86	-0.5
MVA	12.78	13.343	13.343	14.163	14.6	15.21	15.35	15.9	12.2	11.9	13.1
PF	0.948	0.999	0.999	0.999	0.99	0.998	0.997	0.99	0.99	0.99	0.99

Detail calclaculation for table 5.1 is found at Apindex B

Figure 5.2 is modified and reproduced in Figure5.6, in which one TCSC is connected between Mojo and Adama traction line to control power flow . comparing the results from table 5.1, figure 5.4 and figure 5.8 for the case of the system model without TCSC and with TCSC at firing angle $\alpha = 60^0$ .Since the TCSC cannot generate active power, there is an increase in active power flow from 11.98MW to 14.33 MW (measured at the load), which is just about16.34% active power increase. Thus TCSC with firing angle control provides a good series compensation in the transmission line for controlling the active power flow. While at the same time :

Figure (5.5) and (5.9) are showing that the received reactive power at load side of the transmission line is about 4.708M VAR while the transmitted reactive power along the transmission line is only0.888M VAR and approximately other four fifth amounts has been compensated from the TCSC. This improves the substation power factor from 0.94 to 0.99. Thus TCSC with firing angle control provides a good for improving the substation power factor.

Figure 5.3 and figure 5.7 together with table 5.1 shows, the load voltage for train one and train two are increased from 21.69kV to 25kV and 21.61kv to 25kV respectively . Thus TCSC with firing angle control provides a good for increasing the load voltage.

Table 5.1 also shows the voltage drop is decreased from 2.72kv to almost zero for both catenary lines. Thus TCSC with firing angle control provides a good for decreasing voltage drop across the catenary line .

CHAPTER SIX

CONCLUSION, RECOMMENDATION AND FUTURE WORK

6.1 Conclusion

This thesis reached at a conclusion that Thyristor-Controlled Series Capacitor is one of the fast acting power electronic controllers which can provide power flow control in the catenary line by varying its firing angle. Thus TCSC can be used as a series capacitor to reduce the overall catenary line reactance. Depending on the enhancement of power transfer desired at that time, without affecting other system-performance criteria, series compensation can be varied by TCSC. Thus TCSC is one of the important FACTS controller, which increases the overall power transfer capacity in the catenary line. This thesis work shows that the real power is enhanced from 11.9MW to 14.33MW (measured at the load side), which is 16.34% enhancement by using TCSC controlling of catenary line.

Integration of TCSC has the advantage of improving the substation power factor. In this thesis it is shown that the power factor is improved from 0.94 to 0.99 by controlling the impendence of the catenary line with TCSC.

At the same time TCSC can be used as the load voltage improving device. As shown from result part of this thesis the load voltages of train one and train two are improved from 21.69kV to 25kV and 21.61kV to 25kV respectively.

Integration of TCSC device with catenary line has also an advantage of reducing the voltage load across the catenary line. This thesis reduces the voltage drop across the catenary line from 2.72kV to almost zero by integrating TCSC compensation.

6.2 Recommendation

Based on the result of this thesis work, it is strongly recommended that the Ethiopian Railway Corporation has to consider the integration of TCSC to its upcoming Sebeta to Adama railway power system to enhance overall system power transfer capability, improving the network voltage and reduce voltage losses across the line in the system.

6.3 Suggestions for Future Works

Works on the topic never ends with limited application. It has much more area of application such as damping of the power swings from local and inter-area oscillations and reduction of short-circuit current. Various research works are going on control interaction between multiple Thyristor -Controlled Series Capacitor

(TCSC). Also SVC-TCSC can be combined and used within power systems to enhance inter-area stability. In this work MATLAB SIMULINK/SIMPOERSYSTEM is used for simulation purpose. Train simulator software's to determine the exact power flow from one bus to another. Further study can be made on the Influence of TCSC on Fault Component Distance Protection and Impact of TCSC on the Protection of Transmission Lines. Thus TCSC can be used in many fields.

The power feeding systems used in this thesis is assumed to operate in normal
feeding conditions. However, railway schemes are designed to operate in various emergency conditions, e.g. short-circuits, power equipment outage, etc. The extension of the power flow analysis for such emergency conditions would help the system operator to prepare, prevent and restore the system.

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Appendix: A

Double-track AC Railway Power Feeding System

Substation:

25 kV voltage source in series with 0.5 + j3.0 Ω

29-km feeding length

Overhead catenary feeding system:

Equivalent feeding impedance = 0.1 + j0.3 Ω/km

Train power :

Active power p=7.2MW at 0.95 PF

Appendix: B

calculation for table 5.1

i. <u>Without TCSC</u>

Voltage drop calculation

The voltage drop across the catenary line for train 1:

V_{DROP1} = 25KV-21.69 = 3.31KV > 5% of 25kv(i.e 1.25kv)

The voltage drop across the catenary line for train 1:

V_{DROP2} = 25KV-21.61 = 3.39KV > 5% of 25kv(i.e 1.25kv)

The real and reactive power delivered to the loads(trains)

The real power delivered to train 1:

P_{TR1} = 6.013MW

The real power delivered to train 2:

P_{TR2} = 5.973MW

The total real power delivered to the load:

$P_{TOTAL} = P_{TR1} + P_{TR2} = 6.013 + 5.973 = 11.986MW$

The reactive power delivered to train 1:

$Q_{TR1} = 1.693MVAR$

The reactive power delivered to train 1:

$Q_{TR2} = 1.681MVAR$

The total reactive power delivered to the load:

$Q_{TOTAL} = Q_{TR1} + Q_{TR2} = 1.693 + 1.681 = 3.374MVAR$

The load power factor

$$PF_L = \cos(\tan^{-1}(\frac{Q_{TOTAL}}{P_{TOTAL}})) = 0.96$$

The real , reactive and apparent power delivered by traction substation

The real power delivered by substation:

$P_{SOURCE} = 12.12MW$

The reactive power delivered by substation:

$Q_{SOURCE} = 4.047MVAR$

The apparent power delivered by substation:

$$S_{SOURCE} = \sqrt{(P^2{}_{SOURCE} + Q^2{}_{SOURCE}} = 12.77MVA$$

Substation power factor:

$$PF_L = \cos(\tan^{-1}(\frac{Q_{SOURCE}}{P_{SOURCE}})) = 0.948$$

ii. with TCSC

The voltage drop across the catenary line for train 1:

$$V_{DROPE1} \approx 0V$$

The voltage drop across the catenary line for train 1:

$$V_{DROPE2} \approx 0V$$

The real and reactive power delivered to the loads(trains)

The real power delivered to train 1:

$P_{TR1} = 7.190MW$

The real power delivered to train 2:

$P_{TR2} = 7.141MW$

The total real power delivered to the load:

$P_{TOTAL} = P_{TR1} + P_{TR2} = 14.331MW$

The reactive power delivered to train 1:

$Q_{TR1} = 2.362MVAR$

The reactive power delivered to train 2:

$Q_{TR2} = 2.346MVAR$

The total reactive power delivered to the load:

$Q_{TOTAL} = Q_{TR1} + Q_{TR2} = 4.708MVAR$

The real, reactive and apparent power delivered by traction substation

The real power delivered by substation:

$P_{SOURCE} = 15.18MW$

The reactive power delivered by substation:

$Q_{SOURCE} = 0.8832MVAR$

The apparent power delivered by substation:

$$S_{SOURCE} = \sqrt{(P^2{}_{SOURCE} + Q^2{}_{SOURCE}} = 15.21MVA < 25\text{MVA}$$

Substation power factor:

$$PF_L = \cos(\tan^{-1}(\frac{Q_{SOURCE}}{P_{SOURCE}})) = 0.998, \text{ (improved from 0.95)}$$

Appendix:c

Instalation location of series compensator

1.<u>Set on catenary</u>

Advantage:

Compensation effect is good.

Disadvantage:

It causing catenary openings and resulting in weakness on the mechanic and electric.

Maintenance management is inconvenient.

2.Set in the feeder

Advantage:

Eliminate the catenary opening,

easy maintenance and management.

Disadvantage:

May cause the over voltage at ***the head of the catenary***