Monitoring Power Transfer Capability of EHV AC Lines under Lightly Loaded Conditions using Compensation

Thesis submitted in partial fulfillment of the requirements for the award of degree of

Master of Engineering
in
Power Systems & Electric Drives

Thapar University, Patiala

By:
Navdeep Kaur
Regn.No.80641013

Under the supervision of:
Ms. Manbir Kaur (AP, EIED)

JUNE 2008

ELECTRICAL & INSTRUMENTATION ENGINEERING DEPARTMENT
THAPAR UNIVERSITY
PATIALA – 147004

Certificate

I hereby certify that the work which is being presented in the thesis entitled, "**Monitoring Power Transfer Capability of EHV AC Lines under Lightly Loaded Conditions using Compensation** ", in partial fulfillment of the requirements for the award of degree of Master of Engineering in *Power Systems & Electric Drives* submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Ms. Manbir Kaur**, Assistant Professor, EIED.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

Navdeep

(Navdeep Kaur)
(Regn.No.80641013)

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

Manbir Kaur 15/7/08.

(Ms.Manbir Kaur)
Assistant Professor
Electrical & Instrumentation Engg. Department
Thapar University
Patiala

Countersigned by

S. Ghosh

(Dr.Smarajit Ghosh)
Professor & Head
Electrical & Instrumentation Engg. Department
Thapar University
Patiala

RK Sharma.

(Dr.R. K. Sharma)
Dean(Academic Affairs)
Thapar University,
Patiala.

Acknowledgement

Words are often less to reveal one's deep regards. An understanding of work like this is never the outcome of the efforts of a single person. I take this opportunity to express my profound sense of gratitude and respect to all those who helped me through the duration of this thesis.

First of all I would like to thank the Almighty, who has always guided me to work on the right path of the life. My greatest thanks are to my parents who bestowed ability and strength in me to complete this work.

This work would not have been possible without the encouragement and able guidance of my supervisor **Ms. Manbir Kaur.** His enthusiasm and optimism made this experience both rewarding and enjoyable. Most of the novel ideas and solutions found in this thesis are the result of our numerous stimulating discussions.

I take this opportunity to express my gratitude and sincere thanks to **Dr. Samarjit Ghosh,** Prof. & Head, Electrical & Instrumentation Engineering Department for their valuable suggestion and for providing me the opportunity to complete my thesis work simultaneously.

I am most indebted to the P.G. coordinator **Dr. Sanjay Kumar Jain** for his help, assistance and suggestions during my work.

I am also very thankful to the entire faculty and staff members of Electrical and Instrumentation Engineering Department for their direct–indirect help, cooperation, love and affection, which made my stay at Thapar University memorable.

I wish to thank all my classmates for their time to time suggestions and cooperation without which I would not have been able to complete my work.

Navdeep Kaur

Abstract

The increase in demand of electrical power has elevated the concern about security and reliability of the interconnected systems of Extra High Voltage (EHV) systems. These increases are brought about by environmental and an economic pressure which has led to an increased complexity in the system. Power-frequency over-voltages and obtaining of the maximum power transfer limit are two major concerns of interconnected systems using long EHV links. It has been proven that by using the series and shunt compensations are the best available methods because the transmission distance can be reduced artificially and hence more power can be transferred.

The effect of shunt compensation on an EHV long transmission line under lightly loaded conditions is studied in this thesis. This is achieved by developing a MATLAB program to calculate the required compensations and by using ETAP power station to conduct a power system analysis on test case system i.e. IEEE 14 bus system to maintain the load voltage profile over the link and determine the maximum power transfer limit that may be transmitted under the influence of various factors such as the line length, load power factor and the degree of compensation. The results obtained have shown that by controlling the shunt compensation, it will improve remarkably on the transmission capability.

Table of Contents

List of Figures

List of Tables

Table No. Title Page No.

Chapter 1
Introduction

1.1 Overview

The increase in demand of electrical power has elevated the concern about security and reliability of the interconnected systems of Extra High Voltage (EHV) systems. These increases are brought about by environmental and an economic pressure which has led to an increased complexity in the system. Power system insulation is subjected to voltage stresses due to lightning surges, internal over-voltages as well as normal service voltages of the system [14].

The importance of the excessive line MVAR in EHV systems as well as the associated voltage and reactive controls increased with continuous increase of the voltage of transmission, line lengths and number of sub-conductors per bundle. During line-charging volt-amperes of a line which have exceeded the inductive vars consumed and operation at light loads, there is an undesirable voltage rises along the line. This voltage rise in turn demands a much higher insulation level, which poses a great problem for the reactive power in the form of capacitor bank or synchronous condenser. Moreover, the problem is further deteriorated when the var is necessary to flow to its maximum, causes transmission losses and take up equipment rating. If the insulation against these over-voltages were to be provided in the system, then the cost of the line becomes enormous. Therefore, in the case of the EHV system, power-frequency over-voltages pay a decisive role in determining the insulation level [4].

In developed countries, power generation and transmission is fully controlled by different power companies, which maintain utmost quality of the power supply. With the interconnection of power stations into power systems, and power systems into power pools, transmission lines should be capable of transmitting the maximum possible energy when demanded. To improve the steady state stability limit of the line, the maximum power transfer limit of the line should be increased. Therefore, due to the present day practice of power industry to transmit large blocks of power over long distances because of economic and environmental reasons, the studies of transient and steady state stability are very important [14].

1.2 Literature Review

Several research papers and reports are presented on the subject of compensation of EHVAC transmission lines. The followings present a brief review of the work undertaken so far.

R. Rajaraman, *et.al* presented the merits of an analytical method for determining the location and amount of series compensation to increase the steady state power transfer capability in the power system based primarily on cascading line overload considerations. Steady state transmission limits define the boundaries of a power system operating point. They also presented tools to identify these boundaries and analytically estimate the change in the boundary limits due to the application of series and shunt compensation. The approach identifies critical lines that can initiate cascading line outages and identifies the optimal location and amount for series compensation.[15]

C.S. Indulkar, *et.al* presented a new mathematical model for analysis of self-excited oscillations in a synchronous machine connected to a long EHV transmission line with different configurations of series and shunt compensation. The model has been developed in terms of line constants of long lines which includes the effect of line shunt susceptance and reactance of line end transformers. The model has been used to directly analyse self-excited oscillations in a transmission system for five types of compensation scheme. The stability limit curves in the $R \sim X_Q$ parametric plane for the five compensation schemes have been compared with that for a series compensated transmission line.[3]

K. Ramar & M.S. Raviprakasha presented a generalized approach to reactive power management in AC transmission lines for maximum power transfer in which voltage stability limit is also considered. The transmission line is represented by its π-equivalent model. Use of controlled shunt compensation and series compensation schemes are separately analyzed for different load models and supported with illustrative examples. The voltage constraints are also taken into consideration during the design of compensation schemes.[8]

M.H. Haque presented a simple and general method of determining the maximum efficiency of a transmission line. The method can be applied to both compensated and uncompensated lines. The maximum efficiency for a given load power factor and the power factor angle at which the highest value of the maximum efficiency occurs are determined from very simple analytical expressions. The method was tested on a 500 kV transmission line with several series and shunt compensation schemes. The influence of various factors such as the load power factor, line length and the degree of series and shunt compensations on the maximum efficiency was also investigated. [10].

M.H. Haque also presented a new method of determining the maximum power transfer capability of a high voltage AC transmission line with different series and shunt compensation schemes. The method determines the maximum power transfer limit by finding the critical value of the receiving-end current beyond which the power cannot be increased by increasing the value of the current because of voltage instability. Simple analytical expressions for the critical or limiting values of the receiving-end quantities (power, voltage and current) and the corresponding phase shift between the sending- and receiving-end voltages are derived. The proposed method was applied to a transmission line with several series and shunt compensation schemes to determine the various critical quantities. The critical quantities obtained for those schemes were also compared. The influence of various factors such as the line length, load power factor and the degree of series and shunt compensation on the maximum power transfer capability was also investigated. [11]

M.T.K. Prasad and B.Thapar presented series and shunt compensation schemes for medium and long distance AC transmission lines and are compared from the points of view of the compensation effectiveness (improvement of system stability), the total compensation MVAR requirement, and the profile of line voltage and the efficiency of power transmission.[13]

G. Joos and B.T. Ooi presented the dangers of sub synchronous resonance in series capacitor compensated transmission lines have led some utilities to consider the alternative of shunt capacitive compensation, since the electrical resonant frequencies in this case are usually considered to be supersynchronous. However, in heavily compensated or very long lines, at least one of the resonant frequencies may become subsynchronous. They examined the torsional interactions between electrical resonant frequencies (which can be supersynchronous or subsynchronous) and the mechanical oscillations of a generator connected to a long transmission line. [5]

S.M. Chandekar and S.G. Tarnekar presented an analytical method to ascertain the performance of uncompensated and series capacitor compensated 500kV line working below the minimum allowable frequency of 48.5Hz. The method is based on the assumption that the ABCD generalised circuit constants of a long line change both in magnitude and phase angle. That method also highlights the effects of change of location of a series capacitor on the receiving end voltage, active and reactive powers transferred by the line and on power factor of system load during the under-frequency operation. They also concluded that a judiciously located series capacitor results in minimum loss of revenue to the supply utility and minimum rise in receiving-end voltage in a series capacitor-compensated long line.[16]

T.W. Kay *et.al* presented optimization algorithms for power system operation and planning employing EHV and UHV line loadability limits as well as var supply limits. Traditional line loadability limits are based on stability limits which assume infinite var supply capability. They showed the critical dependence of line loadability on var supplies and presented a method to compute line loadability limits that are consistent with var supply limits. [20]

C.S. Indulkar presented a method to determine the shunt compensation at the load end of a long transmission line to maintain the load voltage at a fixed percentage of the sending-end voltage. A long-line model to determine the critical power that the line can transmit with and without series compensation is used.[4]

According to M.S. Raviprakasha and H.L Suresh the increase in the interconnections of power systems with increased demand for power has led to a progressively more complex system. The main concern of long transmission line systems is the maximum power transfer limit. It has been proven very well that series and shunt compensations are the best available methods for increasing the maximum power transfer limit. This is largely due to the fact that the transmission distance can be reduced artificially and hence maximum power can be transferred. They presented a method for the determination of shunt compensation at the load-end of a long transmission line for maintaining load voltage. The long transmission line model is used to determine the critical power to be transmitted without series compensation. A program is developed to determine the required shunt and series compensation on a long transmission line. Also the effect of compensation with respect to maintenance of the load voltage and maximum power transfer limit of the transmission lines is evaluated. [12]

Manoel Afonso de Carvalho and Luiz Antônio Magnata da Fonte presented the paper which deals with the replacement of linear reactors, which are often used for reactive compensation on EHV long transmission lines by naturally saturated reactors. Besides a steady state, smoother voltage control that such a change brings, the chief concern is to release the transmission line's entire capacity to load supply. EMTP-ATP simulation results for a specific application of naturally saturated reactors at CHESF´s 500 kV power grid are shown in order to justify this proposal. The reactor's mathematical model is also described in this paper as well as the methodology used to determine the set of the model's parameters.[9]

1.3 Objective

The aim of this thesis work is to develop a program to determine the required shunt compensation on an EHV long transmission line under lightly loaded conditions and after which, conduct a power system analysis using ETAP power station simulation package to evaluate the effect of compensations on the line with respect to the following objectives:

1. To maintain the receiving-end voltage constant with respect to the sending-end voltage.
2. To determine the maximum power transfer capability considering various factors such as the line length, load power factor and the degree of shunt compensation on the maximum power transfer capability.

1.4 Organization of Thesis

Chapter 1 describes introduction to the problem. It presents the literature review on compensating devices and their allocation in power system to minimize losses.

Chapter 2 gives brief idea about EHVAC transmission lines. It also covers long line model of transmission lines.

Chapter 3 covers reactive power compensation. It covers series and shunt compensation and their effects.

Chapter 4 covers the methodology to calculate the shunt compensation required for the transmission lines and after that Newton Raphson load flow method is discussed which is used to calculate the flows of uncompensated and compensated lines.

Chapter 5 covers results and discussions.

Chapter 6 presents the conclusion of thesis work and discusses the future scope of the work

Chapter 2
EHV Transmission Line

2.1 Introduction

Extra High Voltage (EHV) transmission lines are used for the transmission of electric energy over long distances. The first 735 kV system was commissioned in Canada in 1965. Since then, voltage levels up to 765 kV have been introduced in Russia with neighboring countries, U.S.A, South Africa, Brazil, Venezuela and South Korea. At present time the highest transmission line voltage in India is 765 kV. The examples 765 kV line in India are Kishenpur-Moga, Tehri-Meerut and Sipat-Seoni. In north America there are some experimental lines capable of reaching voltage up to 1100 kV but they are not in operation. Transmission lines voltage up to 800 kV is operational in many countries and 1150 kV EHVAC line is operating in Russia.

For long transmission line analysis, a lumped parameter equivalent of transmission line is no longer accurate and a distributed parameter representation of line is used for transmission line analysis.

2.2 Modeling of Long Line

For a transmission line of 250km and more, as well as for a more accurate solution it is essential to divide the line into sections to consider the exact effect of the distributed parameters per unit length (/km) of resistance(r) conductance(g), inductance(L), capacitance (C) and *ABCD* generalized circuit constants [7]. These parameters can be expressed in the series impedance per unit length and the shunt admittance per phase, written as

$$z = r + j\omega L \tag{2.1}$$

$$y = g + j\omega C \tag{2.2}$$

where z is series impedance per unit length

r is resistance per unit length

$X_L = \omega L$ is inductive reactance per unit length

g is conductance per unit length

$X_C = \dfrac{1}{\omega C}$ is capacitive reactance per unit length

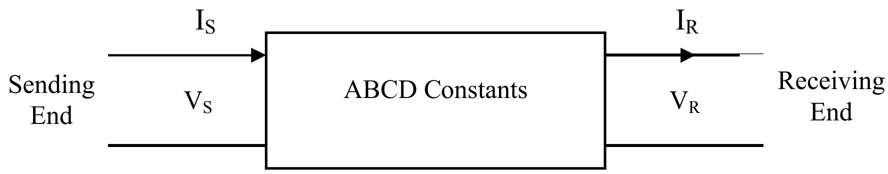


Fig 2.1 Two-port Four-Terminal Model of a Transmission Line

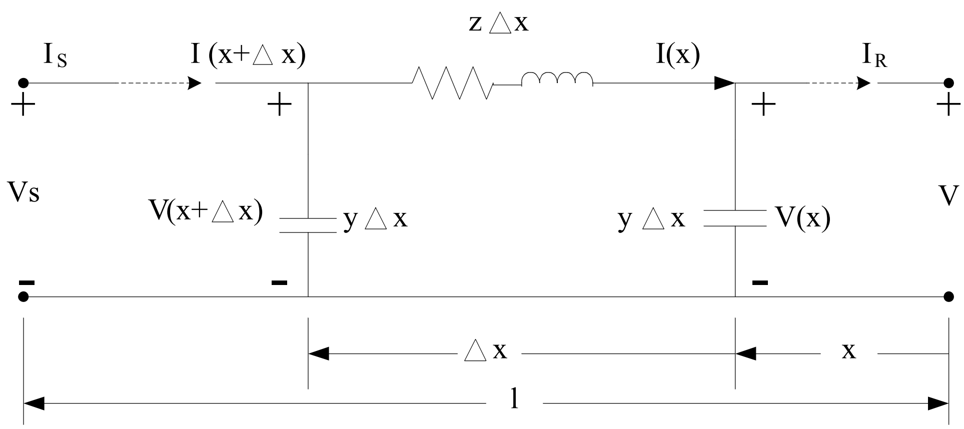


Fig 2.2 Long line with Distributed Parameters [7]

In a long transmission line, it is necessary to define y, known as the propagation constant and the characteristic impedance denoted as Z_c, where

$$\gamma = \sqrt{zy} = \sqrt{(r + j\omega L)(g + j\omega C)} \tag{2.3}$$

$$Z_C = \sqrt{\frac{z}{y}} = \sqrt{\frac{(r + j\omega L)}{(g + j\omega C)}} \tag{2.4}$$

The ABCD constants of an uncompensated transmission line are given by

$$A = D = \cosh(\gamma l) \tag{2.5}$$

$$B = Z_C \sinh(\gamma l) \tag{2.6}$$

$$C = \frac{\sinh(\gamma l)}{Z_C} \tag{2.7}$$

By using the hyperbolic function expansion series for parameters ABCD are [4]:

$$A = \cosh(\gamma l) = 1 + (\frac{YZ}{2}) + (\frac{Y^2 Z^2}{24}) + (\frac{Y^3 Z^3}{720}) + ... \tag{2.8}$$

$$B = Z_C \sinh(\gamma l) = 1 + (\frac{YZ}{6}) + (\frac{Y^2Z^2}{120}) + (\frac{Y^3Z^3}{5040}) + ... \tag{2.9}$$

where Z = Total series impedance of the line

Y = Total shunt admittance of the line.

Neglecting higher order terms.

$$A = 1 + \frac{YZ}{2} \tag{2.10}$$

$$B = 1 + \frac{YZ}{6} \tag{2.11}$$

2.3 Transfer of Power on a Long EHV Transmission Line

Since a transmission line is operated with sources at both ends of the line, power can be derived in terms of *ABCD* constants. Since *A* and *B* constants are related with the sending-end voltage (V_S) and receiving-end voltage (V_R), the relationship could be expressed as

$$\overrightarrow{V_S} = A\overrightarrow{V_R} + B\overrightarrow{I_R} \tag{2.12}$$

Solving for the receiving-end current I_R yields

$$I_R = \frac{V_S - AV_R}{B} = \frac{|V_S|}{|B|}\angle(\delta - \beta) - \frac{|A||V_R|}{|B|}\angle(\alpha - \beta) \tag{2.13}$$

where $A = |A|\angle\alpha$ $B = |B|\angle\beta$

$\overrightarrow{V_R} = |V_R|\angle 0^\circ$ $\overrightarrow{V_S} = |V_S|\angle\delta^\circ$

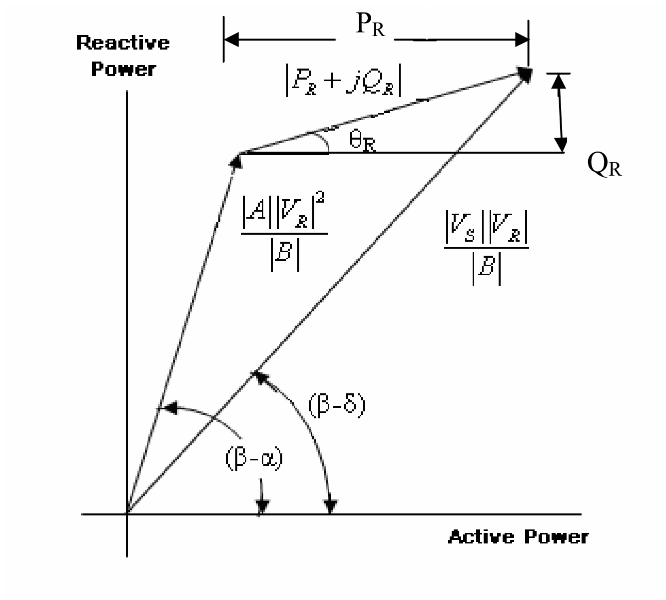


Fig 2.3 Phasor of V_R I_R plotted in Complex Plane

Fig.2.3 shows the two complex quantities and their difference can be solved by the complex power V_R I_R and thus the real and reactive power at the receiving end respectively are written as

$$P_R = \frac{|V_S||V_R|}{|B|}\cos(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\cos(\beta-\alpha) \tag{2.14}$$

$$Q_R = \frac{|V_S||V_R|}{|B|}\sin(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\sin(\beta-\alpha) \tag{2.15}$$

2.4 Stability of the System

The maximum power transfer criteria will consider the stability of the system if the capacity of the Var source at the load end is limited, then. The operating condition is assumed to change due to variations in the active or reactive load powers or due to variations in both [4].

The system for small variations around the nominal operating point can be defined by Eqn. (2.16)

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ |\Delta V| \end{bmatrix} \quad (2.16)$$

The elements of the Jacobian matrix are associated with the derivations Δδ and ΔV in the operating variables that are considered as constants around the nominal operating point. If the determinant of the Jacobian is found to be zero, then any small deviation in either P or Q, or both, may cause infinitely large deviations in δ and V [4].

The corresponding condition is unstable and the system tends to drift away from the initial operating condition. Thus, to check the system for the critical condition, the determinant of the Jacobian matrix is equated to zero [4].

2.5 Determination of Maximum Power Transfer

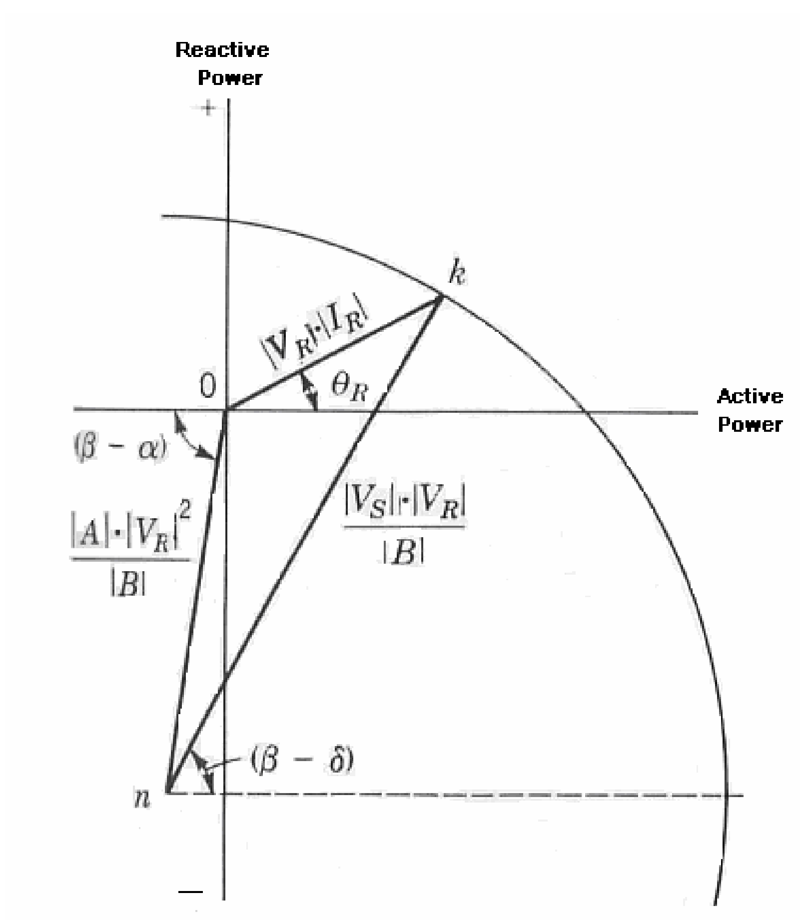


Fig 2.4 Receiving end Power Circle Diagram

Fig. 2.4 shows that there is a limit to the power that can be transmitted to the receiving end of the line for specified magnitudes of sending-end and receiving-end voltages. It is worth noting that as point K moves along the arc towards until the angle δ = β, more power is delivered [6]. As δ increases further beyond δ = β, the lesser power is received. Hence, the maximum power is

$$P_{R,\max} = \frac{|V_S||V_R|}{|B|}\cos(\beta - \delta_{\max}) - \frac{|A||V_R|^2}{|B|}\cos(\beta - \alpha) \qquad (2.17)$$

2.6 Determination of the Critical Quantities

There are several ways to determine the maximum value of the receiving end power, $P_{R,max}$ From the basic formula of a receiving-end power per phase at certain load power factor, this is given by [11].

$$P_{R,\max} = V_{R,\max} I_{R,\max} \cos\theta \qquad (2.18)$$

where $$V_{R,\max} = \frac{V_S}{A[2 + 2\cos(\beta + \theta - \alpha)]^{1/2}} \qquad (2.19)$$

$$I_{R,\max} = \frac{V_S}{B[2 + 2\cos(\beta + \theta - \alpha)]^{1/2}} \qquad (2.20)$$

Solving Eqn. 2.19, 2.20 and the load power factor, cosθ

$$P_{R,\max} = \frac{V_S^{\,2}\cos\theta}{AB[2 + 2\cos(\beta + \theta - \alpha)]} \qquad (2.21)$$

2.7 Effect of Various Factors on Maximum Power Transfer

In planning of an electrical system, it is very useful to know the value of the critical power, which can be delivered to the receiving end of a long transmission line. The effect of the factors such as transmission length, load power factor, degree of series and degree of shunt compensation on obtaining the critical quantities (power, voltage and phase angle) at the receiving end of the system are studied here .

2.7.1 Load Power Factor

All the maximum(critical) quantities (power, voltage and phase angle) are very sensitive to the variation of load power factor. This can be verified by from Eqn.(2.17) to Eqn.(2.21). For any given values of shunt compensation, the maximum power transfer limit is higher for leading pf loads than for the unity and lagging pf loads. However, a very low leading pf may cause an over-voltage at the receiving end [11].

2.7.2 Transmission Length

The maximum power transfer limit decreases with the increase in the transmission length. However, for some schemes it may increase after reaching the minimum value because of the extremely high receiving-end voltage. The deviation between the maximum power transfer capability for different compensation schemes get larger and larger as the transmission length is increased. The critical phase shift angle between the sending end and receiving voltages is less sensitive to the transmission length [11].

2.7.3 Shunt Compensation

For a given degree of shunt compensation, the power transfer limit increases as the degree of series compensation is increased. For given values of series and shunt compensation, the power transfer capability increases as the series compensation is shifted from the sending end to the receiving end of the line. The critical phase shift angle between the sending end and receiving voltages is less sensitive to the degree of shunt compensation [11].

2.7.4 Series Compensation

For zero series compensation, the power transfer limit decreases with an increase in the shunt compensation unless all the shunt compensation is at the sending end. The critical phase shift angle between the sending end and receiving voltages is less sensitive to the degree of series compensation. [11]

Chapter 3
Reactive Power Compensation

3.1 Introduction

With the interconnection of power stations into power systems and power systems into power pools, transmission lines should be capable of transmitting the maximum possible energy when demanded. By using the series and shunt compensations, the transmission distance can be reduced artificially and hence more power can be transferred. These compensations are necessary to maintain a satisfactory voltage level when large block of power is transferred over a long distance [14].

Reactive power compensation is an important issue in electric power systems, involving operational, economical and quality of service aspects. Consumer loads (residential, commercial and industrial sectors) impose real and reactive power demand, depending on their characteristics. Real power is converted into "useful" energy, such as light or heat. Reactive power must be compensated to guarantee an efficient delivery of real power to loads.

The reactive power is essential for creating the needed coupling fields for energy devices. It constitutes voltage and current loading of circuits but does not result in average (active) power consumption and is an important component in all ac power networks. Reactive power control for a line is often called Reactive Power Compensation. External devices or subsystems that control reactive power on transmission lines are known as Compensators. The objectives of line compensation are

- To increase the power transmission capacity of the line, and/or
- To keep the voltage profile of the line along its length within acceptable bounds to ensure the quality of supply to the connected customers.

Because reactive power compensation influences the power transmission capacity of the connected line, controlled compensation can be used to improve the system stability by changing the maximum power- transmission capacity.

There are two methods to achieve the increase in the maximum power transfer limit of the line. The first method is to increase the transmission voltages. However, this will lead to an accumulating effect of cost increase in the generator. The second method is by reducing the characteristic impedance of the line. The reduction of the characteristic impedance of the line can be achieved either by changing the line dimensions or by addition of capacitors in series or shunt reactors with their compensating effect on the capacitive generation with the line. The line dimensions cannot be changed widely and it only creates a small impact on the characteristic impedance value.

3.2 Series Capacitor Compensation

Series capacitors are used to partially offset the effects of the series inductances of the lines. Series compensation results in the improvement of the maximum power-transmission capacity of the line. The reactive power absorption of a line depends on the transmission current, so when series capacitors are employed, automatically the resulting reactive power compensation is adjusted proportionately. Also, because the series compensation effectively reduces the overall line reactance, it is expected that the net line-voltage drop would become less susceptible to the loading conditions.

Series capacitors, which are connected in series with the line are used to reduce the series reactance between the receiving-end and sending-end. Series compensation may be provided as lumped or distributed [13].

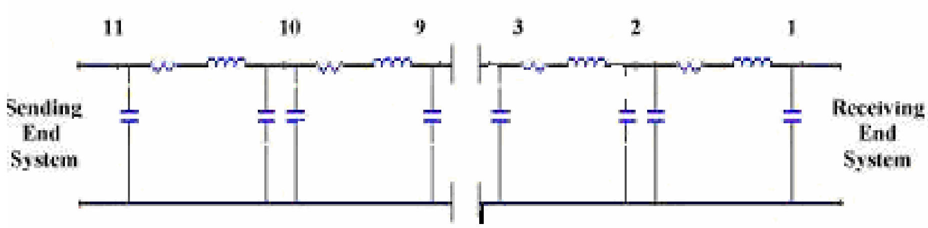


Fig 3.1 Location of Series Compensation

In Fig 3.1, a transmission line is divided into 10 equal sections and an equivalent π model represents each section. A lumped compensation can be placed at any locations marked 1 to 11 and a distributed compensation consists of splitting the compensation from a range of locations, for example, from location 4 to 8 or location 1 to 11. In comparison between these two types of series compensation, a lumped compensation gives a better result than a distributed compensation from the point of view of obtaining the maximum power transfer. However, if the compensation is distributed, splitting of the compensation into five equal parts and locating them at (nearly 10-20% of length of line) of the line length from receiving end, obtain the best results [13].

3.3 Percentage Compensation (K_s)

The percentage or the degree of series compensation is used to analyse a transmission line with the required addition of series capacitors. It is defined as the fraction of Xc, which refers to the total capacitive reactance of series compensators and X_l, which refers to the total inductive reactance of the line, as defined in Eqn.(3.1).

$$K_S = \frac{X_c}{X_l} \tag{3.1}$$

To determine the required series capacitor in the transmission line of different degree of series compensation, the value of constant Ks can be computed. Since the objective is to determine the amount of series capacitor on the line, it will therefore be useful to define the degree of compensation (K_s) in the total line impedance, which is

$$Z = R + j[X_l(1 - K_S)] \tag{3.2}$$

3.4 Effect of Location of Compensation

The identification of the optimum location of the series compensation on the line is very important because compensation at this location has been proven that it could obtain more economical loading and results in minimum loss of revenue to the supply utility and minimum rise in receiving end voltage [15].

In this section, the different conditions that will determine the location of series compensation will be discussed.

3.4.1 Effect of Sending-End Voltage to Receiving-End Voltage Ratio

When a lumped and distributed compensated line compensation for different voltage ratios, namely 0.8, 1.0, 1.1 and 1.2 were tested, similar results were obtained for every degree of compensation and for all long transmission lines. Therefore, for the same degree of compensation, the sending end to receiving-end voltage ratio has no effect on the location of compensation of any transmission line from the point of view of the highest power transfer capability [13].

3.4.2 The Best Location and Percentage Compensation

For developing generalized curves to determining the best location and percentage of series compensation, several lines which are specified by the values of R/XL and l/YX_L, are used for studies. The best percentages and locations of series compensation for these lines are shown in Fig 3.2 and Fig3.3. These two general curves are useful in determining the best location and percentage series compensation of any transmission line of length about 1000km for maximum power transfer [13].

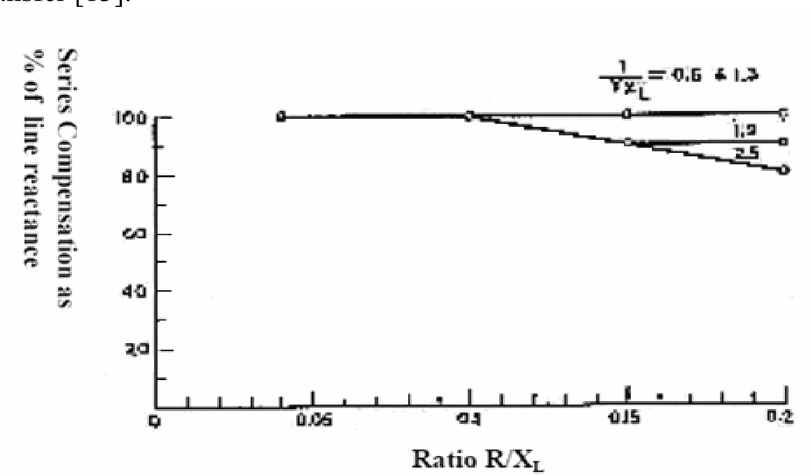


Fig 3.2 Best Percentage of Series Compensation with respect to % of Line Reactance [13]

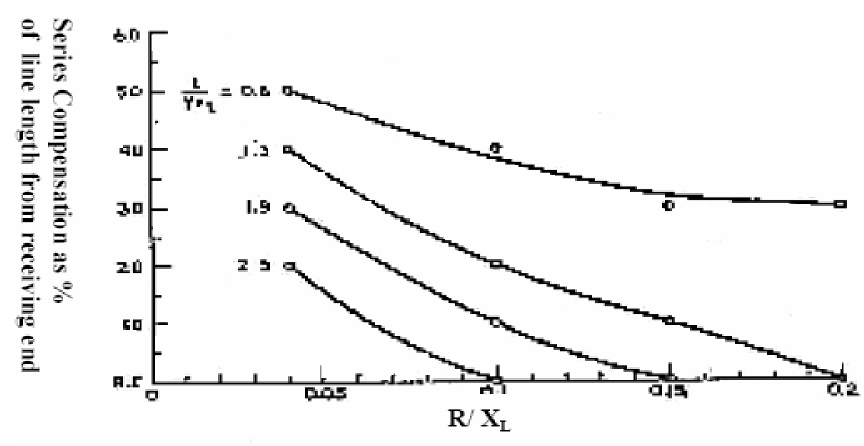


Fig 3.3 Best Location of Series Compensation with respect to % of Line Length from Receiving End [13]

3.5 Drawback of Series Compensation

One major drawback with the series capacitor compensation is that special protective devices are required to protect the capacitors and bypass the high current produced when a short circuit occurs. Also, the inclusion of the series capacitors establishes a resonant circuit that can oscillate at a frequency below the normal synchronous frequency when stimulated by a disturbance. This phenomenon is referred to as sub synchronous resonance (SSR). [7]

3.6 Shunt Compensation

When fixed inductors and/or capacitors are employed to absorb or generate reactive power, they constitute passive control. Shunt devices may be connected permanently or through a switch. Shunt reactors compensate for the line capacitance, and because they control over voltages at no loads and light loads, they are often connected permanently to the line, not to the bus. Shunt capacitors are used to increase the power transfer capacity and to compensate for the reactive voltage drop in the line. The applications of shunt capacitors require careful system design. Shunt reactors with their compensating effect on the capacitive generation of the line offer an economical and technically sound means of controlling the undesirable over-voltage.

3.7 Degree of Shunt Compensation

In many investigations of determining the maximum power transfer, the amount of shunt reactors required on the transmission line is defined as the degree of shunt compensation (K_d), where $X_C = \frac{1}{\omega C}$

$$K_d = \frac{B}{\mathrm{Im}\{y\}l} = \frac{B_1}{B_2} \tag{3.3}$$

where B_1 is total inductive susceptance

B_2 is total charging susceptance of line $\mathrm{Im}\{y\}\, l$.

K_d is defined as the fraction of the total inductive susceptance of shunt compensation (B_1) and the total charging susceptance of line $\mathrm{Im}\{y\}\, l$ taken as B_2.

3.8 Ferranti Effect

Some operating conditions such as non-simultaneous tripping of circuit-breaker of both ends of the line and synchronization of one line with the other may, for a short period, leave the transmission line energized from one end, while leaving the other end being as open. Situation like this may cause power frequency over-voltages on the open end of the line. These over-voltages can be controlled by shunt reactor compensation in the line. An identical reactor will have to be mounted at the sending-end of the line for the same reason for which it is required at the receiving-end. [17]

3.9 Effect of Distributing Reactors along the Line

Splitting of reactors along the line affects the rating of the reactors in controlling the power-frequency over-voltages within limit.

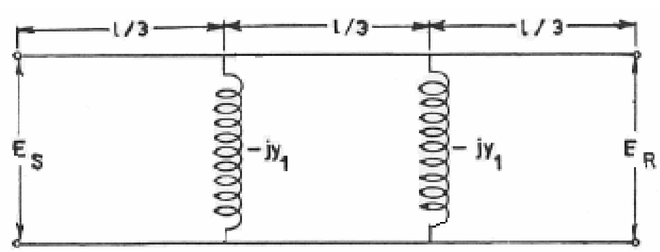


Fig 3.4 Two Symmetrical Reactors Mounted at l/3km apart [17]

By calculating the voltage at different points along the line in Fig 3.4, one can concludes that in this type of arrangement where the reactors are symmetrically mounted from both ends, the point of maximum voltage remains the middle of the line. This is clearly shown in Fig. 3.5 [17]

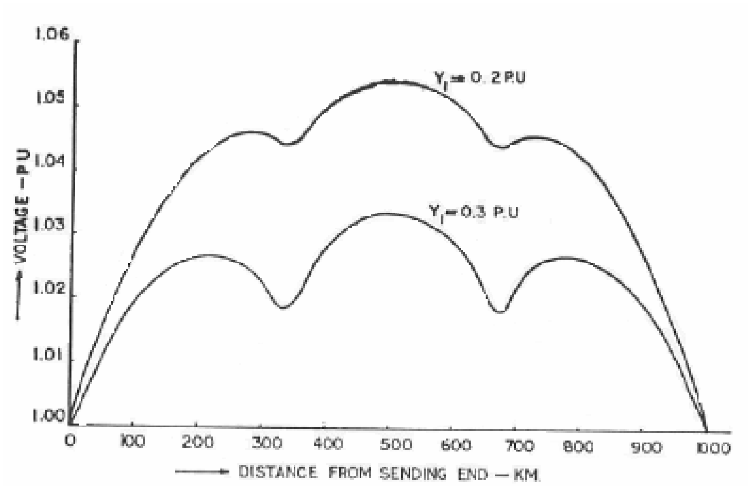


Fig 3.5 Voltage Profile for 1000km Line with Reactors Located at L/3 from Both Ends

Shunt reactors must be mounted at the terminals of the line to control the open-end line-frequency over-voltages and a reactor is essential at the point of maximum voltage (mid-point) on the line to limit the rise of voltage along the line under no-load or light condition [17].

It has already been shown that the shunt reactors mounted at the terminals of the line have no control on the voltage profile along the line when the system is synchronized. The presence of the reactor at the mid-point of the line modifies the necessary rating of reactors to be mounted at each end of the line for controlling the over-voltages due to the Ferranti effect [17].

The distribution of shunt reactors along the line affects the total rating and the minimum value of shunt reactors to be mounted at the line ends to control Ferranti over-voltages. The feasibility of splitting shunt reactors in connection with controlling over-voltages under all conditions of synchronization is investigated. This can be achieved by comparing a system with three shunt reactors and four reactors arrangement to determine the total compensation. The two systems are shown in Fig 3.6 and Fig. 3.7. [17]

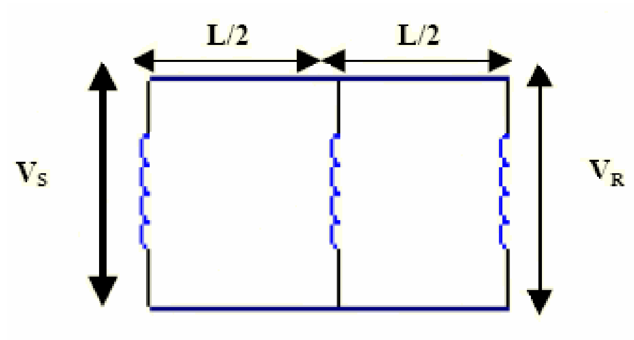


Fig3.6 Three Reactors Arrangement for Total Compensation of Over-Voltages [17]

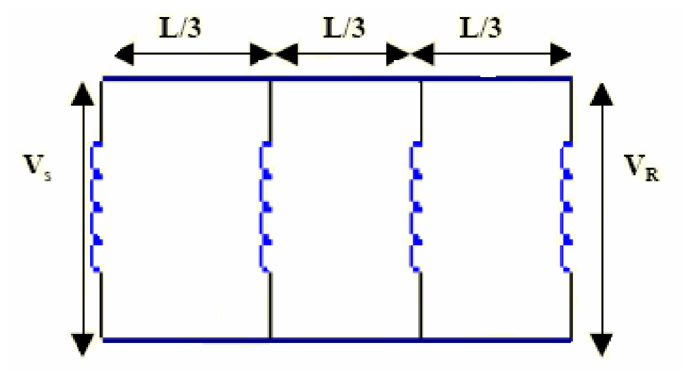


Fig 3.7 Four Reactors Arrangement for Total Compensation of Over-Voltages [17]

It is proven that the four reactors arrangement enables better reduction in the total shunt compensation requirements. Therefore, one can conclude that it is desirable to split the reactors. However further splitting of the shunt reactor will increase the number of reactor-points on the line and eventually, the cost of the lines will increase constantly [17].

3.10 Shunt Capacitive Compensation

In order to avoid the phenomenon of SSR, some utilities have considered the use of shunt capacitive compensation as an alternative means of increasing transmission capacity [5].

One advantage claimed by shunt capacitive compensation is that it is possible to maintain nodal voltage at nominal value through injection of reactive power along the line. Another advantage is its capability to extend the steady state stability and improve damping when used in conjunction with static VAR controllers

[5]. Capacitors are connected either directly to a bus bar or to the tertiary winding of a main transformer and are disposed along the route to minimize the losses and voltage drops. Fig. 3.8 shows an example of shunt capacitors compensation in an electrical system model.

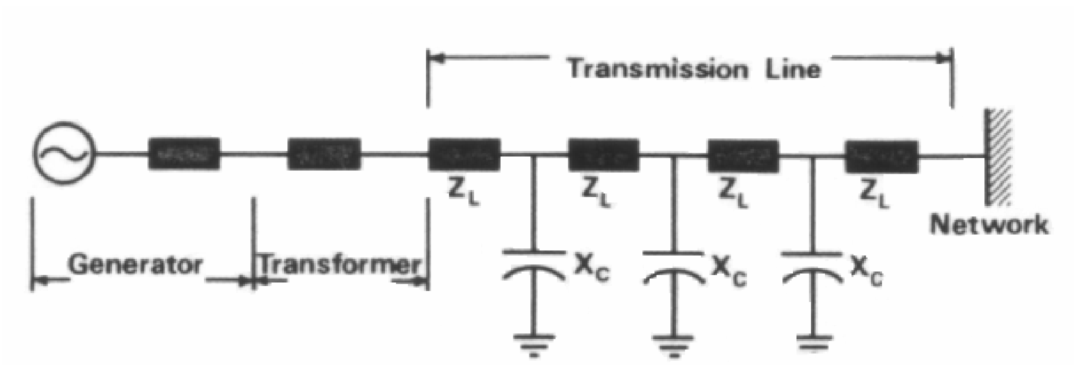


Fig 3.8 Electrical System Model

Given the receiving-end voltage (V_R), sending-end voltage (V_S), real power (P_R) and reactive power (Q_R) at the receiving end of the line, the required capacitor Mvar at the receiving end for a specified load can be easily computed. The Mvar value of the capacitor can be obtained by the definition given below

$$M\text{ var} = \frac{V^2}{X_C} \tag{3.4}$$

$$\text{where} \quad X_C = \frac{1}{\omega C} \tag{3.5}$$

3.11 Maintaining Receiving-End Voltage Constant with respect to Sending-End Voltage

To find the shunt compensation at the receiving end, it is important to understand the behaviour of the voltage profile between the two ends of the long transmission line. Suppose there is a shunt reactor of X_L connected at the receiving end of the long transmission line as shown in fig3.9.

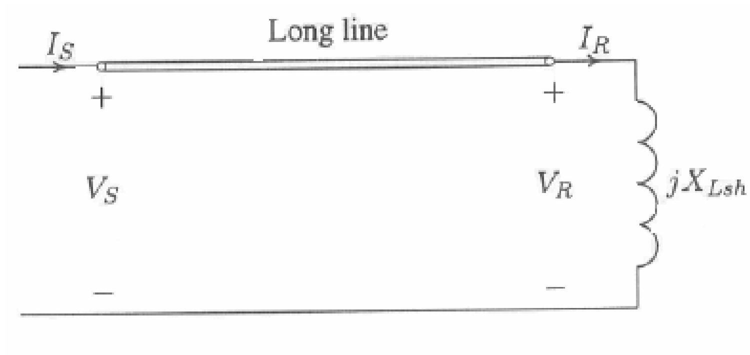


Fig 3.9 Shunt Reactor at Receiving End

This simple circuit can be used to find the amount of shunt reactor to maintain the the receiving end voltage at a specified value. With one reactor only at the receiving end, the voltage profile will not be uniform and the maximum rise occurs at the midspan and the current at the midspan is zero [7]. This is illustrated in fig 3.10.

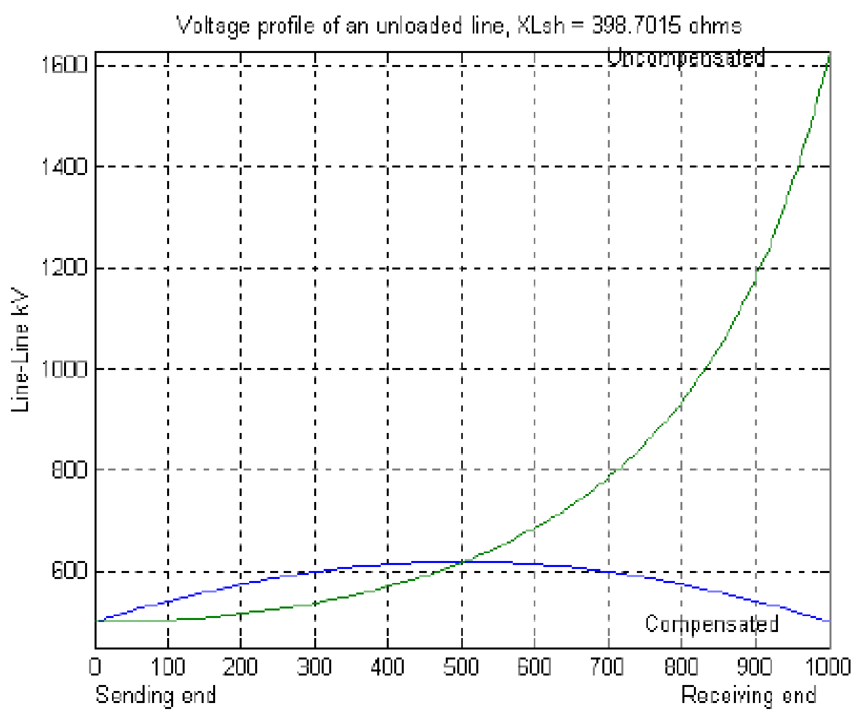


Fig 3.10 Voltage Profile of Compensated and Uncompensated Lines

Chapter 4
Formulation of Problem

4.1 Introduction

This chapter will highlight the methodology to find the required shunt compensation of line and load flow method in detail which is used in simulation of the IEEE-14 Bus test system and 500 kV EHV AC sample system.

4.2 Load Flow Analysis

Load flow studies are the backbone of power system analysis and design. They are necessary for planning, operation, economic scheduling and exchange of power between utilities. It is also required for many other analyses such as transient stability and contingency studies [7].

4.3 Iterative Techniques

The most common techniques used for iterative solution of non-linear algebraic equations are the Gauss-Siedel and the Newton-Raphson methods. In comparison between the two techniques, Newton-Raphson method is mathematically superior and is less prone to divergence with ill-conditioned problems than the Gauss-Siedel method. For large power system, the Newton-Raphson method is found to be more efficient and practical [7].

4.3.1 Newton Raphson Power Flow Method

The newton's method is a successive approximation procedure based on an initial estimate of the unknown and the use of Taylor's series expansion [7]. To apply this method to the solution of the power-flow equations, the Real Power P, and reactive power Q, entering the network at typical bus *i* can be expressed as

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \tag{4.1}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \tag{4.2}$$

Expanding Eqn.(4.1) and Eqn.(4.2) in Taylor's series about the initial estimate and neglecting all higher order terms results in the following linear equations, where bus 1 is assumed to be slack bus.

$$\left[\begin{array}{c}\Delta P_2^{(k)}\\ \vdots \\ \Delta P_n^{(k)}\\ \hline \Delta Q_2^{(k)}\\ \vdots\\ \Delta Q_n^{(k)}\end{array}\right]=\left[\begin{array}{ccc|ccc}\frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|}\\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots\\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|}\\ \hline \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|}\\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots\\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|}\end{array}\right]\left[\begin{array}{c}\Delta \delta_2^{(k)}\\ \vdots\\ \Delta \delta_n^{(k)}\\ \hline \Delta |V_2^{(k)}|\\ \vdots\\ \Delta |V_n^{(k)}|\end{array}\right] \tag{4.3}$$

In short, it can be written in the form of Jacobian Matrix as

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta \delta\\ |\Delta V|\end{bmatrix} \tag{4.4}$$

Elements of the Jacobian matrix are the partial derivatives of Eqn.(4.1) and Eqn.(4.2), evaluated at $\Delta\delta_i^{(k)}$ and $|\Delta V_i^{(k)}|$. The Jacobian matrix gives the linearized relationship between small changes in voltage angle $\Delta\delta_i^{(k)}$ and voltage magnitude $|\Delta V_i^{(k)}|$ with small changes in real and reactive power $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$. These changes can be obtained by the difference between the scheduled and calculated values

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \tag{4.5}$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \tag{4.6}$$

The new estimates for bus voltages are

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{4.7}$$

$$\left|V_i^{(k+1)}\right| = \left|V_i^{(k)}\right| + \left|\Delta V_i^{(k)}\right| \tag{4.8}$$

The process is continued until the power residuals $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are less than the specified accuracy.[7]

4.4 Methodology

The approach and methodologies adopted for the system studies is outlined in this section. Firstly the required shunt compensation is calculated and after that the effect of shunt compensations on test case system1 i.e. IEEE 14 Bus system is evaluated. After that required shunt compensation for isolated 500kV sample system is calculated. The code is developed in MATLAB to calculate the required shunt compensation for test case system and EHV sample system and after that simulation is run in the ETAPS to see the effect of compensation on flows of line using Newton Raphson Load Flow method.

4.4.1 Methodology for Calculation of Shunt Compensation

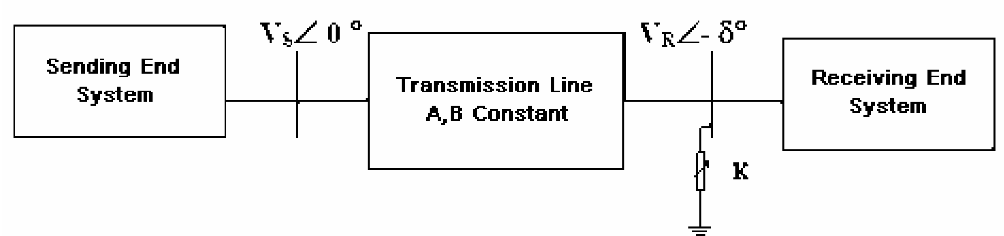


Fig 4.1 Shunt Susceptance at the Receiving End

Since the investigation of thesis is restricted to compensation at the receiving end of the line, Fig. 4.1 will be used as the basis of Module 1. To find the shunt susceptance *K* at the receiving end, it is required to derive an equation for the reactive power (Q_R) at the receiving end, with respect to K [18]. With the addition of K into the reactive power, as stated in Eqn.2.15, the new equation can be derived as

$$Q_R = \frac{|V_S||V_R|}{|B|}\sin(\beta-\delta) - \frac{|A||V_R|^2}{|B|}\sin(\beta-\alpha) + K|V_R|^2 \qquad (4.9)$$

Using the power triangle rule, the reactive power can also be defined as

$$Q_R = P_R \tan(\theta) \qquad (4.10)$$

where cos(θ) is load power factor.

From Eqn. 4.9 and Eqn. 4.10, the shunt susceptance K is derived as

$$K = -\frac{|V_S|}{|V_R||B|}\cos(\beta-\delta)\tan(\theta) + \frac{|A|}{|B|}\cos(\beta-\alpha)\tan(\theta) - \frac{|V_S|}{|V_R||B|}\sin(\beta-\delta) + \frac{|A|}{|B|}\sin(\beta-\alpha) \qquad (4.11)$$

To find the ratio of the real power and critical power, $\frac{P_R}{P_{R,\max}}$, first determine the critical angular separation, δ_{crit} and to analyze the system for the critical condition, the condition of the sending-end voltage for maximum power transfer is stated as

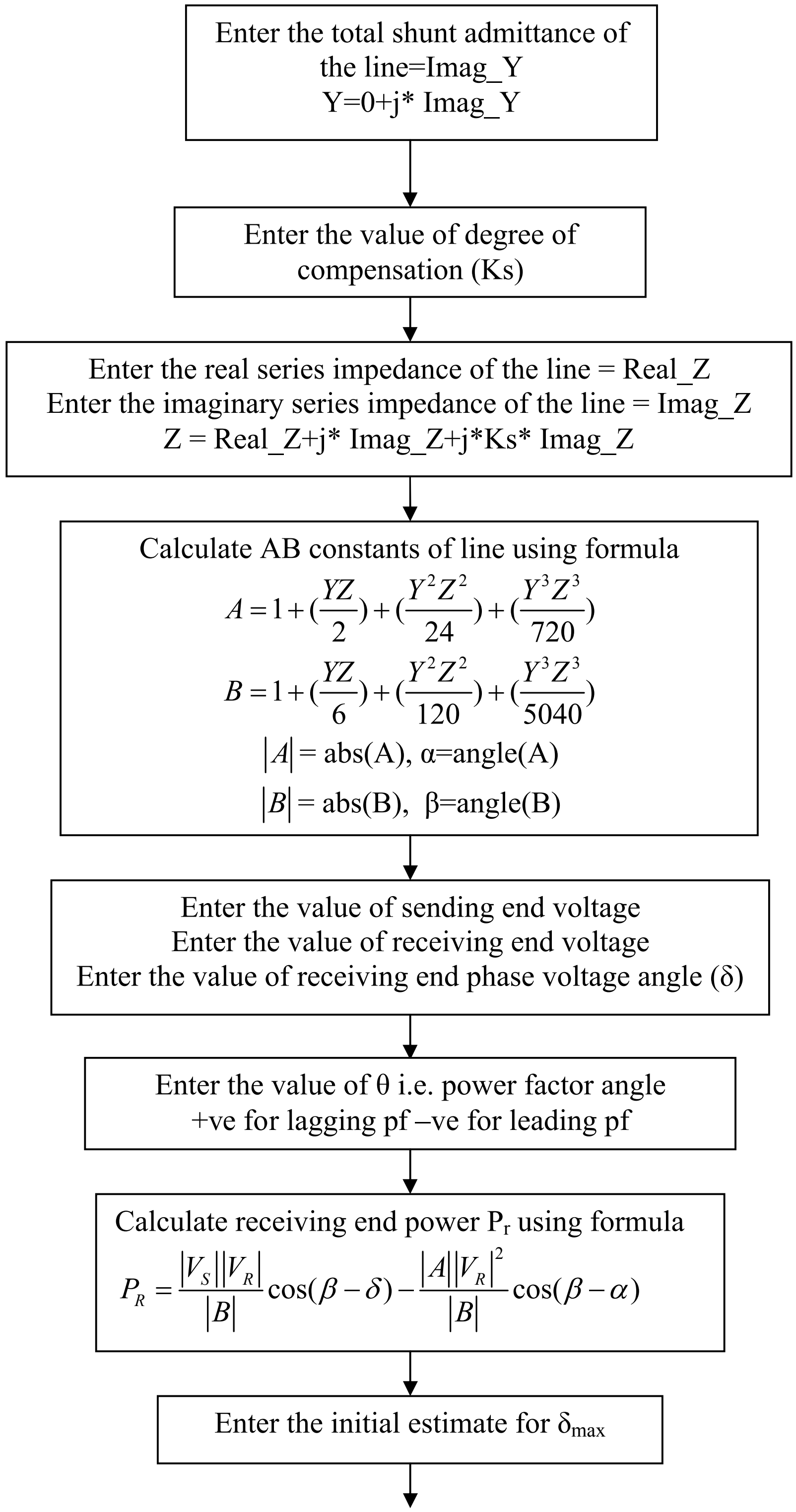
$$V_S = 2AV_R\cos(\alpha-\delta) - 2KBV_R\sin(\beta-\delta) \qquad (4.12)$$

Since K and δ_R are the unknowns in Eqn.4.12 and Eqn.4.13, respectively, K can be eliminated from these two equations to obtain the following transcendental equation in δ_R**.**

$$2A\cos(\alpha-\delta) - \frac{|V_S|}{|V_R|} = -2|V_S||V_R|\sin(\beta-\delta)\cos(\beta-\delta)\tan(\theta) + 2A\sin(\beta-\delta) \cos(\beta-\delta)\tan(\theta) - 2\frac{|V_S|}{|V_R|}\sin^2(\beta-\delta) + 2A\sin(\beta-\delta)\sin(\beta-\alpha) \qquad (4.13)$$

The maximum angular separation, δ_{max} can obtained by solving Eqn. 4.13. However using simple algebraic method will not solve for δ_{max}. Therefore the best method is using the Newton method, as mentioned in section 4.3.1.

4.4.2 Flow Chart



$\delta_{max} = \delta_{max} + d\delta_{max}$

where $d\delta_{max} = dc/J$, $J = 2B_1 \cos\delta - D\sin\delta + E\cos\delta$

$$dc = 0 - A_1\cos^2\delta + B_1\sin 2\delta + C\sin^2\delta + D\cos\delta + E\sin\delta + \frac{V_1}{V_2}$$

$$A_1 = -2V_1V_2\sin\beta\cos\beta\tan\theta - 2\frac{V_1}{V_2}\sin^2\beta$$

$$B_1 = 2V_1V_2\tan\theta(\cos^2\beta - \sin^2\beta) + 4\frac{V_1}{V_2}\sin\beta\cos\beta$$

$$C = 2|A|\sin\beta\cos\beta\tan\theta - 2\frac{V_1}{V_2}\cos^2\beta$$

$$D = 2|A|\sin\beta\cos(\beta-\alpha)\tan\theta - 2V_1V_2\cos^2\beta$$

$$E = 2|A|\cos\beta\cos(\beta-\alpha)\tan\theta - 2|A|\sin\alpha$$

$|d\delta| \geq 0.001$

Iter<100

No

Yes

P_max_angle=min(δ_{max})=δ_{max}

$$P_{R,\max} = \frac{|V_S||V_R|}{|B|}\cos(\beta - \delta_{\max}) - \frac{|A||V_R|^2}{|B|}\cos(\beta-\alpha)$$

Calculate the required shunt admittance by using formula

$$K = -\frac{|V_S|}{|V_R||B|}\cos(\beta-\delta)\tan(\theta) + \frac{|A|}{|B|}\cos(\beta-\alpha)\tan(\theta) - \frac{|V_S|}{|V_R||B|}\sin(\beta-\delta) + \frac{|A|}{|B|}\sin(\beta-\alpha)$$

Fig 4.2 Flow Chart for the Methodology used in Calculation of Shunt Admittance

4.5 Case Study 1

In this case study the effect of uncompensated transmission lines and the effect of shunt compensation is evaluated on IEEE 14-Bus system [21].

4.5.1 14-Bus System

From the information retrieved from the bus data of the 14-Bus System, Bus 2 is known to be the slack bus and only Bus 9 has a shunt susceptance at the load end. Since the investigation of this thesis is restricted to compensation at the receiving end of the line, therefore Bus 9 will be assumed to be the sending-end system and bus 10 is assumed to be receiving end.

4.6 Case Study 2

In this test case system 2, the analyses of relationship of the shunt susceptance at the load end (K) with the critical power, degree of series compensation and $\frac{P_R}{P_{R,\max}}$, which is also denoted as Kl is studied..

Chapter 5
Results and Discussions

5.1 Introduction

In this chapter results of MATLAB code for required compensation are discussed and after that results of load flow simulation in ETAPS are discussed with and without shunt compensation.

The var source required at the load end to maintain $\frac{V_S}{V_R} = 1$ under different loading and power factor condition is determined by implementing the analytical calculation technique in section 4.4.1. The study is carried out for two different values of transmission length, maximum power, shunt susceptance at the load end, degree of series compensation and $\frac{P_R}{P_{R,\max}}$, which is also denoted as Kl. [18]

5.2 IEEE-14 Bus Test System

The effect of the shunt compensation is evaluated on selected transmission line between Bus 9 and Bus 10 and. The data for IEEE-14 Bus Test System is given in appendix I. The results of the power transfer are discussed in detail. Fig 5.1 shows the IEEE-14 Bus Test System.

Results for IEEE 14 bus system without compensation and after implementing for different degree of compensation on the IEEE 14 Bus test system for two different line lengths i.e. 400 Kms and 480 Kms are summarized below and and detailed results of load flow are listed in appendix II. The relationships of the various factors computation are summarized in the Fig 5.2, Fig 5.3, Fig 5.4 and Fig 5.5.

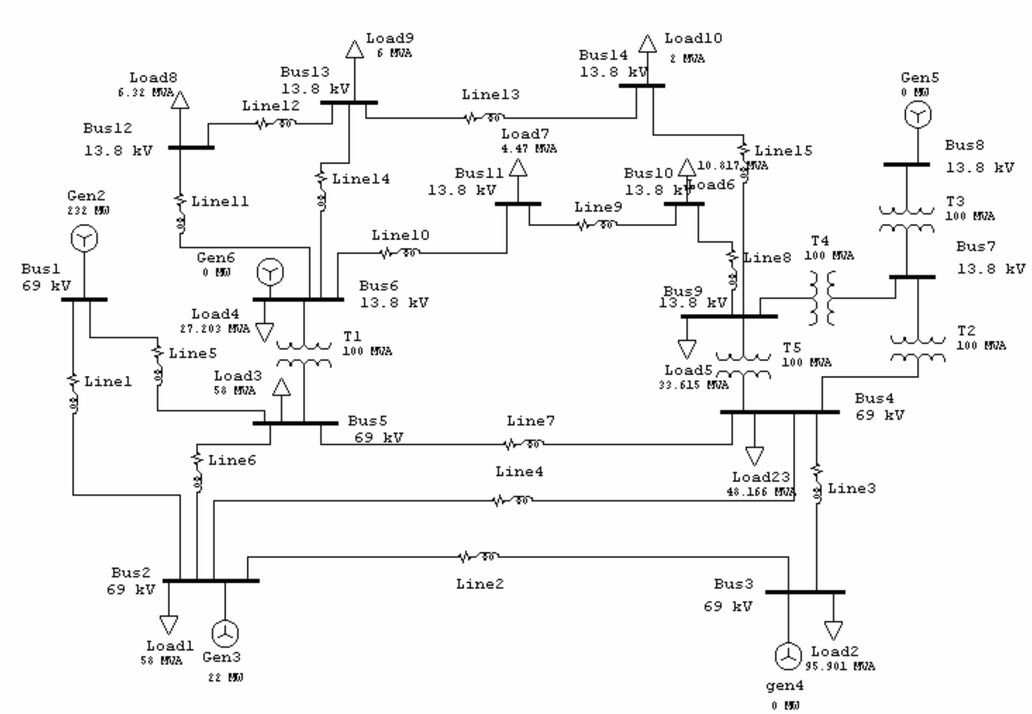


Fig 5.1 IEEE 14 Bus System

Table 5.1 Power Flows from Bus 9 to Bus 10 for 400 kms line length

Ks	MW	Mvar
Without compensation	1.39	1.47
0.1	3.17	-470.65
0.2	3.24	-485.52
0.3	3.27	-499.47
0.4	3.54	-511.8
0.5	3.47	-522.90
0.6	3.26	-533.30
0.7	3.26	-542.14
0.8	3.42	-549.89
0.9	3.34	-556.09

Table 5.2 Power Flows from Bus 9 to Bus 10 for 480 kms line length

Ks	MW	Mvar
Without compensation	1.18	1.25
0.1	2.63	-471.94
0.2	2.71	-487.12
0.3	2.91	-512.11
0.4	2.43	-513.46
0.5	2.72	-524.73

0.6	2.72	-534.79
0.7	2.72	-543.81
0.8	2.72	-551.22
0.9	2.72	-557.66

Table 5.3 Voltage Profile at bus 9 and bus 10 for line length 400kms

Ks	**V_9**	**δ_9**	**V_{10}**	**δ_{10}**
Without compensation	1.0453	-3.5	0.8268	-9.4
0.1	1.0457	-3.4	0.9415	8.1
0.2	1.0461	-3.4	0.9365	9.2
0.3	1.0464	-3.4	0.9208	-48.9
0.4	1.0466	-3.6	0.9105	-53.7
0.5	1.0469	-3.6	0.9109	-57.3
0.6	1.0471	-3.6	0.9112	-65.7
0.7	1.0473	-3.6	0.9117	-60.4
0.8	1.0475	-3.6	0.9122	-80.2
0.9	1.0476	-3.6	0.9140	-79.4

Table 5.4 Voltage Profile at bus 9 and bus 10 for line length 480kms

Ks	**V_9**	**δ_9**	**V_{10}**	**δ_{10}**
Without compensation	1.0350	-3.2	.8219	-9.5
0.1	1.0458	-3.4	0.8889	9.1
0.2	1.0461	-3.4	0.8892	4.9
0.3	1.0467	-3.6	0.8897	-45.8
0.4	1.0467	-3.6	0.8879	-58.9
0.5	1.0469	-3.6	0.8585	-59.0
0.6	1.0472	-3.6	0.8587	-45.8
0.7	1.0474	-3.6	0.8590	-33.8
0.8	1.0475	-3.6	0.8592	-64.0
0.9	1.0477	-3.6	0.8593	-55.9

Fig 5.2 shows the variation maximum power with degree of compensation (Ks). Fig 5.3 shows the power transfer from Bus 9 to Bus 10 with different values of degree of compensation (Ks) and Fig 5.4 shows the reactive power transfer from Bus 9 to Bus 10 with different values of degree of compensation (Ks) for different lengths of line. From the plot it can be said that power transfer decreases with increase in line length. Fig. 5.5 and Fig. 5.6 shows the variation of sending end voltage and receiving end voltage with degree of compensation respectively.

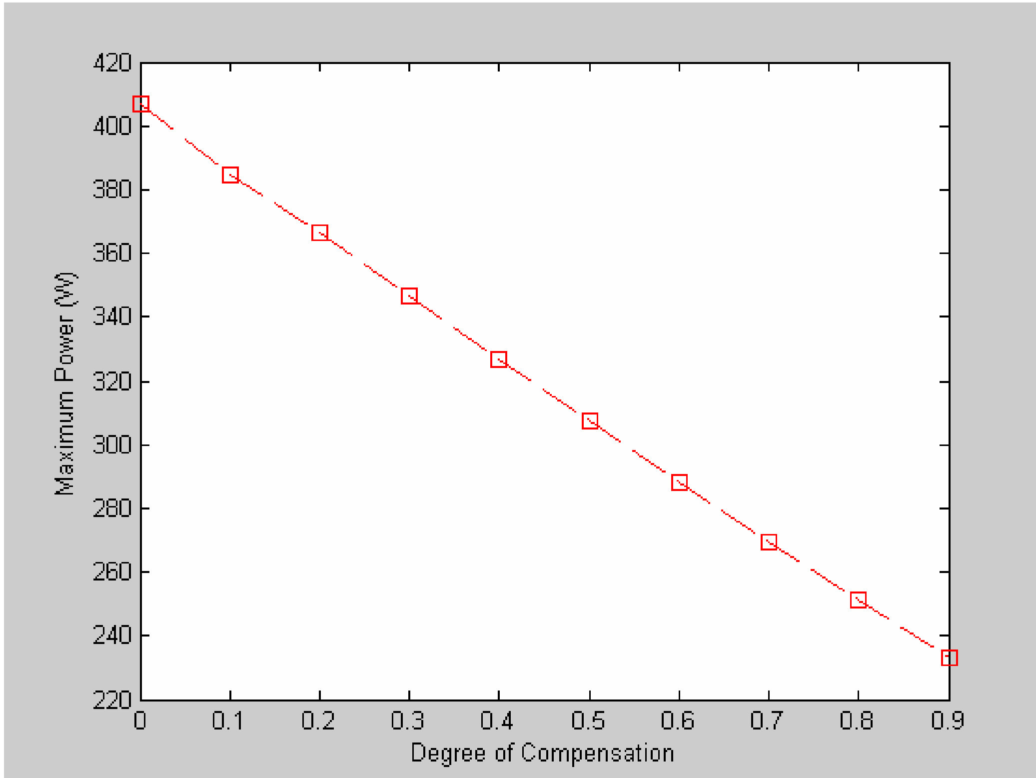


Fig 5.2Maximum Power Transfer

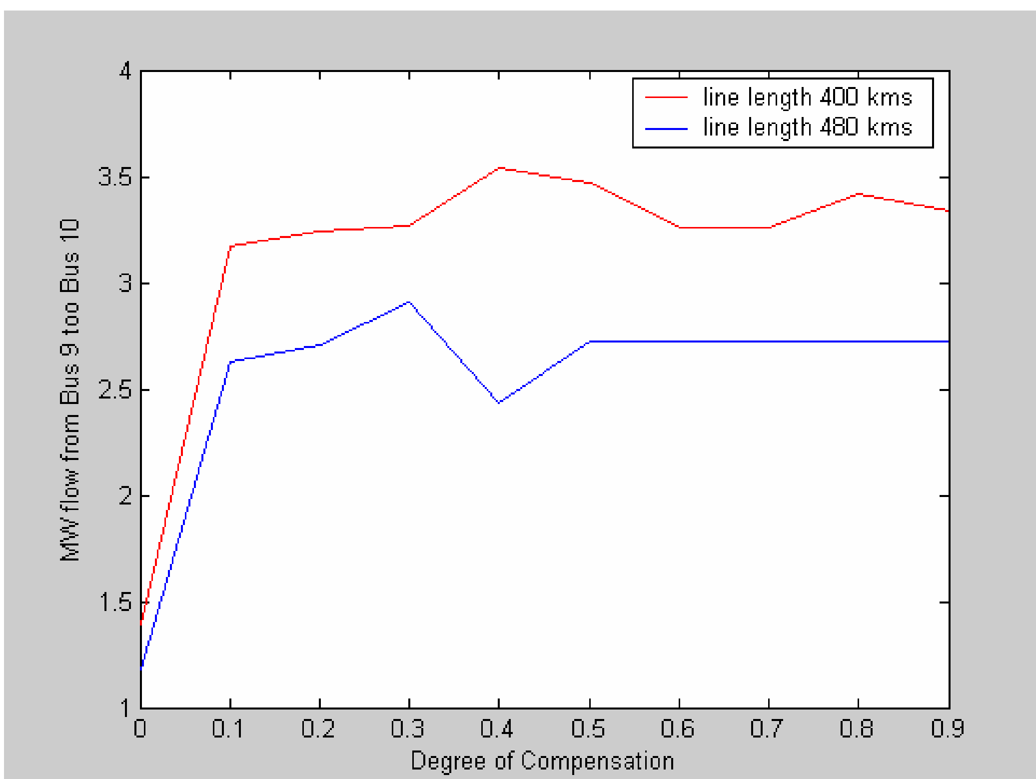


Fig 5.3 Power Transfer from Bus 9 to Bus 10 with various values of Ks

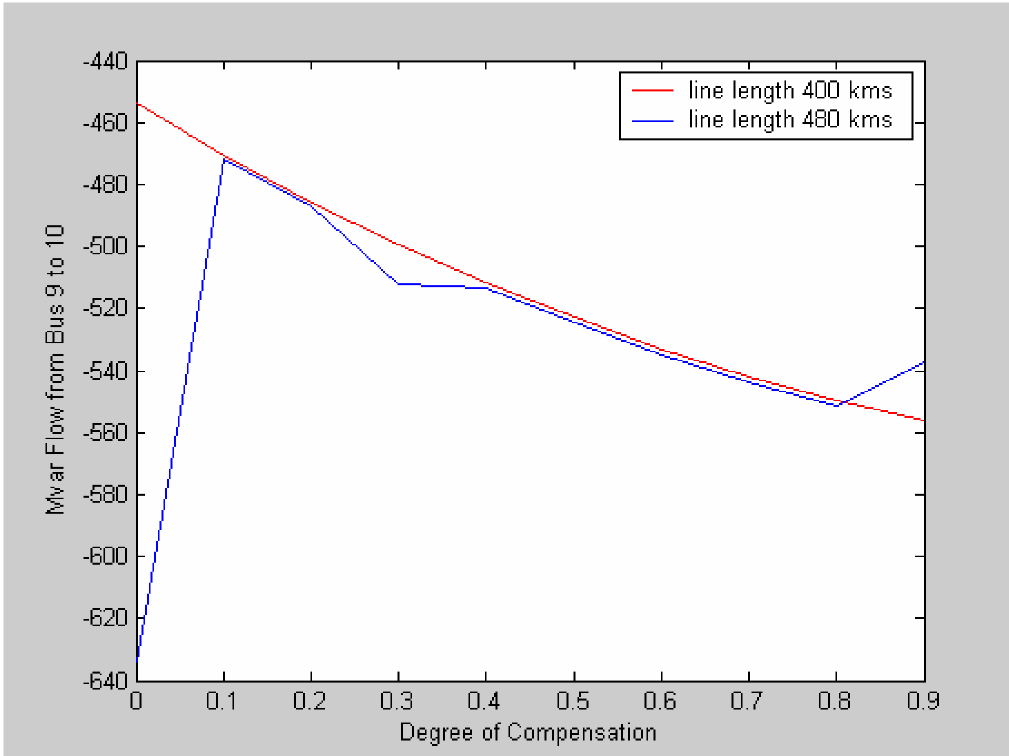


Fig 5.4 Reactive Power Transfer from Bus 9 to Bus 10 with various values of Ks

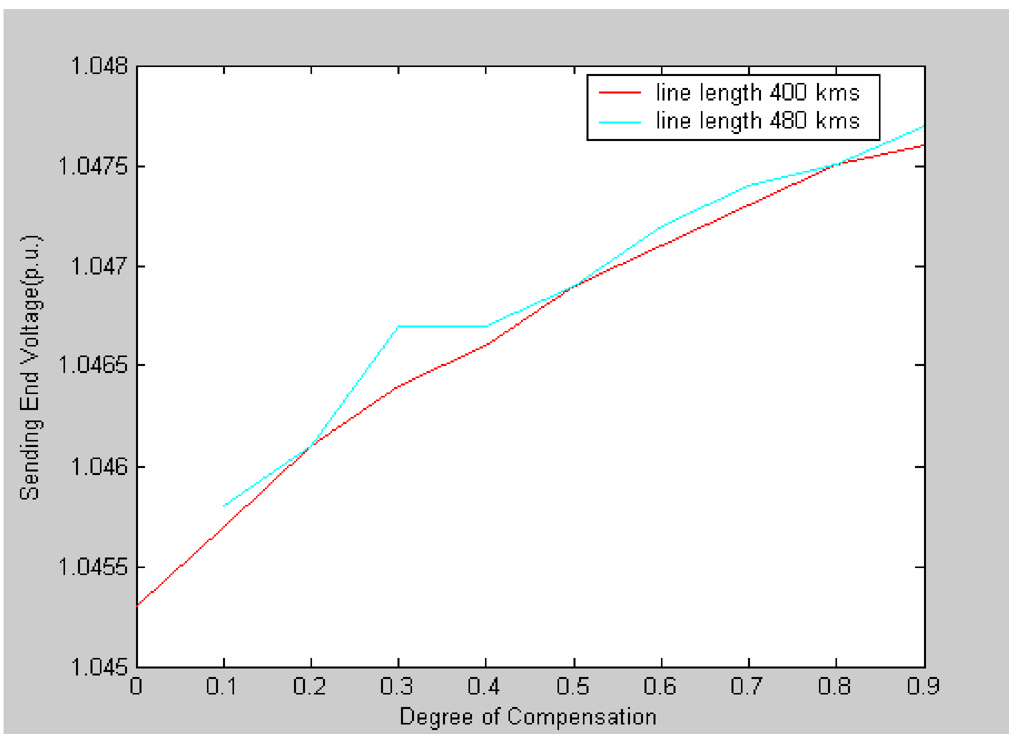


Fig. 5.5 Variation of Sending End Voltage

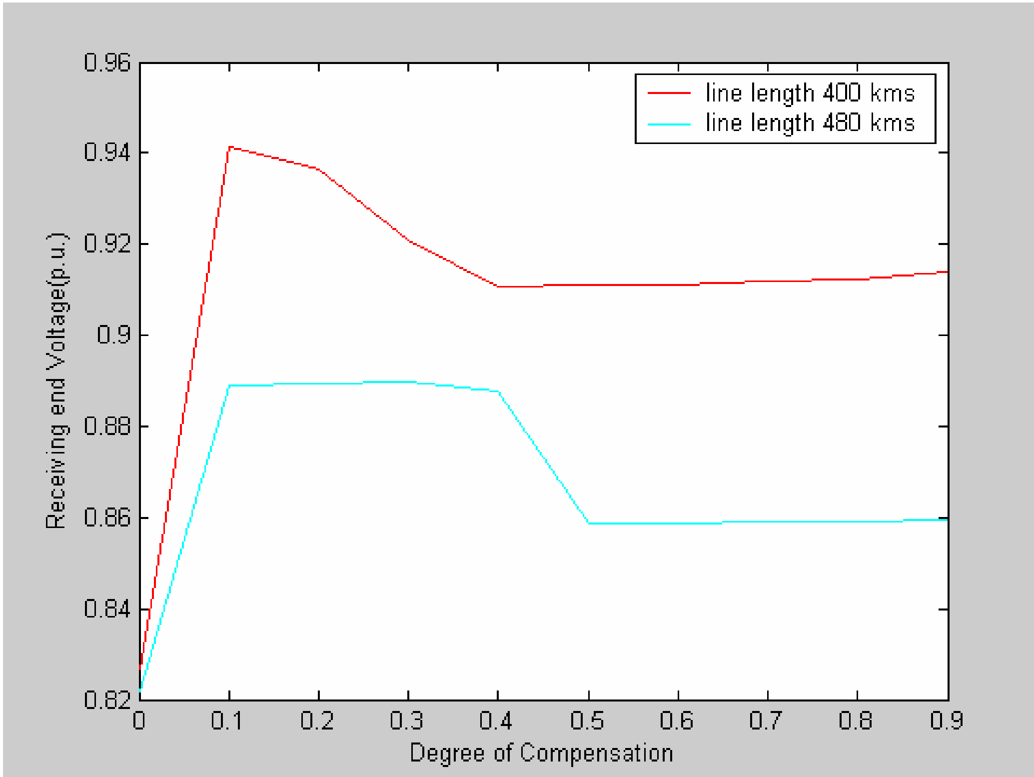


Fig. 5.6 Variation of Receiving End Voltage

5.3 EHVAC Sample System

The sample system is isolated 500kV EHV AC system, having length 1125km with the following parameters:

Total Shunt Admittance = j4500*E-6 Siemens

Total Series Impedance = 0.0282 + j0.272 ohms/km

Sending End Voltage = 500 kV

Receiving End Voltage = 500 kV

The results obtained from implementing different degree of compensation with different values of power factor on the sample system for shunt admittance to added at receiving end are summarized below:

Table 5.1 Results for Receiving End Real Power, Maximum Power and Shunt Admittance

Ks	Power factor	Receiving End Real Power(MW)	Maximum Power	Pr_max_ angle	K1 = Pr/Pr_max	K=Shunt admittance (Siemen)
0	0.965484 (lagging)	0.233644	1.00381	1.5708	0.232757	3.45594
0.3	0.965484 lagging	1.181101	0.758762	1.5708	0.238679	2.503
0.5	0.965484 lagging	0.157432	0.652170	1.5708	0.241397	2.06085
0.7	0.965484 lagging	0.139214	0.571692	1.5708	0.243511	1.7098
0	0.965484 leading	0.233644	1.00381	1.5708	0.232757	3.30537
0.3	0.965484 leading	1.181101	0.758761	1.5708	0.23868	2.44644
0.5	0.965484 leading	0.157432	0.652169	1.5708	0.241397	2.04189
0.7	0.965484 leading	0.139214	0.571692	1.5708	0.243511	1.71854
0	0.920006 lagging	0.348907	1.00381	1.5708	0.347583	3.50092
0.3	0.920006 lagging	0.270922	0.758762	1.5708	0.357058	2.51991
0.5	0.920006 lagging	0.235697	0.652170	1.5708	0.361405	2.06631
0.7	0.920006 lagging	0.208546	0.571692	1.5708	0.364788	1.70666
0	0.920006 leading	0.348907	1.00381	1.5708	0.347583	3.29253

0.3	0.920006 leading	0.270922	0.758761	1.5708	0.357058	2.46909
0.5	0.920006 leading	0.235697	0.652169	1.5708	0.361405	2.08094
0.7	0.920006 leading	0.208546	0.571692	1.5708	0.364788	1.77113
0	0.850006 lagging	0.464975	1.00381	1.5708	0.463211	3.54965
0.3	0.850006 lagging	0.361777	0.758762	1.5708	0.476799	2.53168
0.5	0.850006 lagging	0.315020	0.652170	1.5708	0.483033	2.06246
0.7	0.850006 lagging	0.278920	0.571692	1.5708	0.487885	1.69074
0	0.850006 leading	0.464975	1.00381	1.5708	0.463211	3.28949
0.3	0.850006 leading	0.361777	0.758761	1.5708	0.476799	2.51441
0.5	0.850006 leading	0.315020	0.652169	1.5708	0.483033	2.14949
0.7	0.850006 leading	0.278920	0.571692	1.5708	0.487885	1.85937

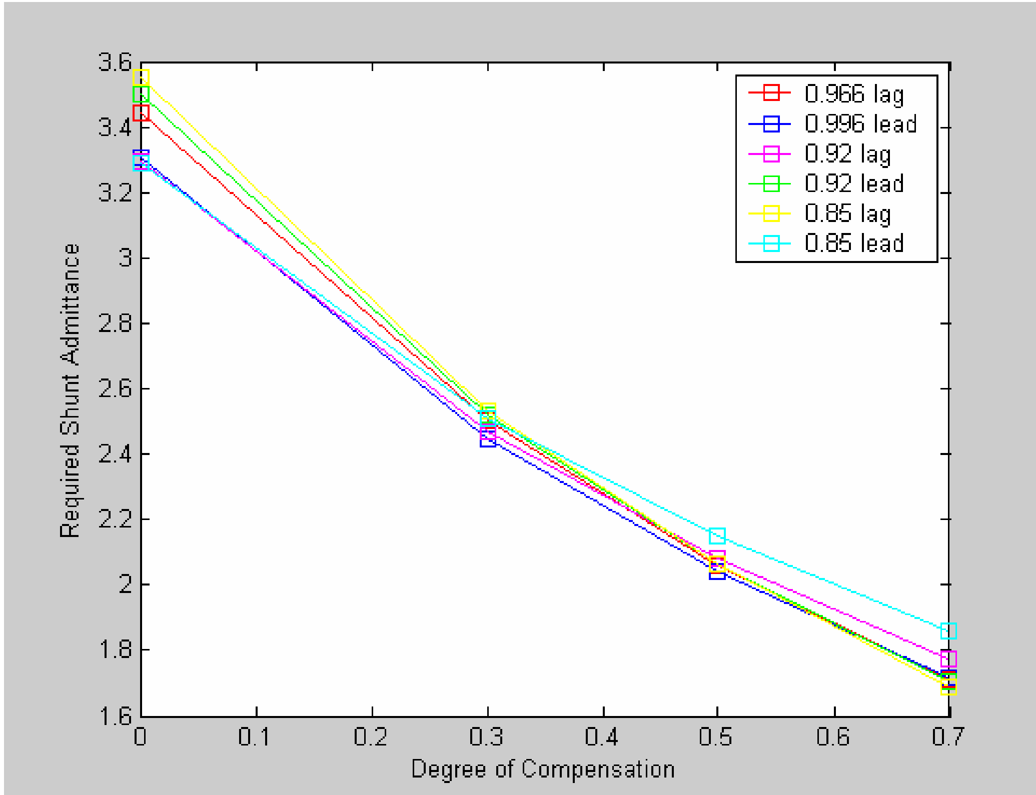


Fig 5.7Required Shunt Compensation

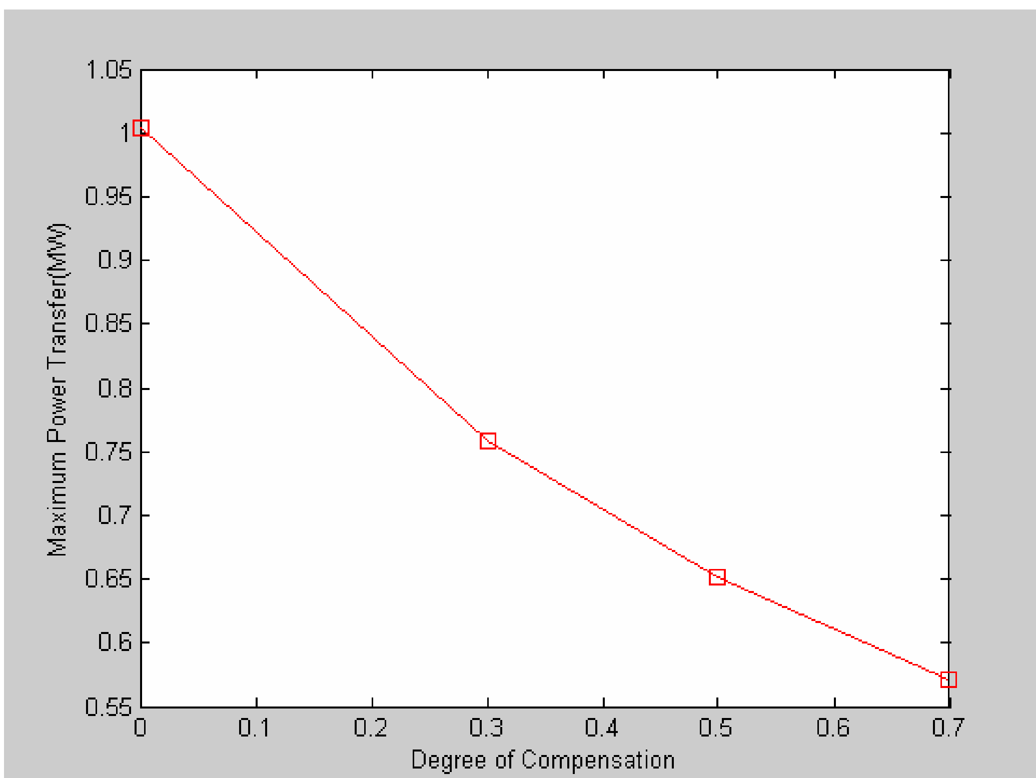


Fig 5.8 Maximum Power Transfer

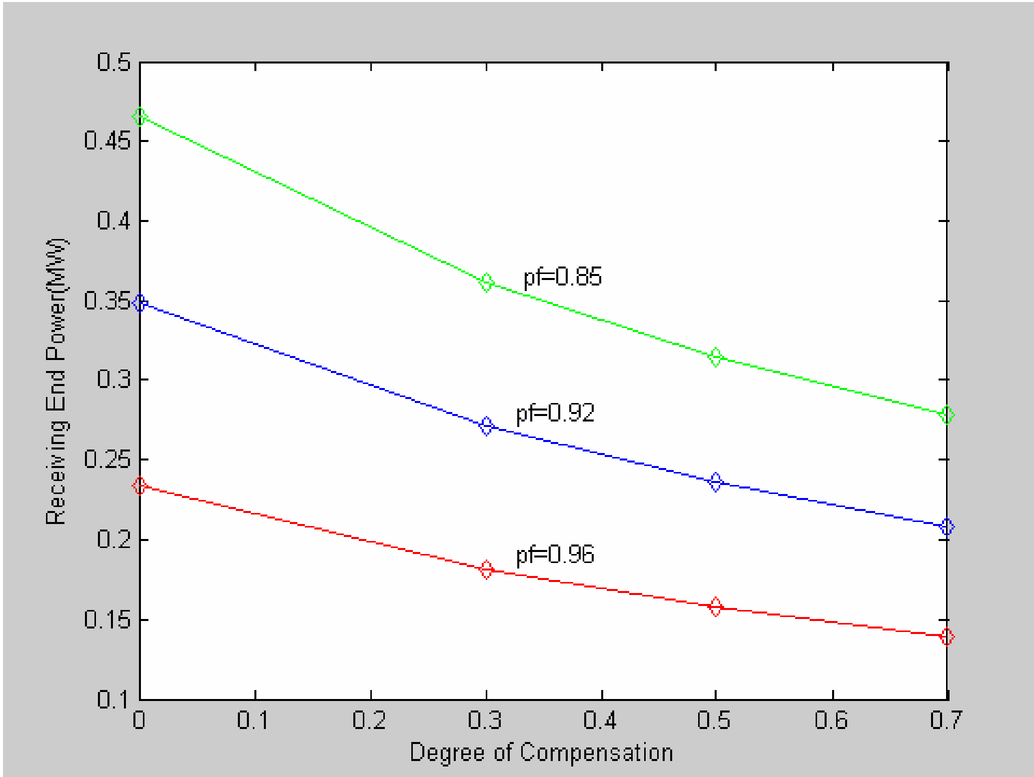


Fig 5.9 Receiving End Power

The Fig. 5.7 shows the relationship between a required shunt admittance and degree of compensation for different values of power factor. Fig 5.8 shows relation between maximum power transfer and degree of compensation. Fig 5.9 shows the relation of receiving end power and degree of compensation with various values of power factor. It is clear from the graph that power transfer decreases with increase of degree of compensation and increases with increase in power factor.

The results obtained from implementing different degree of compensation with constant value of power factor i.e.0.85 lagging on the sample system for shunt admittance to added at 25%, 50%, 75% and 100% of line length are summarized below:

Ks	**% Line Length**	**Receiving End Real Power(MW)**	**Maximum Power**	**Pr_max_ angle**	**K1 = Pr/Pr_max**	**K=Shunt admittance (Siemen)**
0	25	0.464901	1.00367	1.5708	0.463202	3.55072

0.3	25	0.361703	0.758621	1.5708	0.47679	2.53273
0.5	25	0.314946	0.652029	1.5708	0.483024	2.06348
0.7	25	0.278846	0.571551	1.5708	0.487875	1.69173
0	50	0.464927	1.00372	1.5708	0.463206	3.55035
0.3	50	0.361729	0.758670	1.5708	0.476793	2.53236
0.5	50	0.314971	0.652078	1.5708	0.483027	2.06313
0.7	50	0.278872	0.571600	1.5708	0.487879	1.69138
0	75	0.464951	1.00376	1.5708	0.463208	3.55
0.3	75	0.361753	0.758716	1.5708	0.476796	2.53202
0.5	75	0.314995	0.652124	1.5708	0.48303	2.06279
0.7	75	0.278896	0.571646	1.5708	0.487882	1.69106
0	100	0.464975	1.00381	1.5708	0.463211	3.54965
0.3	100	0.361777	0.758762	1.5708	0.476799	2.53168
0.5	100	0.315020	0.652170	1.5708	0.483033	2.06246
0.7	100	0.278920	0.571692	1.5708	0.487885	1.69074

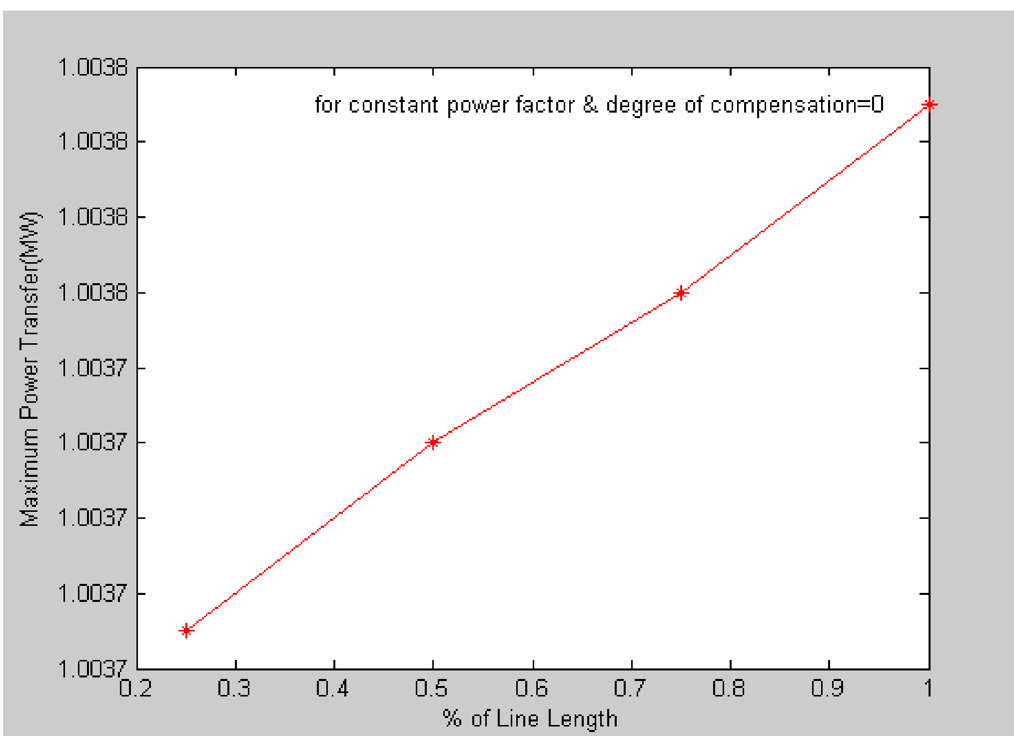


Fig 5.10 Maximum Power Transfer Variation with % of Line Length for constant pf and degree of compensation = 0

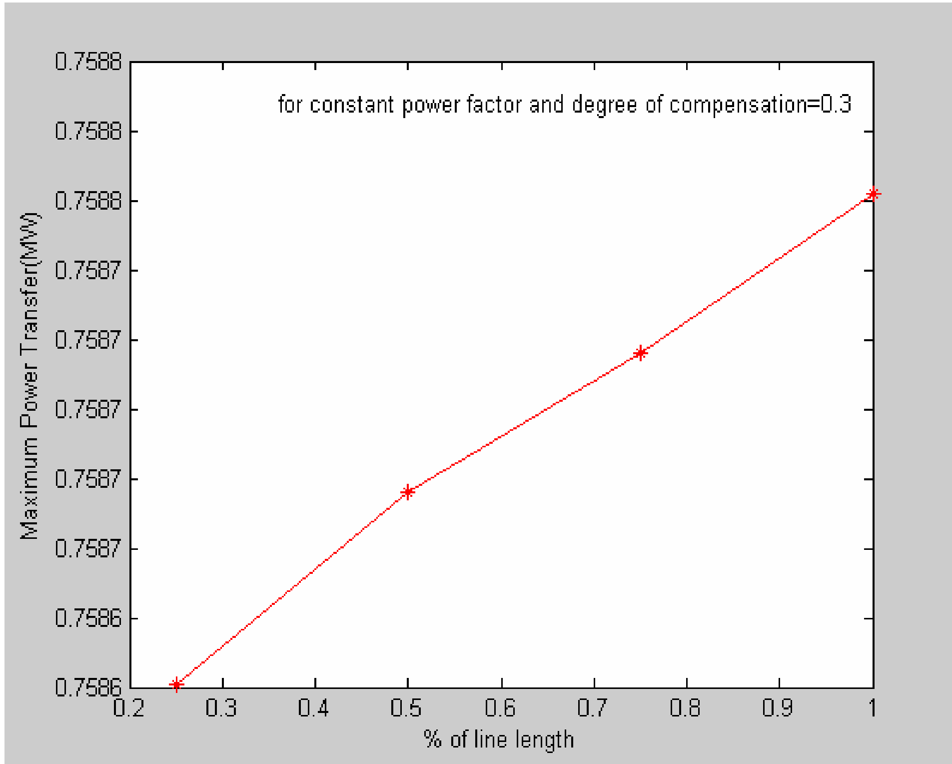


Fig 5.11 Maximum Power Transfer Variation with % of Line Length for constant pf and degree of compensation = 0.3

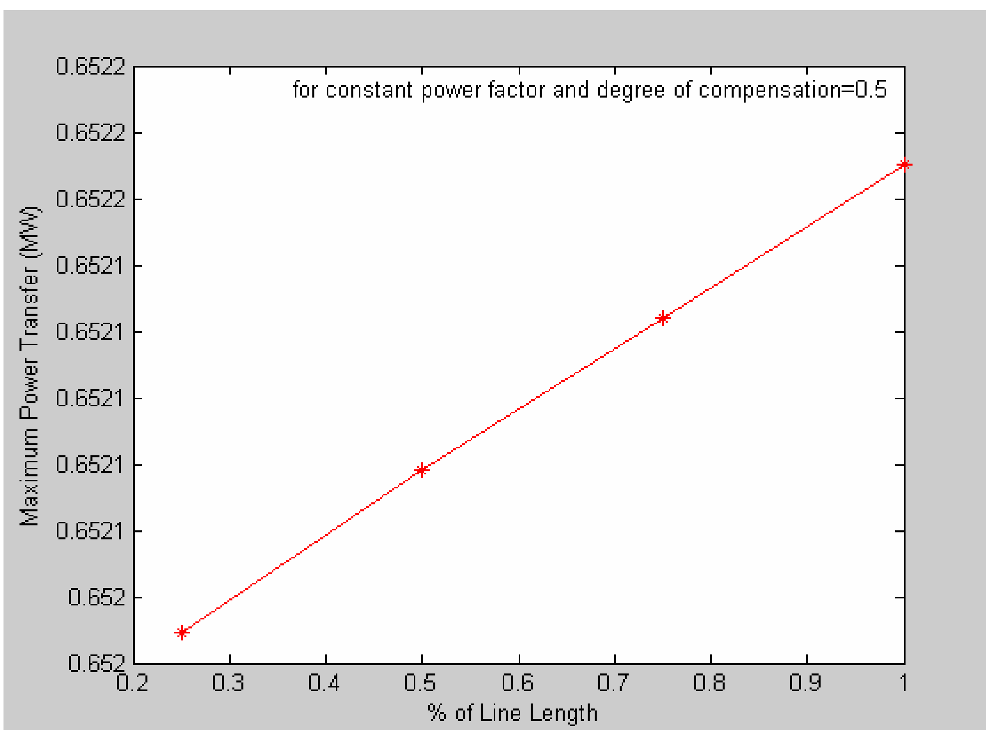


Fig 5.12 Maximum Power Transfer Variation with % of Line Length for constant pf and degree of compensation = 0.5

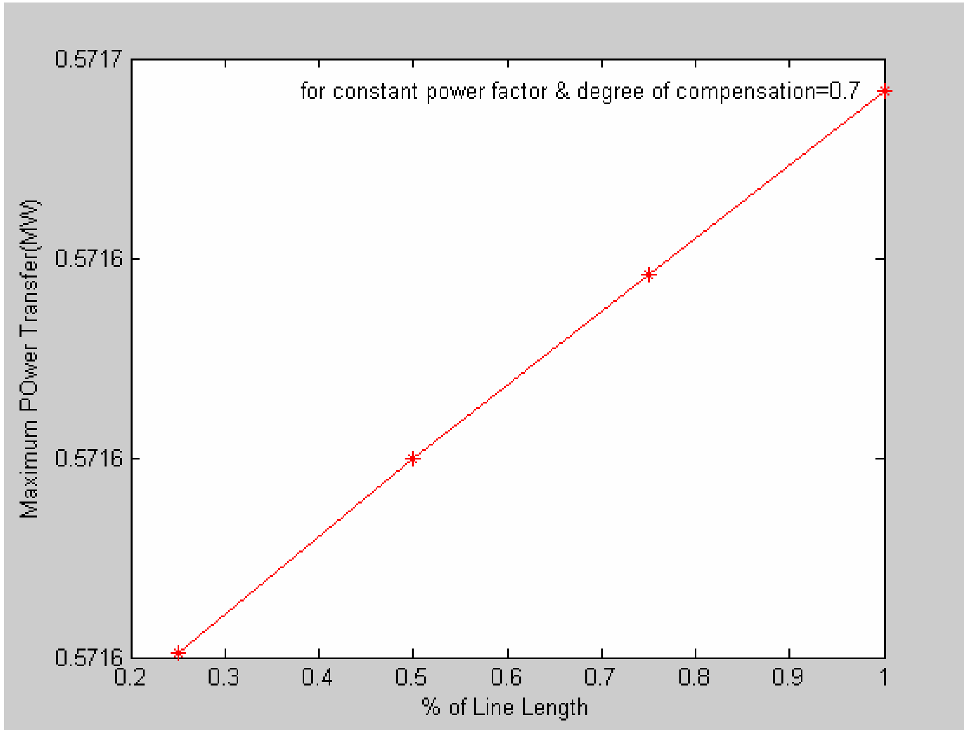


Fig 5.13 Maximum Power Transfer Variation with % of Line Length for constant pf and degree of compensation = 0

Fig 5.10 to Fig 5.13 shows the variation Maximum power transfer with % of Line Length for constant pf and different degrees of compensation. It is concluded from the plots that for constant value of power factor maximum power transfer increases as we shift the shunt admittance from sending end to receiving end and power factor maximum power transfer decreases with increase in degree of compensation.

CHAPTER 6

Conclusion and Future Scope

6.1 Conclusion

This thesis deals with the shunt compensation of EHV AC lines. The aim is to find the required amount of shunt compensation in given power system such that we get maximum reactive power compensation. The uncompensated system results are then compared with compensated results. IEEE 14 bus test system is considered for the above said problems and then implemented on 500 kV sample system.

The two modules of the thesis have emphasized on the ability of the shunt compensation on a long transmission line. They have also covered the various influencing factors, such as the load power factor and the transmission length, which will affect the performance of a power system. From the 14-Bus system and 500 kV sample system the results shows how influential the degree of compensation (K_s) has on the power transfer capability. With the shunt compensation at the receiving end, the load end voltage can be maintained at a percentage of the sending end voltage.

In conclusion, it can said that by controlling the shunt compensation, the transmission capability is improved remarkably. It has been noted that

- With addition of shunt admittance the power transfer increases.
- With increase of degree of compensation required shunt admittance decreases and hence maximum power transfer decreases.
- For constant value of power factor maximum power transfer increases as we shift the shunt admittance from sending end to receiving end.

Similar results were obtained from the 14-Bus System and 500kV sample System. Therefore, one can say that the effect of shunt compensation is universal on any system, regardless of how massive the power system design is. However, an extensively huge power system will demand for more compensation schemes and the cost of the line will be enormous.

5.2 Future Work

After many years, the shunt and series compensation are still the best methods to improve on the transmission capability. The shunt and series configuration schemes have been used extensively in many EHV long transmission lines. One suggestion for future work in this area of study is to explore or investigate more configuration schemes such as Flexible AC Transmission Systems (FACTS) device, which could produce optimum results for the appropriate power system. The other suggestions are related to the expansive study of the configuration schemes are as follows:

1. To emphasis on the investigation of line loss factor
2. To conduct fault analysis of power system using different configuration schemes
3. To conduct in-depth study of the voltage and transient stability
4. To determine the optimum location of the different configuration schemes.

References

[1] A. Chakraborty & P. Sen," An Analytical Investigation of Voltage Stability of an EHV Transmission Network Based on Load Flow Analysis," *Journal-of-the-Institution-of-Engineers-(India)-Electrical-Engineering-Division*, Vol. 76, May. 1995

[2] C.S. Indulkar and B. Viswanathan, "Determination of Shunt Compensation for an EHV Transmission Line," *International-Journal-of-Electrical-Engineering-Education*, Vol. 21, No. 1, Jan. 1984, pp 85-89

[3]] C.S. Indulkar, K. Ramalingam & P.R. Bijw, "Self Excited Oscillations in Series and Shunt Compensation Schemes of AC Transmission Systems," *International-Journal-of-Electrical-Power-&-Energy-systems*, Vol. 19, No. 7, Oct. 1997, pp 481-488

[4] C.S. Indulkar, "Required Shunt Compensation for an EHV Transmission Line," *IEEE Power Engineering Review,* Sep. 1999, pp 61-62

[5] G. Joos and B.T. Ooi, "Torsional Interactions Between Synchronous Generators and Long Transmission Lines," *IEEE Transactions on Power Systems*, Vol. PWRS-2, No. l,Feb. 1987, pp 17 - 24

[6] G. Stevenson, *Power System Analysis*, McGraw Hill, Electrical And Computer Engineering Series, 1994

[7] H. Saadat, *Power System Analysis*, McGraw Hill, Singapore, 1999

[8] K. Ramar & M.S. Raviprakasha, "Design of Compensation Schemes for Long AC Transmission Lines for Maximum Power Transfer Limited By Voltage Stability," *International-Journal-of-Electrical-Power-&-Energy-Systems,* Vol.17, No.2, April. 1995, pp 83-89

[9] Manoel Afonso de Carvalho and Luiz Antônio Magnata da Fonte, "Steady State and Transient Voltage Control on Long EHV Transmission lines" *IEEE Proceedings on Transmission and Distribution Conference and Exposition,* Oct 2001, vol1,pp 409-414.

[10] M.H. Haque, "Maximum Efficiency of Series and Shunt Compensated AC Transmission Systems," *International-Journal-of-Electrical-Power-&-Energy-Systems,* Vol. 15, No. 2, April. 1993, pp 79-84

[11] M.H. Haque, "Maximum Power Transfer Capability Within the Voltage Stability Limit of Series and shunt compensation Schemes for AC Transmission Systems," *Electric-Power-Systems-Research*, Vol. 24, No. 3, Sept. 1992, pp 227-235

[12] M.S. Raviprakasha and H.L Suresh, "Reactive Power Requirements for Voltage Control of Long Lines," *Asian Power and Energy Proceedings* 2007.

[13] M.T.K. Prasad and B.Thapar, "Best Location and Percentage Series Compensation of Long Transmission Line for Maximum Power Transfer," *IE(I) Journal-EL,* Vol. 55, April 1975, pp 147-150

[14] N.H. Yukseler, "The Effects of Voltage Stability Boundaries on Capability Charts for Shunt Compensated Power Systems," *Electrotechnical Conference, 1994. Proceedings, 7th Mediterranean ,* Vol. 3, 12-14 Apr 1994, pp 936 -939

[15] R. Rajarman, F. Alvarado, A. Maniaci, R. Camfield and S. Jalali, "Determination of Location and Amount of Series Compensation to IncreasePower Transfer Capability," *IEEE-Transactions-on-Power-Systems,* Vol. 13, No. 2, May. 1998, pp. 294-300

[16] S.M. Chandekar and S.G. Tarnekar, "Performance of Uncompensated and Series Capacitor-Compensated 500kV Long Transmission Line under Subnormal Fequency Conditions," *IEE Proc-Gener. Transm. Distrib.* Vol. 145, No. 3, May. 1998, pp 315 -319

[17] S.P. Gupta and S.P Seth, "Shunt Compensation of EHV Long Lines," *IE(I) Journal-EL,* Vol. 53, June 1973, pp 223-229

[18] S.P. Seth, "Comparative Analysis of Shunt and Series Compensation Schemes for 400 kV lines," *Journal-of-the-Institution-of-Engineers-(India)-Electrical-Engineering-Division,* Vol. 64, pt. EL 1, Aug. 1983, pp 46-50

[19] The Math Works: Developer of MATHLAB and Simulink for Technical Computating, http://www.mathworks.com/

[20] T.W. Kay, P.W. Sauer, R.D. Shultz and R.A. Smith, "EHV and UHV Line Loadability Dependence on VAR Supply Capability," *IEEE Transactions on Power Apparatus and Systems,* Vol. PAS-101, No. 9, Sept. 1982, pp 3568 - 3575

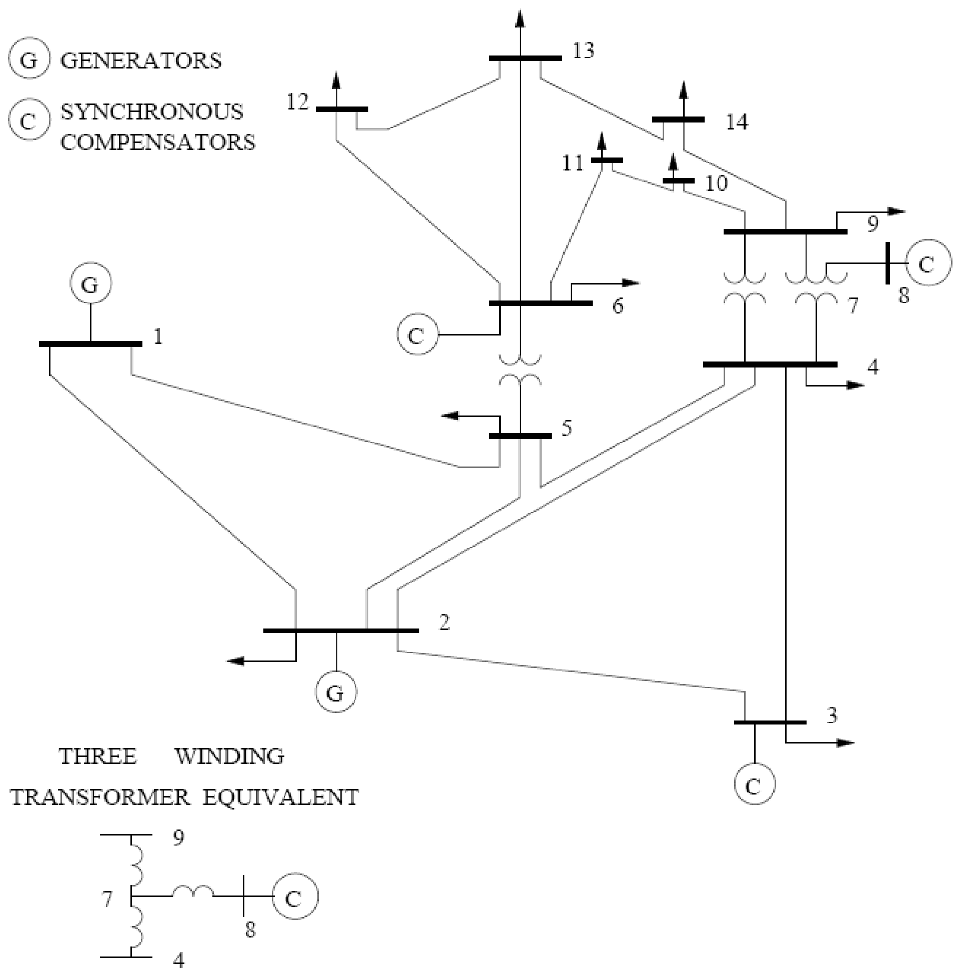
[21] University of Washington Homepage, "Power Systems Test Case Archieve," http://www. ee. Washington, edu/research/pstca

Appendix I

IEEE 14 BUS TEST SYSTEM

Line Data=

From Bus	To Bus	Resistance(p.u.)	Reactance(p.u.)	Line Charging(p.u)	Tap Raio
1	2	0.01938	0.05917	0.0528	1
1	5	0.05403	0.22304	0.0492	1
2	3	0.04699	0.19797	0.0438	1
2	4	0.05811	0.17632	0.0374	1
2	5	0.05695	0.17388	0.034	1
3	4	0.06701	0.17103	0.0346	1
4	5	0.01335	0.04211	0.0128	1
4	7	0.00	0.20912	0.00	0.978
4	9	0.00	0.55618	0.00	0.969
5	6	0.00	0.25202	0.00	0.932
6	11	0.09498	0.1989	0.00	1
6	12	0.12291	0.25581	0.00	1
6	13	0.06615	0.13027	0.00	1
7	8	0.00	0.17615	0.00	1
7	9	0.00	0.11001	0.00	1
9	10	0.03181	0.08450	0.00	1
9	14	0.12711	0.27038	0.00	1
10	11	0.08205	0.19207	0.00	1
12	13	0.22092	0.19988	0.00	1
13	14	0.17093	0.34802	0.00	1



IEEE 14-Bus Test System

Appendix II

Detailed load flow results for IEEE 14 bus system

LOAD FLOW(without compensation line length 400kms)		
i-j	**MW**	**Mvar**
1-2	-24	-1256
1-5	24	-1289
2-1	24	-1257
2-3	86	-1061
2-4	97	-1075
2-5	96.35	-981.28
3-2	-85	-1021
3-4	-9.01	-981.88
4-3	12.55	-755.21
4-2	-92.15	-795.80
4-5	-9.60	-271.86
4-7	23	1389
4-9	12.61	438.63
5-1	-22	-1173
5-2	-91.70	-710.89
5-4	9.72	-406.69
5-6	60	2245
6-11	9	6
6-12	3.47	3.06
6-13	2.13	6.22
6-5	-41	-2132
7-4	-22	-1353
7-8	2	1760
7-9	20.23	-407.29
8-7	0	-1707
9-10	1.39	1.47
9-14	0.05	0.31
9-7	-20.18	409.02
9-4	-12.33	-429.01
10-9	-1.23	-1.05
10-11	-4.93	-3.06
11-10	5.14	3.55
11-6	-8.31	-5.14
12-6	-3.33	-2.77
12-13	-1.93	1.02
13-12	2.00	-0.96
13-14	-0.02	1.47
13-6	-1.98	-5.93

14-13	0.04	-1.43
14-9	-0.04	-0.27

LOAD FLOW(without compensation line length 480 kms)		
i-j	**MW**	**Mvar**
1-2	-24	-1256
1-5	24	-1289
2-1	24	-1257
2-3	86	-1061
2-4	97	-1075
2-5	96.28	-981.25
3-2	-85	-1021
3-4	-9.01	-981.78
4-3	12.54	-755.25
4-2	-92.15	-795.84
4-5	-9.88	-272.12
4-7	23	1389
4-9	12.72	439.05
5-1	-22	-1174
5-2	-91.64	-710.93
5-4	10.00	-406.41
5-6	60	2244
6-11	9	7
6-12	3.31	2.58
6-13	1.79	4.21
6-5	-40	-2132
7-4	-22	-1353
7-8	2	1758
7-9	20.42	-405.11
8-7	0	-1705
9-10	1.18	1.25
9-14	0.56	3.12
9-7	-20.37	406.81
9-4	-12.44	-429.41
10-9	-1.04	-0.89
10-11	-5.04	-3.17
11-10	5.27	3.69
11-6	-8.42	-5.27
12-6	-3.20	-2.35
12-13	-2.15	0.56
13-12	2.21	-0.51
13-14	-0.49	-1.01
13-6	-1.72	-4.07
14-13	0.50	1.03
14-9	-0.50	-2.99

For shunt admittance between bus 9 and bus 10 i.e. line 8

For Ks = 0.1

Power factor = 0.967673 (leading)

Vs = 13.8 kV (L-L)

Vr = 13.8 kV (L-L) at 0^o

Receiving real power = 511.614 W

Pr_max_angle = 1.5637

Maximum Power = 384.505W

K1 = Pr/Pr_max = 1.3306

K=Shunt admittance= 1.42536 Siemen

LOAD FLOW(with compensation between Bus 9 and Bus 10 with Ks = 0.1 line length 400 kms)		
i-j	**MW**	**Mvar**
1-2	-25	-1256
1-5	25	-1292
2-1	25	-1257
2-3	87	-1062
2-4	102	-1094
2-5	99.57	-985.73
3-2	-86	-1020
3-4	-8	-1000
4-3	12.29	-746.06
4-2	-95.25	-786.85
4-5	-10.55	-213.55
4-7	25	1390
4-9	13.85	360.77
5-1	-23	-1173
5-2	-94.66	-707.92
5-4	10.98	-469.06
5-6	62	2304
6-11	7	36
6-12	3.29	2.54
6-13	1.75	4.02
6-5	-42	-2186
7-4	-24	-1355
7-8	2	2151
7-9	21.94	-796.53
8-7	0	-2074
9-10	3.17	-470.65
9-14	0.65	3.42
9-7	-21.75	803.02

9-4	-13.66	-354.33
10-9	0.17	-0.11
10-11	1.10	0.17
11-10	12.18	30.91
11-6	-0.18	-21.99
12-6	-3.18	-2.31
12-13	-2.17	0.52
13-12	2.24	-0.46
13-14	-0.56	-1.25
13-6	-1.68	-3.89
14-13	0.59	1.27
14-9	-0.59	-3.25

LOAD FLOW (with compensation between Bus 9 and Bus 10 with Ks = 0.1 line length 480 kms)		
i-j	**MW**	**Mvar**
1-2	-25	-1256
1-5	25	-1292
2-1	25	-1257
2-3	87	-1062
2-4	101	-1094
2-5	99.20	-985.65
3-2	-86	-1021
3-4	-8	-1000
4-3	12.46	-746.09
4-2	-94.91	-786.96
4-5	-10.56	-213.36
4-7	25	1390
4-9	13.66	360.60
5-1	-23	-1173
5-2	-94.31	-708.05
5-4	10.99	-469.26
5-6	62	2304
6-11	6	36
6-12	3.29	2.54
6-13	1.75	4.02
6-5	-41	-2186
7-4	-24	-1355
7-8	2	2152
7-9	21.61	-797.64
8-7	0	-2075
9-10	2.63	-471.94
9-14	0.65	3.43
9-7	-21.42	804.14
9-4	-13.47	-354.17
10-9	0.16	-0.17

10-11	1.29	0.22
11-10	12.25	31.50
11-6	0.45	-22.08
12-6	-3.18	-2.31
12-13	-2.17	0.52
13-12	2.24	-0.46
13-14	-0.56	-1.25
13-6	-1.68	-3.89
14-13	0.57	1.29
14-9	-0.57	-3.27

For Ks = 0.2

Power factor = 0.967673 (leading)

Vs = 13.8 kV (L-L)

Vr = 13.8 kV (L-L) at 0^o

Receiving real power = 504.076 W

Pr_max_angle = 1.5638

Maximum Power = 366.417W

K1 = Pr/Pr_max = 1.3757

K=Shunt admittance= 1.46913 Siemen

LOAD FLOW(with compensation between Bus 9 and Bus 10 with Ks = 0.2 line length 400 kms)		
i-j	**MW**	**Mvar**
1-2	-25	-1256
1-5	25	-1292
2-1	25	-1257
2-3	88	-1062
2-4	104	-1095
2-5	102.80	-986.64
3-2	-87	-1020
3-4	-7	-1001
4-3	11.21	-745.34
4-2	-97.63	-785.68
4-5	-7.32	-212.62
4-7	25	1390
4-9	13.92	358.21
5-1	-24	-1173
5-2	-97.78	-706.68
5-4	7.76	-470.10
5-6	69	2303
6-11	17	40
6-12	3.29	2.54

6-13	1.74	4.02
6-5	-49	-2186
7-4	-24	-1354
7-8	2	2163
7-9	22.04	-808.72
8-7	0	-2085
9-10	3.24	-485.92
9-14	0.66	3.43
9-7	-21.85	815.40
9-4	-13.73	-351.86
10-9	0.02	0.00
10-11	0.11	0.01
11-10	8.99	21.29
11-6	-7.76	-20.19
12-6	-3.18	-2.31
12-13	-2.17	0.52
13-12	2.24	-0.46
13-14	-0.57	-1.25
13-6	-1.67	-3.89
14-13	0.59	1.29
14-9	-0.59	-3.27

LOAD FLOW (with compensation between Bus 9 and Bus 10 with Ks = 0.2 line length 480 kms)		
i-j	**MW**	**Mvar**
1-2	-25	-1256
1-5	25	-1292
2-1	25	-1257
2-3	88	-1062
2-4	104	-1095
2-5	102.77	-986.65
3-2	-87	-1020
3-4	-7	-1001
4-3	11.27	-745.33
4-2	-97.53	-785.69
4-5	-6.99	-212.50
4-7	25	1390
4-9	13.74	357.97
5-1	-24	-1173
5-2	-97.75	-706.68
5-4	7.43	-470.24
5-6	69	2304
6-11	17	40
6-12	3.29	2.54
6-13	1.74	4.02
6-5	-49	-2186
7-4	-24	-1354
7-8	2	2164

7-9	21.74	-810.04
8-7	0	-2086
9-10	2.71	-487.12
9-14	0.66	3.43
9-7	-21.54	816.75
9-4	-13.55	-351.64
10-9	0.01	0.00
10-11	0.03	0.01
11-10	8.92	20.95
11-6	-7.96	-20.11
12-6	-3.18	-2.31
12-13	-2.17	0.52
13-12	2.24	-0.46
13-14	-0.57	-1.25
13-6	-1.67	-3.89
14-13	0.59	1.29
14-9	-0.59	-3.27

For Ks = 0.3

Power factor = 0.967673 (leading)

Vs = 13.8 kV (L-L)

Vr = 13.8 kV (L-L) at 0^o

Receiving real power = 493.131 W

Pr_max_angle = 1.5638

Maximum Power = 346.458W

K1 = Pr/Pr_max = 1.43201

K=Shunt admittance= 1.50923 Siemen

LOAD FLOW(with compensation between Bus 9 and Bus 10 with Ks = 0.3 line length 400 kms)		
i-j	**MW**	**Mvar**
1-2	-25	-1256
1-5	25	-1292
2-1	25	-1257
2-3	88	-1062
2-4	104	-1095
2-5	102.89	-986.77
3-2	-87	-1020
3-4	-7	-1002
4-3	11.20	-745.07
4-2	-97.74	-785.41
4-5	-7.41	-210.89
4-7	26	1390

4-9	13.98	355.91
5-1	-24	-1173
5-2	-97.86	-706.59
5-4	7.86	-471.94
5-6	69	2305
6-11	17	39
6-12	3.29	2.54
6-13	1.74	4.02
6-5	-49	-2187
7-4	-24	-1354
7-8	2	2174
7-9	22.14	-820.17
8-7	0	-2095
9-10	3.27	-499.47
9-14	0.66	3.44
9-7	-21.94	827.04
9-4	-13.80	-349.65
10-9	-0.03	-0.02
10-11	-0.19	-0.06
11-10	9.33	21.45
11-6	-7.49	-20.31
12-6	-3.18	-2.30
12-13	-2.18	0.52
13-12	2.24	-0.46
13-14	-0.57	-1.26
13-6	-1.67	-3.88
14-13	0.59	1.30
14-9	-0.59	-3.28

LOAD FLOW (with compensation between Bus 9 and Bus 10 with Ks = 0.3 line length 480 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	110	-1097
2-5	111.30	-988.93
3-2	-90	-1019
3-4	-4	-1003
4-3	8.42	-743.70
4-2	-103.75	-782.84
4-5	1.84	-211.88
4-7	25	1389
4-9	13.81	353.58
5-1	-25	-1173
5-2	-105.96	-703.45
5-4	-1.40	-471.06

5-6	88	2301
6-11	37	78
6-12	3.29	2.54
6-13	1.71	4.02
6-5	-68	-2183
7-4	-24	-1354
7-8	2	2184
7-9	21.83	-830.52
8-7	0	-2105
9-10	2.91	-512.11
9-14	0.69	3.43
9-7	-21.62	837.56
9-4	-13.63	-347.40
10-9	-0.11	-0.19
10-11	0.02	0.06
11-10	0.00	0.00
11-6	-0.15	0.01
12-6	-3.18	-2.31
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.25
13-6	-1.65	-3.89
14-13	0.62	1.29
14-9	-0.62	-3.27

For Ks = 0.4

Power factor = 0.967673 (leading)

Vs = 13.8 kV (L-L)

Vr = 13.8 kV (L-L) at 0^o

Receiving real power = 487.827 W

Pr_max_angle = 1.5639

Maximum Power = 326.712W

K1 = Pr/Pr_max = 1.49314

K=Shunt admittance= 1.54565 Siemen

LOAD FLOW(with compensation between Bus 9 and Bus 10 with Ks = 0.4 line length 400 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	111	-1097
2-5	111.54	-988.99
3-2	-90	-1019

3-4	-4	-1003
4-3	8.29	-743.66
4-2	-104.03	-782.74
4-5	1.62	-211.90
4-7	26	1389
4-9	14.04	353.60
5-1	-25	-1173
5-2	-106.20	-703.36
5-4	-1.18	-471.03
5-6	88	2301
6-11	37	78
6-12	3.29	2.54
6-13	1.72	4.02
6-5	-68	-2183
7-4	-25	-1354
7-8	2	2184
7-9	22.24	-830.16
8-7	0	-2104
9-10	3.54	-511.83
9-14	0.69	3.43
9-7	-22.03	837.20
9-4	-13.86	-347.42
10-9	-0.13	-0.30
10-11	0.04	0.10
11-10	0.00	0.00
11-6	-0.12	0.01
12-6	-3.18	-2.31
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.25
13-6	-1.65	-3.89
14-13	0.62	1.29
14-9	-0.62	-3.27

LOAD FLOW (with compensation between Bus 9 and Bus 10 with Ks = 0.4 line length 480 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	111	-1097
2-5	111.46	-988.98
3-2	-90	-1019
3-4	-4	-1003
4-3	8.36	-743.66
4-2	-103.89	-782.77
4-5	1.93	-211.80

4-7	25	1389
4-9	13.85	353.43
5-1	-25	-1173
5-2	-106.11	-703.38
5-4	-1.48	-471.15
5-6	89	2301
6-11	37	78
6-12	3.29	2.54
6-13	1.71	4.02
6-5	-68	-2183
7-4	-24	-1354
7-8	2	2185
7-9	21.90	-831.27
8-7	0	-2105
9-10	2.43	-513.46
9-14	0.69	3.43
9-7	-21.69	838.33
9-4	-13.67	-347.25
10-9	0.20	-0.93
10-11	0.04	0.13
11-10	0.01	-0.01
11-6	0.30	0.01
12-6	-3.17	-2.31
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.25
13-6	-1.65	-3.89
14-13	0.62	1.29
14-9	-0.62	-3.27

For Ks = 0.5

Power factor = 0.967673 (leading)

Vs = 13.8 kV (L-L)

Vr = 13.8 kV (L-L) at 0^o

Receiving real power = 479.212W

Pr_max_angle = 1.5639

Critical Power = 307.243W

K1 = Pr/Pr_max = 1.55972

K=Shunt admittance= 1.57842 Siemen(2.4071 pu)

LOAD FLOW(with compensation between Bus 9 and Bus 10 with Ks = 0.5 line length 400 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	111	-1098
2-5	111.65	-989.10
3-2	-90	-1019
3-4	-4	-1003
4-3	8.25	-743.44
4-2	-104.17	-782.51
4-5	1.44	-210.54
4-7	26	1389
4-9	14.16	351.81
5-1	-25	-1173
5-2	-106.29	-703.28
5-4	-0.98	-472.47
5-6	88	2302
6-11	37	78
6-12	3.29	2.54
6-13	1.71	4.02
6-5	-68	-2184
7-4	-25	-1354
7-8	2	2193
7-9	22.44	-839.02
8-7	0	-2112
9-10	3.47	-522.90
9-14	0.69	3.44
9-7	-22.22	846.21
9-4	-13.99	-345.70
10-9	0.06	-0.55
10-11	0.06	0.17
11-10	0.01	0.00
11-6	-0.21	0.02
12-6	-3.17	-2.31
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.26
13-6	-1.65	-3.89
14-13	0.62	1.30
14-9	-0.62	-3.28

LOAD FLOW (with compensation between Bus 9 and Bus 10 with Ks = 0.5 line length 480 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256

1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	111	-1098
2-5	111.33	-989.04
3-2	-90	-1019
3-4	-4	-1004
4-3	8.44	-743.47
4-2	-103.77	-782.62
4-5	1.85	-210.34
4-7	25	1389
4-9	13.79	351.53
5-1	-25	-1173
5-2	-105.99	-703.39
5-4	-1.40	-472.70
5-6	88	2302
6-11	37	78
6-12	3.29	2.54
6-13	1.71	4.02
6-5	-68	-2185
7-4	-24	-1354
7-8	2	2195
7-9	21.79	-840.87
8-7	0	-2114
9-10	2.72	-524.73
9-14	0.69	3.44
9-7	-21.58	848.09
9-4	-13.61	-345.42
10-9	0.00	0.00
10-11	0.00	0.00
11-10	0.00	0.00
11-6	0.00	0.00
12-6	-3.17	-2.31
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.26
13-6	-1.65	-3.88
14-13	0.62	1.30
14-9	-0.62	-3.28

For Ks = 0.6

Power factor = 0.967673 (leading)

Vs = 13.8 kV (L-L)

Vr = 13.8 kV (L-L) at 0^o

Receiving real power = 470.334 W

Pr_max_angle = 1.5640

Maximum Power = 288.103W

K1 = Pr/Pr_max = 1.6325

K=Shunt admittance= 1.60757 Siemen

LOAD FLOW(with compensation between Bus 9 and Bus 10 with Ks = 0.6 line length 400 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	111	-1098
2-5	111.50	-989.14
3-2	-90	-1019
3-4	-4	-1004
4-3	8.36	743.27
4-2	-103.99	-782.40
4-5	1.57	-209.23
4-7	26	1389
4-9	14.00	350.08
5-1	-25	-1173
5-2	-106.14	-703.29
5-4	-1.11	-473.89
5-6	88	2303
6-11	37	78
6-12	3.29	2.54
6-13	1.71	4.01
6-5	-68	-2186
7-4	-25	-1354
7-8	2	2202
7-9	22.14	-847.90
8-7	0	-2121
9-10	3.26	-533.30
9-14	0.69	3.45
9-7	-21.93	855.24
9-4	-13.82	-344.03
10-9	0.00	0.00
10-11	0.00	0.000
11-10	0.00	0.00
11-6	-0.01	0.00
12-6	-3.17	-2.31
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.26
13-6	-1.65	-3.88
14-13	0.62	1.30
14-9	-0.62	-3.29

LOAD FLOW (with compensation between Bus 9 and Bus 10 with Ks = 0.6 line length 480 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	111	-1098
2-5	111.32	-989.11
3-2	-90	-1019
3-4	-4	-1004
4-3	8.47	-743.28
4-2	-103.77	-782.45
4-5	1.78	-209.08
4-7	25	1390
4-9	13.80	349.88
5-1	-25	-1173
5-2	-105.97	-703.36
5-4	-1.32	-474.04
5-6	88	2304
6-11	37	78
6-12	3.29	2.54
6-13	1.71	4.01
6-5	-68	-2186
7-4	-24	-1354
7-8	2	2203
7-9	21.80	-849.13
8-7	0	-2122
9-10	2.72	-534.79
9-14	0.69	3.45
9-7	-21.58	856.49
9-4	-13.62	-343.83
10-9	-0.01	-0.01
10-11	0.00	0.00
11-10	0.00	0.00
11-6	0.00	0.00
12-6	-3.17	-2.31
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.26
13-6	-1.65	-3.88
14-13	0.62	1.30
14-9	-0.62	-3.29

For Ks = 0.7

Power factor = 0.967673 (leading)

Vs = 13.8 kV (L-L)

Vr = 13.8 kV (L-L) at 0^o

Receiving real power = 461.237 W

Pr_max_angle = 1.5640

Maximum Power = 269.344W

K1 = Pr/Pr_max = 1.71245

K=Shunt admittance= 1.6332 Siemen

LOAD FLOW(with compensation between Bus 9 and Bus 10 with Ks = 0.7 line length 400 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	111	-1099
2-5	111.47	-989.20
3-2	-90	-1019
3-4	-4	-1004
4-3	8.39	-743.11
4-2	-103.98	-782.25
4-5	1.49	-208.12
4-7	26	1389
4-9	14.01	348.63
5-1	-25	-1173
5-2	-106.12	-703.27
5-4	-1.02	-475.05
5-6	88	2304
6-11	37	78
6-12	3.29	2.54
6-13	1.71	4.01
6-5	-68	-2187
7-4	-25	-1354
7-8	2	2209
7-9	22.15	-855.20
8-7	0	-2128
9-10	3.26	-542.14
9-14	0.70	3.45
9-7	-21.93	862.67
9-4	-13.83	-342.63
10-9	0.00	0.00
10-11	0.00	0.00
11-10	0.00	0.00
11-6	-0.01	0.00
12-6	-3.17	-2.30

12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.27
13-6	-1.65	-3.88
14-13	0.62	1.31
14-9	-0.62	-3.29

LOAD FLOW(with compensation between Bus 9 and Bus 10 with Ks = 0.7 line length 480 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	111	-1098
2-5	111.09	-989.13
3-2	-90	-1019
3-4	-4	-1004
4-3	8.57	-743.15
4-2	-103.62	-782.36
4-5	1.49	-207.88
4-7	25	1390
4-9	13.81	348.40
5-1	-25	-1173
5-2	-105.75	-703.40
5-4	-1.02	-475.31
5-6	88	2305
6-11	37	78
6-12	3.29	2.54
6-13	1.71	4.01
6-5	-67	-2187
7-4	-24	-1354
7-8	2	2211
7-9	21.81	-856.62
8-7	0	-2129
9-10	2.72	-543.81
9-14	0.70	3.45
9-7	-21.59	864.11
9-4	-13.64	-342.40
10-9	0.00	0.00
10-11	0.00	0.00
11-10	0.00	0.00
11-6	-0.03	0.00
12-6	-3.17	-2.30
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.27
13-6	-1.65	-3.88

14-13	0.62	1.31
14-9	-0.62	-3.29

For Ks = 0.8

Power factor = 0.967673 (leading)

Vs = 13.8 kV (L-L)

Vr = 13.8 kV (L-L) at 0^o

Receiving real power = 451.965 W

Pr_max_angle = 1.5641

Maximum Power = 251.007W

K1 = Pr/Pr_max = 1.80061

K=Shunt admittance= 1.65531 Siemen

LOAD FLOW(with compensation between Bus 9 and Bus 10 with Ks = 0.8 line length 400 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	111	-1099
2-5	111.22	-989.20
3-2	-90	-1019
3-4	-4	1004
4-3	8.49	-743.01
4-2	-103.82	-782.19
4-5	1.14	-207.08
4-7	26	1389
4-9	14.04	347.37
5-1	-25	-1173
5-2	-105.87	-703.33
5-4	88	-476.14
5-6	37	2306
6-11	3.29	78
6-12	1.71	2.53
6-13	-67	4.00
6-5	-25	-2188
7-4	2	-1354
7-8	22.19	2215
7-9	0	-861.51
8-7	3.42	-2133
9-10	3.34	-549.89
9-14	-21.96	3.46

9-7	-13.86	869.09
9-4	-0.18	-341.42
10-9	0.02	-0.20
10-11	0.00	0.04
11-10	0.00	0.00
11-6	0.03	0.00
12-6	-3.17	-2.31
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.27
13-6	-1.65	-3.87
14-13	0.62	1.31
14-9	-0.62	-3.30

LOAD FLOW (with compensation between Bus 9 and Bus 10 with Ks = 0.8 line length 480 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	110	-1099
2-5	111.54	-989.05
3-2	-90	-1019
3-4	-4	-1004
4-3	8.76	-743.09
4-2	-103.24	-782.39
4-5	0.82	-206.80
4-7	25	1390
4-9	13.84	347.21
5-1	-25	-1173
5-2	-105.22	-703.58
5-4	-0.34	-476.44
5-6	86	2306
6-11	37	78
6-12	3.29	2.53
6-13	1.71	4.00
6-5	-66	-2188
7-4	-24	-1354
7-8	2	2217
7-9	21.84	-862.67
8-7	0	-2135
9-10	2.72	-551.22
9-14	0.69	3.46
9-7	-21.62	870.26
9-4	-13.66	-341.26
10-9	0.02	0.02
10-11	0.00	0.00

11-10	0.00	0.00
11-6	-0.10	0.02
12-6	-3.17	-2.30
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.27
13-6	-1.65	-3.87
14-13	0.62	1.31
14-9	-0.62	-3.30

For Ks = 0.9

Power factor = 0.967673 (leading)

Vs = 13.8 kV (L-L)

Vr = 13.8 kV (L-L) at 0^o

Receiving real power = 442.56 W

Pr_max_angle = 1.5641

Maximum Power = 233.13W

K1 = Pr/Pr_max = 1.8983

K=Shunt admittance= 1.67408 Siemen

LOAD FLOW(with compensation between Bus 9 and Bus 10 with Ks = 0.9 line length 400 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	91	-1062
2-4	110	-1099
2-5	110.75	-989.14
3-2	-90	-1019
3-4	-4	-1005
4-3	8.65	-742.95
4-2	-103.51	-782.21
4-5	0.49	-206.15
4-7	26	1390
4-9	14.10	346.37
5-1	-25	-1173
5-2	-105.42	-703.48
5-4	-0.01	-477.12
5-6	86	2307
6-11	37	78
6-12	3.29	2.53
6-13	1.71	4.00

6-5	-66	-2189
7-4	-25	-1354
7-8	2	2220
7-9	22.29	-866.59
8-7	0	-2138
9-10	3.34	-556.09
9-14	0.69	3.46
9-7	-22.06	874.25
9-4	-13.92	-340.44
10-9	0.06	-0.06
10-11	0.01	0.04
11-10	0.00	0.00
11-6	-0.16	0.04
12-6	-3.17	-2.30
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.28
13-6	-1.65	-3.87
14-13	0.62	1.32
14-9	-0.62	-3.30

LOAD FLOW(with compensation between Bus 9 and Bus 10 with Ks = 0.9 line length 480 kms)		
i-j	**MW**	**Mvar**
1-2	-27	-1256
1-5	27	-1293
2-1	27	-1257
2-3	90	-1062
2-4	109	-1099
2-5	109.50	-988.84
3-2	-89	-1020
3-4	-5	-1005
4-3	9.13	-743.11
4-2	-102.50	-782.58
4-5	-0.38	-205.67
4-7	25	1390
4-9	13.87	346.17
5-1	-25	-1173
5-2	-104.21	-703.94
5-4	0.87	-477.63
5-6	84	2308
6-11	37	78
6-12	3.29	2.53
6-13	1.72	4.00
6-5	-64	-2190
7-4	-24	-1354
7-8	2	2222
7-9	21.89	-868.03

8-7	0	-2140
9-10	2.72	-557.66
9-14	0.69	3.46
9-7	-21.67	875.72
9-4	-13.70	-340.25
10-9	0.06	-0.02
10-11	0.00	0.02
11-10	0.00	0.00
11-6	-0.21	0.08
12-6	-3.17	-2.30
12-13	-2.18	0.52
13-12	2.25	-0.46
13-14	-0.60	-1.28
13-6	-1.65	-3.87
14-13	0.62	1.32
14-9	-0.62	-3.30