Load Flow Analysis with SVC and TCSC

A Project Report

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CERTIFICATE

This is to certify that the report titled **Load Flow Analysis with SVC and TCSC** , submitted by **Ashok Kumar B, EE07B007** to the Indian Institute of Technology Madras, for the award of the degree of **Bachelor of Technology** , is a bona fide record of the project work done by him under my supervision. The contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Load Flow Analysis, Flexible AC Transmission System, Newton - Raphson Method, Static Var Compensator,Thyristor Controlled Series Compensator.

Load flow analysis is the backbone of power system analysis and design. They are necessary for planning, operation, economic scheduling and exchange of power between utilities. The principal information of power flow analysis is to find the magnitude and phase angle of voltage at each bus and the real and reactive power flowing in each transmission lines. Power flow analysis is an importance tool involving numerical analysis applied to a power system. In this analysis, iterative techniques are used as there are no known analytical method to solve the problem.

In this work Newton - Raphson Method is used to carry out the load flow analysis of a system with and without FACTS devices. Static Var Compensator (SVC) and Thyristor Controlled Series Controller (TCSC) are the two important types of FACTS controllers used in this work to improve Voltage profile, decrease Power losses and increase the amount of power transferred in the transmission line . The load flow analysis has been done on two test systems,i.e IEEE 6-Bus and IEEE 30-Bus system.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

TCSC	Thyristor Controlled Series Compensator
FACTS	Flexible AC Transmission System
SVC	Static Var Compensator
TCR	Thyristor Controlled Reactor
SLFE	Static Load Flow equations
NR	Newton Raphson
IEEE	Institute of Electrical and Electronics Engineers

NOTATIONS

$V_i; V_j$	Voltage magnitudes at the buses i and j
$\delta_i; \delta_j$	Voltage phase angles at the buses i and j
I_i	Current at the i^{th} bus
Y_{ik}	Short circuit admittance between i^{th} and k^{th} bus
J	Jacobian Matrix
I	Magnitude of transmission line current
R	Resistance of transmission line
X	Reactance of transmission line
X_C	Capacitive reactance
X_L	Inductive reactance
P_i; P_j	Active power injections at buses i and j
Q_i; Q_j	Reactive power injections at buses i and j
x_{TCSC}	Reactance offered by TCSC
Q_C	Reactive power injected by the shunt compensator
P_{Gi}	Real power generation at the i^{th} bus
Q_{Gi}	Reactive power generation at the i^{th} bus
P_{Di}	Real power demand at the i^{th} bus
Q_{Di}	Reactive power demand at the i^{th} bus
$v(t)$	Sinusoidal input source voltage
ω	Angular frequency
$i_L(t)$	Current through the TCR circuit
$i_{LF}(\alpha)$	Fundamental current through the TCR
α	Triggering angle to the thyristor
σ	Conduction angle of the thyristor
$B_{TCR}(\alpha)$	Susceptance of the TCR
$X_{TCR}(\alpha)$	Reactance of the TCR
$X_{TCSC}(\alpha)$	Reactance of TCSC

CHAPTER 1

INTRODUCTION

1.1 General Introduction

In today's highly complex and interconnected power systems, made up of thousands of buses and hundreds of generators, there is a great need to improve electric power utilization maintaining reliability and security. In order to meet the ever-growing power demand, utilities prefer to rely on already existing generation and power export/import arrangements instead of erecting new transmission lines that are subject to environmental and regulatory policies. On the other hand, power flows in some of the transmission lines are well below their thermal limits, while certain lines are overloaded, which has as an overall effect of deteriorating voltage profiles and decreasing system stability and security. In addition, existing traditional transmission facilities, in most cases, are not designed to handle the control requirements of complex, highly interconnected power systems.

This overall situation requires the review of traditional transmission methods and practices, and the development of new concepts which would allow the use of existing generation and transmission lines up to their full capabilities without reduction in system stability and security. Another reason that is forcing the review of traditional transmission methods is the tendency of modern power systems to follow the changes in today's global economy that are leading to deregulation of electrical power markets . FACTS devices can provide an alternative to traditional transmission methods . This project is about load flow analysis with FACTS devices.

1.2 Load Flow Studies

Load flow study in power system parlance is the steady state solution of the power system network. The power system is modelled by an electrical network and solved for the steady state powers and voltages at various buses . The direct analysis of the circuit is not possible, as the loads are given in terms of complex powers rather than impedences , and the generators behave more like power sources rather than voltage sources .The main information obtained from load flow study comprises of magnitudes and phase angles of load bus voltages , reactive powers and voltage phase angles at generator buses , real and reactive power flows on transmission lines together with power at the reference bus , other variables being specified. This information is essential for the continuous monitoring of the current state of the system and for analyzing the effectiveness of the alternate plans for the future , such as adding new generator sites , meeting increased load demand and locating new transmission sites [1].

In load flow analysis , we are mainly interested in voltages at various buses and power injection in to the transmission system . The following show the one line diagram of a power system having 5 buses

Here S_G's and S_D's represent the complex powers injected by generators and complex

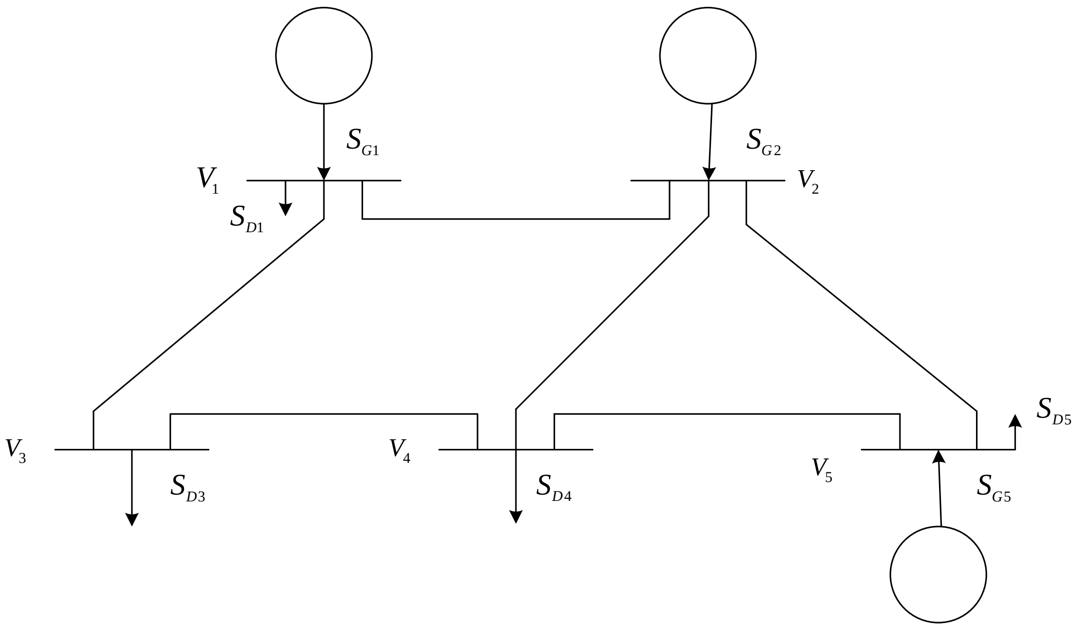

Fig. 1.1: Single line diagram of a 5-Bus system

powers drawn by loads and Vs represent the complex voltages at various buses. Thus, there is a net injection of power in to the transmission system .

In a practical system , there may be thousands of buses and transmission links . The transmission system is to be designed in such a manner that the power power system operation is reliable and economic and no difficulties are encountered in its operation . The likely difficulties are , one or more transmission lines becoming overloaded , generator(s) becoming overloaded or the stability margin for a transmission link being too small etc. Also, there may be emergencies , such that the loss of one or more transmission links, shut down of generators etc which gives rise to overloading of some generators and transmission links . In system operation and planning, the voltages and powers are kept within certain limits and alternate plans are developed for easy and reliable operation .

The two main methods used for Load flow studies are :

- Newton - Raphson Method
- Gauss Seidel Method

1.3 Classification of FACTS

FACTS devices are broadly classified into four categories depending on the placement of the devices with respect to transmission line and they are given as following [2].

- Series Controllers
- Shunt Controllers
- Combined series-series Controllers
- Combined series-shunt Controllers

Series Controllers: These types of controllers are connected in series with the transmission line. The series controller could be variable impedance, such as capacitor, reactor or a power electronic based variable source of main frequency. The basic principle of all series FACTS controllers is that they inject voltage in series with the line. The main series FACTS controllers are given below.

- Static Synchronous Series Compensator (SSSC)
- Interline Power Flow Controller (IPFC)
- Thyristor Controlled Series Capacitor (TCSC)
- Thyristor Switched Series Capacitor (TSSC)
- Thyristor Controlled Series Reactor (TCSR)

Shunt Controllers: These types of controllers are connected in shunt with the transmission line. As in series controller, the shunt controllers may be variable impedance, such as capacitor, reactor, variable source or a combination of these. Shunt Controllers inject current into the system at the point of connection. As long as the injected current is in quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power.The main shunt FACTS controllers are given below.

- Static Synchronous Compensator (STATCOM)
- Static Var Compensator (SVC)
- Thyristor Controlled Reactor (TCR)
- Thyristor Switched Capacitor (TSC)

Combined series-series Controllers: These controllers could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multi line transmission system. Series controllers provide independent series reactive compensation for each line and also transfer real power among lines via DC power link. This real power transfer capability makes it possible to balance both the real and reactive power flow in lines and thereby maximizing the utilization of transmission system.The Interline Power Flow Controller (IPFC) is the important type of combined series-series controller.

Combined series-shunt Controllers: These controllers could be a combination of separate shunt and series controllers, which are controlled in a coordinated manner, in a multi line transmission system. Shunt part of the controller inject current into the system and Series part of the controller will provide voltage in series in the line. There is real power exchange between the series and shunt controllers via power link

- Unified power flow controller (UPFC)
- Thyristor controlled phase shifting transformer (TCPST)

The main purpose of the series and shunt FACTS devices is to increase the transmittable power through the transmission line, improves the steady-state transmission characteristics and enhance the stability of the system.

1.4 Objective

The main objectives of the present work are :

- Load Flow analysis of different systems using Newton - Raphson Method.
- Load flow analysis with SVC and TCSC .

Despite the availability of large number of Load Flow methods , the Newton - Raphson method is preferred because of its high versatility , accuracy , and reliability . As such it is used for a variety of system optimization calculations.

1.5 Organization of Thesis

Chapter 1 gives a general introduction to the Load Flow Studies ,FACTS controllers used in the power system network and their classification. Main objectives of the work and organization of thesis are also presented.

Chapter 2 discusses the load flow problem in detail .It also introduces the Newton - Raphson method which is used to carry out load flow analysis.

Chapter 3 introduces SVC and TCSC . The operation of these devices and their application in load flow has also been disucssed

Chapter 4 gives the detailed simulation results for the load flow analysis using Newton - Raphson . It has also been carried out with SVC/TCSC

Chapter 5 gives the important conclusions and the scope for future work.

The IEEE 6-BUS and the IEEE 30-BUS system data is given in Appendix A and B, respectively.

CHAPTER 2

LOAD FLOW STUDIES

2.1 Network Model Formulation

Consider an i^{th} bus of a 'n' bus power system as shown in the Fig. 2.1

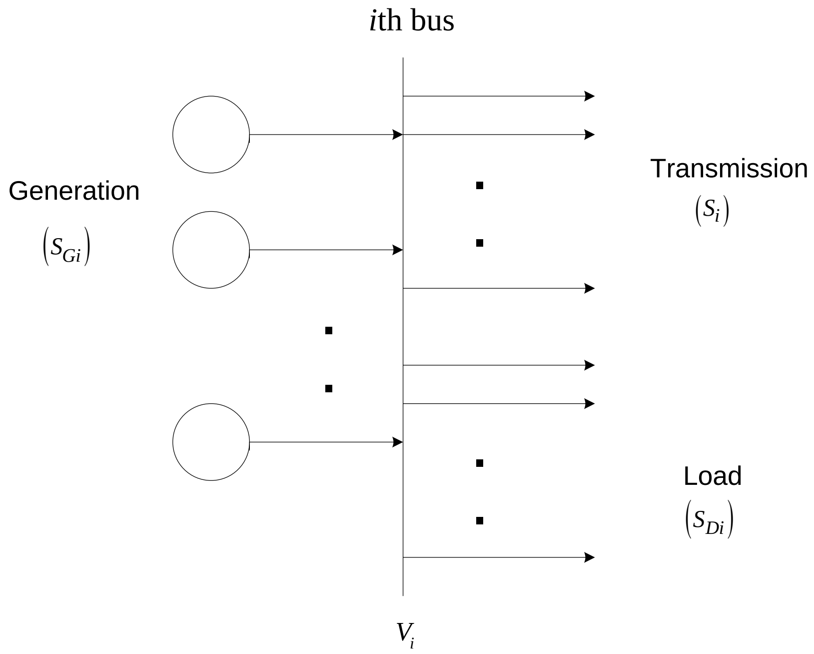

Fig. 2.1: i^{th} bus in general connected to generators, loads and transmission lines

S_{Gi}, S_i and S_{Di} are the complex generator, transmission line and load powers respectively.

It is convenient to work with power at each bus injected in to the transmission system called the "Bus Power" . The ith bus power is defined as [1]

$$S_i = S_{Gi} - S_{Di}$$

Writing the complex powers in terms of real and reactive powers, we have

$$S_{Gi} = P_{Gi} + jQ_{Di} \tag{2.1}$$

$$S_{Di} = P_{Di} + jQ_{Gi} \tag{2.2}$$

$$S_i = P_i + jQ_i \tag{2.3}$$

i = 1,....n

The "Bus Current"' at the i^{th} bus is defined as,

$$I_i = I_{Gi} - I_{Di} \tag{2.4}$$

The relationship between bus currents and bus voltages are developed under the following assumptions :

- There is no mutual coupling between the transmission lines , and
- There is an absence of regulating transformers.

Let y_{ik} (i≠k)= 0 if there is no transmission line between ith and kth bus .

By applying KCL at the i^{th} bus , we get

$$\begin{aligned} I_i &= y_{i0}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + ... + \\ &\quad y_{i,i-1}(V_i - V_{i,i-1}) + y_{i,i+1}(V_i - V_{i,i+1}) + ... \\ &\quad + y_{in}(V_i - V_n) \end{aligned} \tag{2.5}$$

or

$$\begin{aligned} I_i &= -y_{i1}V_1 - y_{i2}V_2 - y_{i3}V_3 - .... - y_{i,i-1}V_{i-1} \\ &\quad + (y_{i0} + y_{i1} + ... + y_{i,i-1} + y_{i,i+1} + ... + y_{in})V_i \\ &\quad - y_{i,i+1}V_(i+1) - .... - y_{in}V_n \end{aligned} \tag{2.6}$$

Thus, in general ,

$$\begin{aligned} I_i &= Y_{i1}V_1 + Y_{i1}V_1 + Y_{i2}V_2 + ... + Y_{ii}V_i + ... + Y_{in}V_n \\ &= \sum_{k=1}^{n} (Y_{ik}V_k) \qquad (2.7) \\ \text{where,} \quad i &= 1, ...n \end{aligned}$$

where

$$Y_{ik}(i \neq k) = \frac{I_i}{V_k}(\text{ all } V = 0 \text{ except } V_k \text{ }) \qquad (2.8)$$

$= $ Short circuit transfer admittance between i^{th} and k^{th} bus

$$\text{and} \quad Y_{ii} = \frac{I_i}{V_i}(\text{ all } V = 0 \text{ except } V_i) \qquad (2.9)$$

$=$ Short circuit driving point impedence or self impedence at the i^{th} bus

From equations (2.7) and (2.9)

$$Y_{ik} = -y_{ik} = \text{negative of the total admittance connected between } i_{th} \text{ and } k_{th} \text{ bus} \qquad (2.10)$$

From equations (2.7) and (2.10)

$$Y_{ii} = y_{i0} + y_{i1} + ... + y_{i,i-1} + y_{i.i+1} + ... + y_{in} \qquad (2.11)$$

$=$ Sum of the admittances directly connected to the i_{th} bus

Writing equation for all the n buses we can write its matrix form as

$$\mathbf{I}_{BUS} = \mathbf{Y}_{BUS}\mathbf{V}_{BUS}$$

where $\mathbf{I}_{BUS}$ is a n X 1 column vector of bus currents

$\mathbf{V}_{BUS}$ is a n X 1 column vector of bus voltages

$_{BUS}$ is a n X n matrix of admittances given as

$$Y_{BUS} = \begin{bmatrix} \mathbf{Y}_{11} & \mathbf{Y}_{12}\ldots\ldots & \mathbf{Y}_{1n} \\ \mathbf{Y}_{21} & \mathbf{Y}_{22}\ldots\ldots & \mathbf{Y}_{21} \\ . & . & . \\ . & . & . \\ . & . & . \\ \mathbf{Y}_{n1} & \mathbf{Y}_{n2} & \mathbf{Y}_{nn} \end{bmatrix}$$

It follows that,

- The diagonal element of $\mathbf{Y}_{BUS}$ is given by (2.11) and is the self admittance . The off diagonal element of the $\mathbf{Y}_{BUS}$ is given by (2.10) and is the transfer admittance .
- $\mathbf{Y}_{BUS}$ is a n x n matrix where N is the number of buses .
- $\mathbf{Y}_{BUS}$ is a symmetric matrix .
- $Y_{ik}(\mathrm{i}{\neq}\mathrm{k}) = 0$ if the i_{th} and k_{th} buses are not connected.

Since in a power network each bus is connected only to a few other buses (2 or 3) , the $\mathbf{Y}_{BUS}$ of a large network is very sparse , i.e it has a large number of zero elements .

$\mathbf{Y}_{BUS}$ is often used in solving load flow problems . It has gained widespread application owing to its simplicity in data preparation , and the ease with which it can be formed and modified for network changes . One of the greatest advantage is its sparsity , as it heavily reduces computer memory and time changes .

2.1.1 Algorithm for the formation of $\mathbf{Y}_{\mathbf{BUS}}$

Assuming no mutual coupling between transmission lines :

Initially all elements of $\mathbf{Y}_{BUS}$ are set to zero. Addition of an element of admittance y between buses i and j affects four entries in $\mathbf{Y}_{BUS}$, Y_{ii}, Y_{ij}, Y_{ji}, Y_{jj} as follows [1]:

$$Y_{iinew} = Y_{iiold} + y$$
$$Y_{ijnew} = Y_{ijold} - y$$
$$Y_{jinew} = Y_{jiold} - y$$
$$Y_{jjnew} = Y_{jjold} + y$$

Addition of an element of admittance y from bus i to ground will only effect Y_{ii} ,

$$Y_{iinew} = Y_{iiold} + y$$

2.2 Load flow problem

The complex power injected by the source in to the i^{th} bus of a power system is

$$S_i = P_i + jQ_i = V_i I_i^*, i = 1, 2, ..., n$$

Since it is convenient to work with I_i instead of I_i^*, we take the complex conjugate of the above equation,

$$P_i - jQ_i = V_i^* I_i, i = 1, 2, ...n$$

Substituting

$I_i = \left(\sum_{k=1}^{n} (Y_{ik}V_k)\right)$ from (2.7) in the above equation we have

$$P_i - Q_i = V_i^* \left(\sum_{k=1}^{n} (Y_{ik}V_k)\right), i = 1, 2, ...n$$

Equating real and imaginary parts we get,

$$P_i = \text{Real}\left(V_i^* \left(\sum_{k=1}^{n} (Y_{ik}V_k)\right)\right) \tag{2.12}$$

$$Q_i = -\text{Imaginary}\left(V_i^* \left(\sum_{k=1}^{n} (Y_{ik}V_k)\right)\right) \tag{2.13}$$

Let

$$\begin{aligned} V_i &= |V_i|e^{j\delta_i}, V_k = |V_k|e^{j\delta_k} \\ Y_{ik} &= |Y_{ik}|e^{j\theta_{ik}} \end{aligned}$$

Then

$$P_i = |V_i| \sum_{k=1}^{n} |V_i||V_k| cos\,(\theta_{ik} + \delta_k - \delta_i) \quad (2.14)$$

$$Q_i = -|V_i| \sum_{k=1}^{n} |V_k||Y_{ik}| sin(\theta_{ik} + \delta_k - \delta_i) \quad (2.15)$$

(i = 1,2,...n)

Equations (2.14) and (2.15) are called Power Flow Equations . There are n real and n reactive power flow equations giving a total of $2n$ power flow equations .

At each bus there are 4 variables , $|V_i|$, δ_i , P_i and Q_i , giving a total of $4n$ variables (for n buses) . If at every bus two variables are specified (thus specifying a total of $2n$ variables), the remaining two variables at every bus (remaining $2n$ variables) can be found by solving the $2n$ power flow equations (2.14) and (2.15) .

When a physical problem is considered , specifying variables at every bus depends on what devices are connected to that bus . In general there are four possibilities giving rise to four types of buses .

Slack Bus / Swing Bus / Reference Bus :

This bus is distinguished from the remaining types by the fact that real and reactive powers at this bus are not specified. Instead voltage magnitude (normally set equal to 1 pu) and voltage phase angle(normally set equal to zero) are specified . Usually , there is only one bus of this type in a given power system . The slack bus is numbered 1 for convenience.

PQ BUS/Load Bus

At this type of bus , the net powers P_i and Q_i are known are known (P_{Di} and Q_{Di} are known from load forecasting) . The unknowns are $|V_i|$ and δ_i. A pure load bus (no generating facility at the bus , i.e P_{Gi} = Q_{Gi} = 0) is a PQ bus . PQ buses are the most common , comprising almost 80% of all the buses in the given power system

PV Bus/Generator Bus

This bus always has a generator connected to it. Thus P_{Gi} and $|V_i|$ are specified. Hence the net power P_i is known (as P_{Di} is known from load forecasting) . Hence the knowns are P_i and $|V_i|$ and the unknowns are Q_i and δ_i . PV buses comprises about 10% of all the buses of a power system .

Voltage controlled Bus

Frequently the PV buses and the voltage controlled buses are grouped together. But they have physical differences and slightly different calculation strategies . The voltage controlled bus has also voltage control capabilities , and uses a tap-adjustable transformer/ or a static var compensator instead of a generator . Hence P_{Gi} = 0 at theses buses. Thus P_i = - P_{Di} , Q_i = Q_{Gi}- Q_{Di} and $|V_i|$ are known at these buses and the unknown is δ_i .

The following equations are referred to as Static Load Flow Equations (SLFE)

$$P_i = |V_i| \sum_{k=1}^{n} |V_i||V_k| cos\,(\theta_{ik} + \delta_k - \delta_i) \quad (2.16)$$

$$Q_i = -|V_i| \sum_{k=1}^{n} |V_k||Y_{ik}| sin(\theta_{ik} + \delta_k - \delta_i) \quad (2.17)$$

where i = 1,2,...n

By transposing all the variables on one side , these equations can be written in the vector form

$$\mathbf{f(x,y) = 0} \quad (2.18)$$

Where $\boldsymbol{f}$ = vector function of dimension $2n$ x 1

$\boldsymbol{x}$ = vector of dependent or state variables of dimension $2n$ x 1

$\boldsymbol{y}$ = vector of independent variables of dimension $2n$ x 1

Some of the independent variables in x can be used to manipulate some of the state variables . These adjustable independent variables are called control variables . The remaining independent variables which are fixed are called fixed parameters. Vector x can be partitioned in to vector u of control variables and a vector p of fixed parameters ,

$$\mathbf{x} = \begin{bmatrix} \mathbf{u} \\ \mathbf{p} \end{bmatrix} \tag{2.19}$$

Control variables may be voltage magnitude on PV bus , P_{Gi} at buses with controllable power etc . Fixed parameters are those which are uncontrollable .

For SLFE solution to have practical significance , all the state and control variables must be within specified practical limits . These limits are dictated by specifications of power system hardware and operating constraints , and are described below :

(1) Voltage magnitude $|V_i|$ must satisfy the inequality constraint

$$|V_i|_{min} \leq |V_i| \leq |V_i|_{max} \tag{2.20}$$

This limit arises due to the fact that the power system equipment is deisgned to operate at fixed voltages with allowable variations of $\pm(5-10)\%$ of rated values .

(2) The total power flowing in the line is limited by the maximum permissibile value .

$$|S_l| < |S_{lmax}| \tag{2.21}$$

(3) Owing to physical limitations of P and/or Q generated at the generator buses , P_{Gi} and Q_{Gi} are considered as follows :

$$P_{Gi,min} \leq P_{Gi} \leq P_{Gi,max} \tag{2.22}$$

$$Q_{Gi,min} \leq Q_{Gi} \leq Q_{Gi,max} \tag{2.23}$$

Also we have

$$\sum_i P_{Gi} = \sum_i (P_{Di}) + P_L \tag{2.24}$$

$$\sum_i P_{Qi} = \sum_i (Q_{Di}) + Q_L \tag{2.25}$$

Where P_L and Q_L are system real and reactive power losses .

The load flow problem can now be fully defined as follows :

Assume a certain nominal bus load configuration. Specify P_{Gi} + Q_{Gi} at all PQ buses (this specifies P_i + Q_i at these buses , specify P_{Gi} (this specifies P_i) and $|V_i|$ at all PV buses ; and specify $|V_i|$ and δ_i (=0) at the slack bus. Thus all the vaiables of vector **x** are specified . Thus $2n$ SLFE , which are non linear algebraic equations , can be solved (iteratively) to determine the values of the $2n$ variables of the vector **y** comprising voltages and angles at the PQ buses ;reactive powers and angles at the PV buses ; and active and reactive powers at the slack bus.

Since the load flow equations are essentially non linear , they have to be solved through iterative numerical techniques . At the cost of solution accuracy , it is possible to linearize load flow equations by making suitable assumptions and approximations so that fast and explicit solutions become possible . Such techniques have value , particularly for planning studies where load flow solutions have to be carried out repeatedly.

2.3 Newton - Raphson Method

The Newton - Raphson (NR) method is a powerful method of solving non-linear algebraic equations . It works faster, sure to converge in most cases as compared to Gauss siedel method . It is indeed the practical method for load flow solution of large power networks . Its only drawback is the large requirement of computer memory which can be overcome through a compact storage scheme .

We consider the following set of n non linear algebraic equations

$$f_i(x_1, x_2, ..., x_n) = 0 \qquad \text{where} \quad i = 1, 2, ..., n \tag{2.26}$$

We assume the initial values of unknowns as x_1^0, x_2^0,...x_n^0 . Let Δx_1^0, Δx_2^0,......, Δx_n^0 be the corrections to be found out , which on being added to the initial values give the actual solution . Therefore,

$$f_i\left(x_1^0+\Delta x_1^0,....+x_n^0+\Delta x_n^0\right)=0; \tag{2.27}$$

Expanding these equations around the initial values by Taylor series , we have

$$f_i^0\left(x_1^0,....,x_n^0\right)+\left[\left(\frac{\partial f_i}{\partial x_1}\right)^0\Delta x_1^0+...+\left(\frac{\partial f_i}{\partial x_n}^0\right)\Delta x_n^0\right]+\text{higher order terms}=0 \tag{2.28}$$

where $\left(\frac{\partial f_i}{\partial x_i}\right)^0,....,\left(\frac{\partial f_i}{\partial x_i}\right)^0$ are the derivatives of f_i w.r.t x_1, x_2 ,...., x_n
evaluated at x_1^0,....x_n^0

Neglecting the higher order terms , (2.29) can be written in matrix form as

$$\begin{bmatrix} f_1^0 \\ \cdot \\ \cdot \\ f_n^0 \end{bmatrix}+\begin{bmatrix} \left(\frac{\partial f_1}{\partial x_1}\right)^0 & \cdots & \left(\frac{\partial f_1}{\partial x_n}\right)^0 \\ \vdots & \ddots & \vdots \\ \left(\frac{\partial f_n}{\partial x_1}\right)^0 & \cdots & \left(\frac{\partial f_n}{\partial x_n}\right)^0 \end{bmatrix}\begin{bmatrix} \Delta x_1^0 \\ \cdot \\ \cdot \\ \Delta x_n^0 \end{bmatrix}\cong\begin{bmatrix} 0 \\ \cdot \\ \cdot \\ 0 \end{bmatrix} \tag{2.29}$$

or, in the vector matrix form

$$f^0+J^0\Delta x^0=0 \tag{2.30}$$

Where J^0 is the Jacobian matrix evaluated at x^0 . In compact notation ,

$$J^0=\left(\frac{\partial f(x)}{\partial x}\right)^0 \tag{2.31}$$

In above equation , Δx^0 is the vector of approximate correction. This can be written in the form

$$\Delta x^0=(J^0)^{-1}f^0 \tag{2.32}$$

Thus Δx^0 can be evaluated by calculating inverse of J^0 . But , in practice the inverse matrix is not evaluated as it is computationally expensive . So we write it in the form

$$J^0 \Delta x^0 \cong -f^0 \tag{2.33}$$

These being a set of linear algebraic equations , can be solved for Δx^0 efficiently by LU decomposition . Updated values of x are then

$$x^1 = x^0 + \Delta x^0 \tag{2.34}$$

In general for the (r+1)th iteration

$$(J(x^r))\Delta x^r = -f(x^r) \tag{2.35}$$

$$(-J(x^r))\Delta x^r = f(x^r) \tag{2.36}$$

$$(-J^r)\Delta x^r = f^r \tag{2.37}$$

$$x^{r+1} = x^r + \Delta x^r \tag{2.38}$$

Iterations are continued till

$$|f_i(x^r)| < \varepsilon(\text{ a specified value}), i = 1, 2, ..n \tag{2.39}$$

Thus each iteration involves the evaluation of $f(x^r)$, $J(x^r)$ and the correction Δx^r .

2.3.1 NR Algorithm for load flow solution

We first consider the presence of PQ buses only apart from a slack bus . From equations (2.16) and (2.17) for an ith bus

$$P_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}|cos(\theta_k + \delta_{ik} - \delta_i) = P_i(|V|, \delta) \tag{2.40}$$

$$Q_i = -\sum_{k=1}^{n} |V_i||V_k||Y_{ik}|sin(\theta_k + \delta_{ik} - \delta_i) = Q_i(|V|, \delta) \tag{2.41}$$

i.e both real and reactive powers are functions of ($|V|$, δ), where

$$|V| = (|V_1|, ..., |V_n|)^T \tag{2.42}$$

$$\delta = (\delta_1, ..., \delta_n)^T \tag{2.43}$$

We write

$$P_i(|V|, \delta) = P_i(x) \tag{2.44}$$

$$Q_i(|V|, \delta) = Q_i(x) \tag{2.45}$$

Where $x = \begin{bmatrix} \delta \\ |V| \end{bmatrix}$

Let P_i (scheduled) and Q_i (scheduled) be the scheduled powers at the load buses . In the course of iteration x should tend to the value which makes

$$P_i(scheduled) - P_i(x) = 0 \quad \text{and} \quad Q_i(scheduled) - Q_i(x) = 0 \tag{2.46}$$

Writing Eq (2.46) for all load buses , we get its matrix form

$$f(x) = \begin{bmatrix} P(scheduled) - P(x) \\ Q(scheduled) - Q(x) \end{bmatrix} = \begin{bmatrix} \Delta P(x) \\ \Delta Q(x) \end{bmatrix} \cong 0 \tag{2.47}$$

At the slack bus (Bus no 1) P_i and Q_i are unspecified . Therefore , the values $P_1(x)$ and $Q_1(x)$ do not enter in (2.46) . and hence (2.47) . Thus, x is a 2(n - 1) vector (n - 1 load buses) with each element function of (n - 1) variables given by the vector

$x = \begin{bmatrix} \delta \\ |V| \end{bmatrix}$

From Eq (2.37) we can write

$$f(x) = \begin{bmatrix} \Delta P(x) \\ \Delta Q(x) \end{bmatrix} = \begin{bmatrix} -J_{11}(x) & -J_{12}(x) \\ -J_{21}(x) & -J_{22}(x) \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{2.48}$$

where

$$|V| = (|V_2|, ..., |V_n|)^T \ \delta = (\delta_2, ..., \delta_n)^T \tag{2.49}$$

$J(x)$ is the Jacobian matrix , each J_{11}, J_{12}, J_{21}, J_{22} are (n - 1) x (n - 1) matrices . It follows from (2.29) and (2.47) that

$$-J_{11}(x) = \frac{\partial P(x)}{\partial \delta} \tag{2.50}$$

$$-J_{12}(x) = \frac{\partial P(x)}{\partial |V|} \tag{2.51}$$

$$-J_{21}(x) = \frac{\partial Q(x)}{\partial \delta} \tag{2.52}$$

$$-J_{22}(x) = \frac{\partial Q(x)}{\partial |V|} \tag{2.53}$$

from (2.40) and (2.41) we have

$$\frac{\partial P_i(x)}{\partial \delta_k} = -|V_i||V_k||Y_{ik}|sin(\theta_{ik} + \delta_k - \delta_i)(i \neq k) \tag{2.54}$$

$$= \sum_{k=1,k\neq i}^{n} |V_i||V_k||Y_{ik}|sin(\theta_k + \delta_{ik} - \delta_i)(i = k) \tag{2.55}$$

$$\frac{\partial P_i(x)}{\partial |V|_k} = |V_i||Y_{ik}|cos(\theta_{ik} + \delta_k - \delta_i)(i \neq k) \tag{2.56}$$

$$= 2|V_i||Y_{ii}\ cos(\theta_{ii}) + \sum_{k=1,k\neq i}^{n} |V_k||Y_{ik}|cos(\theta_{ik} + \delta_k - \delta_i)(i = k) \tag{2.57}$$

$$\frac{\partial Q_i(x)}{\partial \delta_k} = |V_i||V_k||Y_{ik}|cos(\theta_{ik} + \delta_k - \delta_i)(i \neq k) \tag{2.58}$$

$$= -\sum_{k=1,k\neq i}^{n} |V_i||V_k||Y_{ik}|cos(\theta_{ik} + \delta_k - \delta_i)(i = k) \tag{2.59}$$

$$\frac{\partial Q_i(x)}{\partial |V|_k} = |V_i||Y_{ik}|sin(\theta_{ik} + \delta_k - \delta_i)(i \neq k) \tag{2.60}$$

$$= 2|V_i||Y_{ii}\ sin(\theta_{ii}) + \sum_{k=1,k\neq i}^{n} |V_k||Y_{ik}|sin(\theta_{ik} + \delta_k - \delta_i)(i = k) \tag{2.61}$$

An important observation can be made with respect to the elements of the Jacobian matrix . if there is no connection between i^{th} and k^{th} bus , then $Y_{ik} = 0$, and from (2.58), (2.59), (2.60) and (2.61) the elements of the Jacobian matrix corresponding to the respective buses are zero . hence like Y_{BUS} matrix, the jacobian matrix is also sparse.

$$H_{im} = \frac{\partial P_i}{\partial \delta_m} \tag{2.62}$$

$$N_{im} = \frac{\partial P_i}{\partial |V_m|} \tag{2.63}$$

$$J_{im} = \frac{\partial Q_i}{\partial \delta_m} \tag{2.64}$$

$$L_{im} = \frac{\partial P_i}{\partial |V_m|} \tag{2.65}$$

It is convenient for numerical solution to normalize the voltage corrections as $\frac{\partial P_i}{\partial |V_m|}|V_m|$, as a consequence of which the corresponding Jacobian elements become

$$N_{im} = \frac{\partial P_i}{\partial |V_m|}|V_m| \tag{2.66}$$

$$L_{im} = \frac{\partial Q_i}{\partial |V_m|}|V_m| \tag{2.67}$$

Expressions for the elements of the Jacobian of load flow are derived to be as follows :

Case 1 : (m = i)

$$H_{im} = L_{im} = a_m f_i - b_m e_i \tag{2.68}$$

$$N_{im} = -J_{im} = a_m e_i + b_m f_i \tag{2.69}$$

where

$$Y_{im} = G_{im} + jB_{im} \tag{2.70}$$

$$V_i = e_i + if_i \tag{2.71}$$

$$a_m + jb_m = (G_{im} + jB_{im})(e_m + if_m) \tag{2.72}$$

Case 2 : (m = i)

$$H_{ii} = -Q_i - B_{ii}|V_i|^2 \tag{2.73}$$

$$N_{ii} = P_i + G_{ii}|V_i|^2 \tag{2.74}$$

$$J_{ii} = P_i - G_{ii}|V_i|^2 \tag{2.75}$$

$$L_{ii} = Q_i - B_{ii}|V_i|^2 \tag{2.76}$$

2.3.2 Iterative Algorithm

The iterative algorithm for the solution of the load flow problem by NR method is as follows :

1. With the voltage and angle at slack bus fixed at $V_1 \angle\delta_1$ (= 1 $\angle 0^0$)$, we \; assume$ |V|,$\angle\delta$ at all PQ buses as 1 pu and zero and δ at all PV buses as zero. In the absence of any information flat voltage start is recommended .

2. In the r^{th} iteration , we have

$$P_i = \sum_{k=1}^{n} |V_i|^r |V_k|^r |Y_{ik}| cos(\theta_{ik} + \delta_k^r - \delta_i^r) \tag{2.77}$$

$$Q_i = -\sum_{k=1}^{n} |V_i|^r |V_k|^r |Y_{ik}| sin(\theta_{ik} + \delta_k^r - \delta_i^r) \tag{2.78}$$

Let

$$e_i^r = |V_i|^r cos\delta_i^r, \quad f_i^r = |V_i|^r sin\delta_i^r \tag{2.79}$$

$$G_{ik} = |Y_{ik}| cos\theta_{ik}, \quad B_{ik} = |Y_{ik}| sin\theta_{ik} \tag{2.80}$$

using (2.79), (2.80) in (2.77) and (2.78) we have

$$P_i^r = \sum_{k=1}^{n} (e_i^r(e_k^r G_{ik} - f_k^r B_{ik}) + f_i^r(f_k^r G_{ik} + e_k^r B_{ik})) \tag{2.81}$$

$$Q_i^r = \sum_{k=1}^{n} (f_i^r(e_k^r G_{ik} - f_k^r B_{ik}) - e_i^r(f_k^r G_{ik} + e_k^r B_{ik})), i = 1,2,...n \tag{2.82}$$

We next compute

$$\Delta P_i^r = P_i(\text{scheduled}) - P_i^r \quad \text{for PV and PQ buses} \tag{2.83}$$

$$\Delta Q_i^r = Q_i(\text{scheduled}) - Q_i^r \quad \text{for PQ buses} \tag{2.84}$$

If all the values of ΔP_i^r and ΔQ_i^r are less than the prescribed tolerance we stop the iteration , calculate P_1 and Q_1 and print the entire solution including line flows .

3. If the convergence criterion is not satisfied , we evaluate the Jacobian using (2.68) , (2.69) ,(2.73) ,(2.74), (2.75)and (2.76) .
4. We solve Eq () for correction of voltage magnitude and $\Delta|V|^r$ and angle $\Delta\delta^r$.
5. Next we update the voltage magnitude and angles ,

$$|V|^{(r+1)} = |V|^r + |\Delta V|^r \tag{2.85}$$

$$\delta^{(r+1)} = \delta^r + \Delta\delta^r \tag{2.86}$$

Then we return to step 2 .

It is to be noted that :

(a) In step (2) , if there are limits on the controllable Q sources at PV buses , Q is computed each time using Eq (2.83) , and if it violates the limits , it is made equal to the limiting value and the corresponding PV bus is made PQ bus in that iteration . If in the subsequent computation , Q comes within the prescribed limits , the bus is switched back to PV bus . Thus if $|Q_i|^r \geq Q_{i,max}$, t we let $|Q_i| = Q_{i,max}$ and continue.
(b) Similarly, if there are any voltage limits on PQ bus and if any of these limits is violated , the corresponding PQ bus is ade a PV bus in that iteration with voltage fixed at limiting value.

2.4 Summary

In this chapter the load flow analysis has been introduced and discussed in detail . We have also looked at the Newton - Raphson method which is one of the most important methods available to carry out the load flow analysis .

CHAPTER 3

SVC and TCSC

3.1 Static Var Compensator (SVC)

The IEEE definition of the SVC is as follows: *A shunt connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage)*

In other words, an SVC is a static var generator whose output is varied in order to maintain or control the specific parameters of an electric power system. SVC's are primarily used in power systems for voltage control or for improving system stability.

Static Var Compensators (SVCs) are used primarily in power systems for voltage control as either an end in itself or a means of achieving other objectives, such as system stabilization.

3.1.1 Operation of SVC

The Static Var Compensator(SVC) is a first generation variable impedence type shunt FACTS controllers . Fixed-Capacitor - Thyristor controlled reactor (FC - TCR) and Thyristor Switched Capacitor-Thyristor controlled reactor (TSC-TCR) are the two main types of configurations to represent SVC .The main principle of operation of TCR is explained as follows :

Fig. 3.1 shows the schematic diagram of TCR . It consists of a reactor with inductance L , and a bidirectional thyristor valve formed by the thyristors T1 and T2 . Thyristor valve can be brought in to conduction by simultaneous application of gate pulses to the thyristors T1 and T2 . $v(t)$ is the voltage applied across TCR , $i(t)$ is the current passing through the circuit and α is the delay angle . The voltage , $v(t)$ and current , $i(t) = i_L(t)$ waveforms are shown in the Fig. 3.2 . The valve will automatically come to blocking

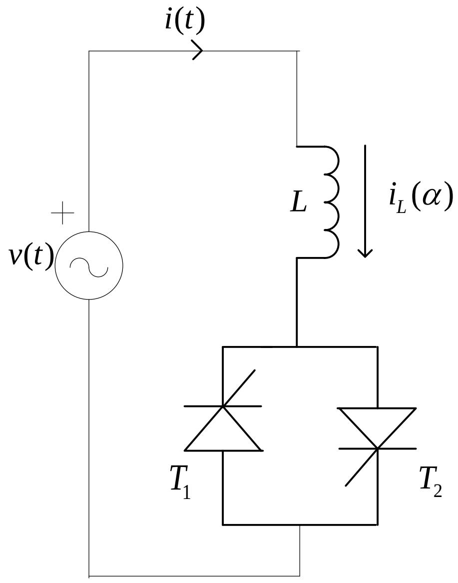

Fig. 3.1: Schematic diagram of TCR

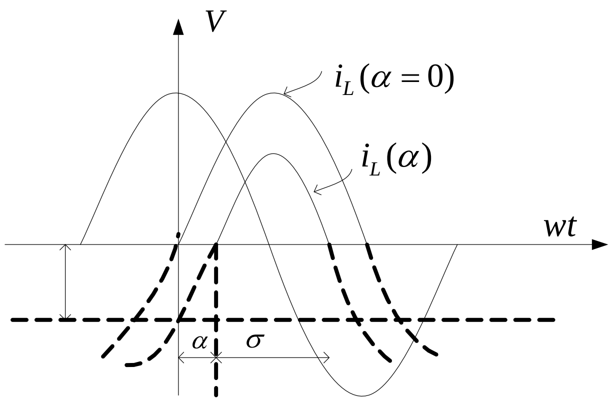

Fig. 3.2: Firing angle delay control of TCR

mode immediately after $i(t)$ crosses zero , unless the gate signal is applied . The current in the reactor can be controlled from maximum (thyristor valve closed) to zero (thyristor valve open) by the method of firing angle (α) control as shown in Fig. 3.2 . The closing of the thyristor valve is delayed with respect to the peak of the applied voltage in each half cycle , and thus the duration of the conduction intervals are controlled . Thus the total inductive reactance offered by the TCR varies according to the control strategies of the thyristor valve .

The value of the reactive susceptance of TCR, $B_{TCR}(\alpha)$ as a function of delay angle α , at fundamental frequency is given as ,

$$B_{TCR}(\alpha) = \frac{V_m}{\omega L}(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}sin2\alpha) \tag{3.1}$$

where , L is the inductance of the thyristor controlled reactor and ω is the angular frequency of the applied voltage .

Lets look at the FC-TCR type SVC connected at a bus . The SVC consists of fixed capacitor and a TCR connected in parallel and is connected in shunt with the bus .

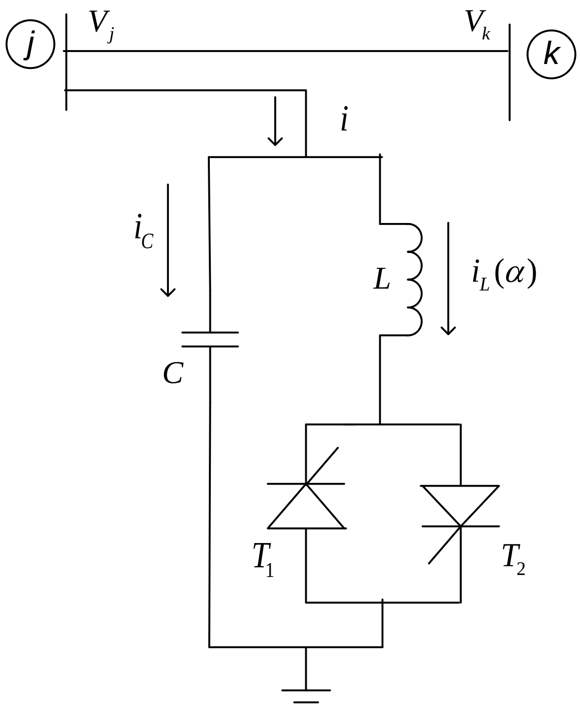

Fig. 3.3: Schematic diagram of SVC

V_j , V_k are the bus voltages at i , i_C, $i_L(\alpha)$ represent the currents passing through the circuit , fixed capacitor and TCR respectively . The value of admittance of B_{SVC} at fundamental frequency is given by [3]:

$$B_{SVC} = \frac{X_C(2\rho + sin(2\alpha) - \pi X_L}{\pi X_C X_L} \tag{3.2}$$

where X_C, X_L are the capacitive and inductive reactances respectively and ρ , α are the conduction and firing angle of the thyristors.

3.1.2 SVC in load flow studies

In its simplest form, the SVC consists of a TCR in parallel with a bank of capacitors. From the operational point of view, the SVC behaves like a shunt-connected variable reactance, which either generates or absorbs reactive power in order to regulate the voltage magnitude at the point of connection to the AC network. It is used extensively to provide fast reactive power and voltage regulation support. The firing angle control of the thyristor enables the SVC to have almost instantaneous speed of response.

The aim here is to maintain the voltage of a specific bus at a particular value and see the effect on the Power losses in the transmission line .

3.1.3 Shunt variable susceptance model

In practice the SVC can be seen as an adjustable reactance with either firing-angle limits or reactance limits .The equivalent circuit shown in Fig. 3.4 is used to derive the SVC nonlinear power equations and the linearised equations required by Newton - Raphson method [4][5] . With reference to Fig. 3.2, the current drawn by the SVC is :

$$I_{svc} = jB_{svc}V_k \tag{3.3}$$

And the reactive power supplied by the SVC, which is also the reactive power injected at bus k, is

$$Q_{svc} = Q_k = -V_k^2 B_{svc} \tag{3.4}$$

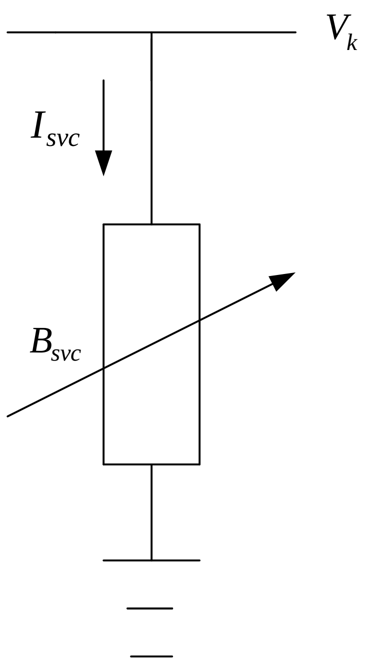

Fig. 3.4: Variable shunt susceptance model

The SVC is included in load flow by declaring the bus at which SVC is connected as a PV BUS with required voltage magnitude and zero real power generation.

3.2 Thyristor Controlled Series Compensator (TCSC)

3.2.1 Operation of the TCSC

A TCSC is a series-controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range.

Fig. 3.5 represents the basic TCSC connected in series with a transmission line connected between two buses . j and k . R and X are the resistance an reactance of the transmission line [1] [3] .

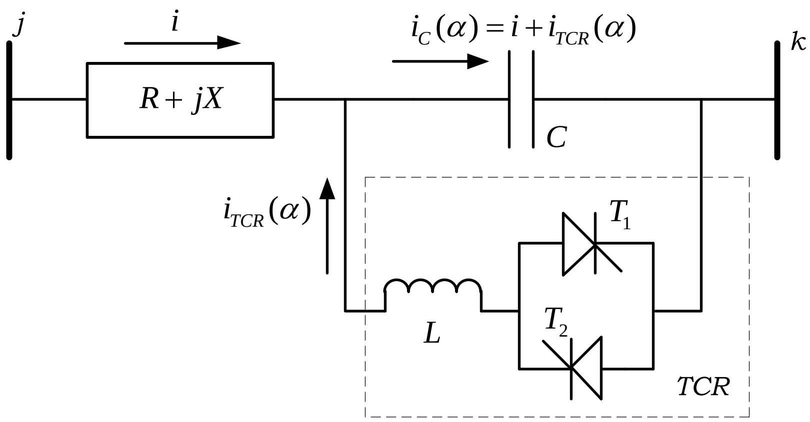

Fig. 3.5: Schematic Diagram of TCSC

TCSC consists of the series compensated capacitor C shunted by a TCR . The currents passing through the capacitor and TCR in terms of delay angle (α) are represented by $I_c(\alpha)$ and $i_{TCR}(\alpha)$, respectively and i is the current in the transmission line . The TCR acts as a continuously variable reactive impedence at fundamental system frequency, and controlled by the delay angle α as explained earlier . Basically TCSC operates in three different modes .:

- Bypassed mode

- Thyristor valve blocked mode
- vernier mode

Blocking mode of operation

This mode is operated when thyristor valve is not triggred and the thyristors are kept in non-conducting state. The line current passes only through capacitor. In this mode, the TCSC performs like a fixed series capacitor with boost factor equal to one. The resulting voltage in the steady state across the TCSC is given by:

$$V_{TCSC} = jX_C I \qquad X_C < 0 \tag{3.5}$$

Bypass mode of operation

If the thyristor valve is triggered continuously the valve stays conducting all the time and the TCSC behaves like a parallel connection of the series capacitor with inductor in the thyristor valve. The resulting voltage in the steady state across the TCSC is given by:

$$V_{TCSC} = \frac{jX_L X_C}{X_L + X_C} I \qquad X_C < 0 \tag{3.6}$$

This voltage is inductive and the boost factor is negative. Therefore the bypass mode is utilized as a means to reduce the capacitor stress during faults.

Vernier mode of operation

If the thyristor valve is triggered with appropriate time gate pulse, the valve stays conducting for some time and for remaining time it will remain in non-conducting state. Here X_{TCR} is varied and hence X_{TCSC} also varies with its value depending on the gate pulse applied. The resulting voltage in the steady state across the TCSC is given by:

$$V_{TCSC} = \frac{jX_{TCR} X_C}{X_{TCR} + X_C} I \qquad X_C < 0 \tag{3.7}$$

3.2.2 TCSC in Load Flow Studies

The effective transmission line reacatance X_{eff} after including the TCSC is given in the following equations,

$$X_{eff} = X - X_{TCSC} \tag{3.8}$$

or

$$X_{eff} = (1-k)X \tag{3.9}$$

where k is the degree of compensation ,

$$k = \frac{X_{TCSC}}{X} \tag{3.10}$$

and X is the reactance of the transmission line .

The real power P transmitted across the line is given by :

$$P = \frac{V^2}{X} sin\delta \tag{3.11}$$

As we can see , the Real Power transmitted across the line is depenedent on the amount of TCSC compensation . In this project a 50% compensated line is considered . The effect of TCSC is included in admittance matrix.

3.3 Summary

In this chapter we have looked at the working of two types of FACTS devices., SVC and TCSC and the role they play in load flow studies .

CHAPTER 4

SIMULATION RESULTS

The Newton - Raphson method was applied to IEEE 6-Bus and 30-Bus systems.

4.1 IEEE 6-Bus System

4.1.1 Without any FACTS devices

In IEEE 6-Bus system there are 2 PV and 3 PQ buses .Bus 1 is declared as slack bus . The voltage magnitude and angles obtained after analysis with Newton - Raphson method is given in Table 4.1 . The line flows are given in Table 4.2.

Table 4.1: Bus Voltage magnitudes and angles of a IEEE 6-BUS system

Bus Number	Voltage(pu)	Angle(Degrees)
1	1.05	0
2	1.05	-3.6656
3	1.07	-4.2673
4	0.9895	-4.1935
5	0.9863	-5.2856
6	1.0052	-5.9503

Table 4.2: Line flows of a IEEE 6-BUS system

From Bus	To Bus	P (MW)	Q (MVAr)	Line Loss (MW)	Line Loss (MVAr)
1	2	28.646	-13.195	0.902	1.804
1	4	43.554	22.268	1.085	4.341
1	5	35.607	14.278	1.068	4.005
2	3	2.927	-8.961	0.04	0.201
2	4	33.088	47.032	1.5	2.999
2	5	15.516	17.271	0.489	1.467
2	6	26.212	14.786	0.575	1.643
3	5	19.082	25.715	1.075	2.329
3	6	43.805	61.081	0.987	4.935
4	5	4.057	-1.187	0.036	0.073
5	6	1.594	-6.719	0.049	0.147

The total real power loss is 7.806 MW and the total reactive power loss is 23.944 MVAr.

4.1.2 With SVC

The objective here is to increase the voltage magnitude at Bus 5 to 1 pu by connecting a SVC to it . Bus 5 is declared as PV bus . Voltage magnitude is then taken as 1 pu and $P_{G5} = 0$. Table 4.3 shows the voltage magnitude and angles of IEEE 6-Bus system with SVC . It can be observed that voltage magnitude at Bus 5 is 1 pu.
The line power flows are given in Table 4.4.

Table 4.3: Bus Voltage magnitudes and angles of a IEEE 6-BUS system with SVC

Bus Number	Voltage(pu)	Angle(Degrees)
1	1.05	0
2	1.05	-3.5924
3	1.07	-4.1685
4	0.9915	-4.1682
5	1	-45.597
6	1.0078	-5.8905

Table 4.4: Line flows of a IEEE 6-BUS system with SVC

From Bus	To Bus	P (MW)	Q (MVAr)	Line Loss (MW)	Line Loss (MVAr)
1	2	28.065	-12.949	0.867	1.733
1	4	43.159	21.29	1.05	4.201
1	5	35.842	9.527	0.998	3.743
2	3	2.734	-8.924	0.04	0.198
2	4	32.955	44.982	1.41	2.82
2	5	15.57	12.493	0.361	1.084
2	6	25.94	13.496	0.543	1.551
3	5	18.645	20.304	0.796	1.726
3	6	44.05	58.219	0.931	4.655
4	5	3.653	-3.868	0.058	0.115
5	6	1.496	-3.09	0.012	0.035

The real power loss is 7.066 MW which is lower when compared to the case without SVC .

4.1.3 With TCSC

TCSC has been placed between bus 4 and 5 . A 50% line compensation is considered . The effect of TCSC is included in the admittance matrix. Table 4.5 shows the volage magnitudes and bus angles of the IEEE 30-Bus system with TCSC. The line flows are given in Table 4.6 .

Table 4.5: Bus Voltage magnitudes and angles of a IEEE 6-BUS system with TCSC

Bus Number	Voltage(pu)	Angle(Degrees)
1	1.05	0
2	1.05	-3.6613
3	1.07	-4.2383
4	0.9902	-4.2581
5	0.9853	-5.2012
6	1.005	-5.9195

Table 4.6: Line flows of a IEEE 6-BUS system with TCSC

From Bus	To Bus	P (MW)	Q (MVAr)	Line Loss (MW)	Line Loss (MVAr)
1	2	28.611	-13.181	0.9	1.8
1	4	44.049	21.794	1.095	4.382
1	5	35.176	14.675	1.054	3.953
2	3	2.741	-8.925	0.04	0.198
2	4	33.784	45.906	1.473	2.947
2	5	15.169	17.703	0.493	1.479
2	6	26.018	14.936	0.571	1.633
3	5	18.898	26.181	1.093	2.368
3	6	43.803	61.268	0.991	4.955
4	5	5.265	-2.764	0.072	0.072
5	6	1.796	-7.029	0.054	0.163

By comparing Tables 4.6 and 4.2 ,We can see that the Real power flow between buses 4 and 5 has increased due to the placement of the TCSC .

The real power loss is 7.837 MW and the reactive power loss is 23.947 MVAr which is higher compared to the case without the TCSC . This can happen sometimes when the TCSC is not optimally placed.

4.2 IEEE 30-Bus Sysytem

4.2.1 Without any FACTS devices

In IEEE 30-Bus system there are 5 PV and 24 PQ buses .Bus 1 is declared as slack bus . The voltage magnitude and angles obtained after analysis with Newton - Raphson method is given in Table 4.7 . The line flows are given in Table 4.8.

Table 4.7: Bus Voltage magnitudes and angles of a IEEE 30-BUS system

Bus Number	Voltage(pu)	Angle(Degrees)
1	1.06	0
2	1.043	-5.342
3	1.0271	-7.612
4	1.0197	-9.3758
5	1.01	-14.1355
6	1.0151	-11.1304
7	1.0053	-12.8894
8	1.01	-11.7947
9	1.0343	-14.4305
10	1.0206	-16.1657
11	1.082	-14.4305
12	1.0289	-15.3358
13	1.071	-15.3358

Continued on next page

Table 4.7 – Continued

Bus Number	Voltage(pu)	Angle(Degrees)
14	1.0023	-15.8098
15	1.0079	-16.307
16	1.018	-15.9778
17	1.0143	-16.3281
18	0.9999	-16.9913
19	0.9983	-17.1952
20	1.0031	-16.9988
21	1.0039	-16.6906
22	1.0109	-16.5085
23	1.0033	-16.6929
24	0.9977	-16.8686
25	0.9921	-16.3925
26	0.9739	-16.8342
27	0.9973	-15.8258
28	1.0134	-11.7773
29	0.9769	-17.1219
30	0.9651	-18.0539

Table 4.8: Line flows of a IEEE 30-BUS system

From Bus	To Bus	P (MW)	Q (MVAr)	Line Loss (MW)	Line Loss (MVAr)
1	2	172.975	-18.068	5.169	15.479
1	3	88.067	2.796	3.123	11.415
2	4	43.481	1.25	0.991	3.021
3	4	82.544	-7.223	0.859	2.466
2	5	82.173	4.042	2.937	12.339
2	6	60.452	-0.348	1.952	5.923
4	6	74.021	-8.795	0.636	2.212

Continued on next page

Table 4.8 – Continued

From Bus	To Bus	P (MW)	Q (MVAr)	Line Loss (MW)	Line Loss (MVAr)
5	7	-14.963	10.266	0.148	0.374
6	7	38.292	0.285	0.38	1.167
6	8	29.46	4.049	0.103	0.36
6	9	29.057	-8.535	0	1.851
6	10	16.354	-0.283	0	1.444
9	11	0	-23.722	0	1.094
9	10	29.057	13.336	0	1.051
4	12	42.553	-1.448	0	4.463
12	13	0	-30.955	0	1.267
12	14	6.892	7.397	0.119	0.247
12	15	17.439	7.799	0.228	0.45
12	16	7.022	2.348	0.049	0.103
14	15	0.573	-3.45	0.027	0.024
16	17	3.473	0.445	0.01	0.023
15	18	5.919	0.837	0.038	0.077
18	19	2.681	-0.14	0.005	0.009
19	20	-6.823	-3.549	0.02	0.04
10	20	9.137	4.498	0.093	0.208
10	17	5.555	5.427	0.019	0.049
10	21	18.991	13.9	0.185	0.398
10	22	5.928	3.733	0.034	0.071
21	23	1.306	2.302	0.001	0.002
15	23	3.638	0.539	0.013	0.027
22	24	5.894	3.662	0.054	0.084
23	24	1.729	1.212	0.006	0.012
24	25	-1.137	2.378	0.013	0.023
25	26	3.547	2.37	0.047	0.07
25	27	-4.697	-0.015	0.025	0.047
28	27	18.019	4.763	0	1.339

Continued on next page

Table 4.8 – Continued

From Bus	To Bus	P (MW)	Q (MVAr)	Line Loss (MW)	Line Loss (MVAr)
27	29	6.197	1.682	0.091	0.172
27	30	7.101	1.679	0.171	0.323
29	30	3.706	0.61	0.035	0.067
8	28	-0.643	-1.53	0.002	0.005
6	28	18.722	-2.368	0.058	0.207

The real power loss is 17.642 MW and the reactive power loss is 70.005 MVAr.

4.2.2 With SVC

The objective here is to increase the voltage magnitude at Bus 19 to 1 pu by connecting a SVC to it . Bus 19 is declared as PV bus . Voltage magnitude is then taken as 1 pu and $P_{G19} = 0$. Table 4.9 shows the voltage magnitude and angles of IEEE 6-Bus system with SVC . It can be observed that voltage magnitude at Bus 19 is 1 pu.
The line power flows are given in Table 4.10.

Table 4.9: Bus Voltage magnitudes and angles of a IEEE 30-BUS system with SVC

Bus Number	Voltage(pu)	Angle(Degrees)
1	1.06	0
2	1.043	-5.3417
3	1.0272	-7.6125
4	1.0198	-9.3763
5	1.01	-14.1348
6	1.0152	-11.1308
7	1.0053	-12.8893
8	1.01	-11.794
9	1.0346	-14.4313

Continued on next page

Table 4.9 – Continued

Bus Number	Voltage(pu)	Angle(Degrees)
10	1.0211	-16.1659
11	1.082	-14.4313
12	1.0292	-15.3314
13	1.071	-15.3314
14	1.0028	-15.8072
15	1.0085	-16.3096
16	1.0184	-15.9753
17	1.0149	-16.3274
18	1.0012	-17.0096
19	1	-17.2233
20	1.0045	-17.0194
21	1.0045	-16.6906
22	1.0114	-16.5082
23	1.0038	-16.693
24	0.9982	-16.8675
25	0.9924	-16.3895
26	0.9743	-16.8309
27	0.9976	-15.8219
28	1.0135	-11.7775
29	0.9772	-17.1174
30	0.9654	-18.0489

Table 4.10: Line flows of a IEEE 30-BUS system with SVC

From Bus	To Bus	P (MW)	Q (MVAr)	Line Loss (MW)	Line Loss (MVAr)
1	2	172.966	-18.066	5.168	15.477
1	3	88.067	2.757	3.123	11.414
2	4	43.478	1.205	0.991	3.021
3	4	82.544	-7.262	0.859	2.466
2	5	82.169	4.042	2.937	12.337
2	6	60.451	-0.387	1.952	5.922
4	6	74.037	-8.774	0.636	2.213
5	7	-14.967	10.233	0.148	0.374
6	7	38.295	0.318	0.38	1.167
6	8	29.457	4.213	0.103	0.361
6	9	29.071	-8.646	0	1.857
6	10	16.363	-0.375	0	1.445
9	11	0	-23.582	0	1.081
9	10	29.071	13.08	0	1.044
4	12	42.535	-1.552	0	4.46
12	13	0	-30.723	0	1.248
12	14	6.88	7.34	0.118	0.244
12	15	17.435	7.575	0.226	0.445
12	16	7.02	2.297	0.049	0.102
14	15	0.562	-3.505	0.028	0.025
16	17	3.472	0.395	0.01	0.023
15	18	5.909	0.535	0.037	0.076
18	19	2.672	-0.44	0.005	0.009
19	20	-6.833	-3.15	0.019	0.038
10	20	9.142	4.089	0.09	0.201
10	17	5.557	5.477	0.019	0.049
10	21	18.999	13.898	0.185	0.398
10	22	5.936	3.751	0.034	0.071

Continued on next page

Table 4.10 – Continued

From Bus	To Bus	P (MW)	Q (MVAr)	Line Loss (MW)	Line Loss (MVAr)
21	23	1.314	2.3	0.001	0.002
15	23	3.634	0.565	0.013	0.027
22	24	5.902	3.681	0.054	0.085
23	24	1.734	1.236	0.006	0.012
24	25	-1.125	2.42	0.013	0.024
25	26	3.547	2.37	0.047	0.07
25	27	-4.685	0.026	0.024	0.047
28	27	18.007	4.718	0	1.336
27	29	6.197	1.682	0.091	0.172
27	30	7.101	1.679	0.171	0.322
29	30	3.706	0.61	0.035	0.067
8	28	-0.646	-1.567	0.002	0.006
6	28	18.713	-2.378	0.058	0.207

The total real power loss is 17.633 MW which is lower compared to the case without SVC.

4.2.3 With TCSC

TCSC has been placed between bus 27 and 30 . A 50% line compensation is considered . The effect of TCSC is included in the admittance matrix. Table 4.11 shows the volage magnitudes and bus angles of the IEEE 30-Bus system with TCSC. The line flows are given in Table 4.12 .

Table 4.11: Bus Voltage magnitudes and angles of a IEEE 30-BUS system with TCSC

Bus Number	Voltage(pu)	Angle(Degrees)
1	1.06	0
2	1.043	-5.3424
3	1.0272	-7.6127
4	1.0197	-9.3767
5	1.01	-14.136
6	1.0151	-11.1317
7	1.0053	-12.8904
8	1.01	-11.7958
9	1.0343	-14.4309
10	1.0207	-16.1655
11	1.082	-14.4309
12	1.0289	-15.3353
13	1.071	-15.3353
14	1.0023	-15.8092
15	1.008	-16.3067
16	1.018	-15.9774
17	1.0144	-16.3279
18	0.9999	-16.9909
19	0.9984	-17.1949
20	1.0032	-16.9985
21	1.004	-16.6905
22	1.011	-16.5087
23	1.0033	-16.6929
24	0.9979	-16.8698
25	0.9925	-16.3978
26	0.9744	-16.8392
27	0.9979	-15.8338
28	1.0135	-11.7804
29	0.9785	-16.7126

Continued on next page

Table 4.11 – Continued

Bus Number	Voltage(pu)	Angle(Degrees)
30	0.9676	-17.1742

Table 4.12: Line flows of a IEEE 30-BUS system with TCSC

From Bus	To Bus	P (MW)	Q (MVAr)	Line Loss (MW)	Line Loss (MVAr)
1	2	172.986	-18.071	5.169	15.481
1	3	88.074	2.785	3.124	11.416
2	4	43.484	1.238	0.992	3.022
3	4	82.55	-7.236	0.859	2.467
2	5	82.175	4.042	2.937	12.339
2	6	60.458	-0.364	1.952	5.924
4	6	74.039	-8.814	0.636	2.214
5	7	-14.962	10.253	0.148	0.374
6	7	38.29	0.299	0.38	1.167
6	8	29.466	4.109	0.103	0.361
6	9	29.051	-8.545	0	1.851
6	10	16.35	-0.293	0	1.443
9	11	0	-23.701	0	1.092
9	10	29.051	13.305	0	1.05
4	12	42.545	-1.455	0	4.462
12	13	0	-30.932	0	1.265
12	14	6.89	7.393	0.119	0.247
12	15	17.435	7.783	0.228	0.449
12	16	7.02	2.339	0.049	0.103
14	15	0.571	-3.454	0.027	0.024
16	17	3.471	0.436	0.01	0.023
15	18	5.918	0.834	0.038	0.077
18	19	2.68	-0.143	0.005	0.009

Continued on next page

Table 4.12 – Continued

From Bus	To Bus	P (MW)	Q (MVAr)	Line Loss (MW)	Line Loss (MVAr)
19	20	-6.824	-3.552	0.02	0.04
10	20	9.138	4.501	0.093	0.208
10	17	5.557	5.435	0.019	0.049
10	21	18.987	13.883	0.185	0.398
10	22	5.919	3.701	0.034	0.07
21	23	1.302	2.285	0.001	0.002
15	23	3.633	0.522	0.013	0.027
22	24	5.885	3.631	0.054	0.084
23	24	1.721	1.178	0.006	0.012
24	25	-1.153	2.314	0.013	0.022
25	26	3.547	2.37	0.047	0.07
25	27	-4.713	-0.078	0.025	0.047
28	27	18.053	4.634	0	1.339
27	29	4.751	2.163	0.06	0.114
27	30	8.565	1.007	0.239	0.225
29	30	2.291	1.149	0.016	0.031
8	28	-0.637	-1.57	0.002	0.006
6	28	18.751	-2.458	0.059	0.208

By comparing Tables 4.12 and 4.8 ,We can see that the Real power flow between buses 27 and 30 has increased due to the placement of the TCSC .

The real power loss is 17.660 MW which is higher compared to the case without the TCSC . This can happen sometimes when the TCSC is not optimally placed.

4.3 Summary

In this chapter , Load Flow Analysis using Newton - Raphson method had been applied to IEEE 6 BUS system and IEEE 30 BUS system . The load flow analysis was also carried out by introducing SVC/TCSC in the respective systems .

CHAPTER 5

CONCLUSIONS

Conclusion :

Power flow or load-flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. The principal information obtained from the power flow study is the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line.

A MATLAB program has been developed for load flow analysis using Newton - Raphson method . The load flow analysis has been done on IEEE 6-Bus and IEEE-30 bus systems. From the results we see that :

- The SVC not only helps in maintaining the required voltage at a bus but also helps in reducing the power loss in the transmission line system .
- Thyristor-Controlled Series Capacitor (TCSC) can control the active power flow between buses. With the use of TCSC, a specified amount of power can be transferred from one bus to other as TCSC does not consume or generate active power.

APPENDIX A

IEEE 6-BUS SYSTEM DATA

The single line diagram of the stranded IEEE 6-BUS system is shown in Fig. A.1. It consists of 3 generator buses, 3 load buses, 11 transmission lines and no tap changing transformers . The bus data and line data are given in tables A.1 and A.2, respectively. The values given in tables are the $p.u$ values. In bus data table A.1 Q_{min} and Q_{max} are the minimum and maximum reactive power limits respectively, that can be supplied by the corresponding generator. The base power is 100 MVA .

A.1 Single Line Diagram of IEEE 6-BUS System

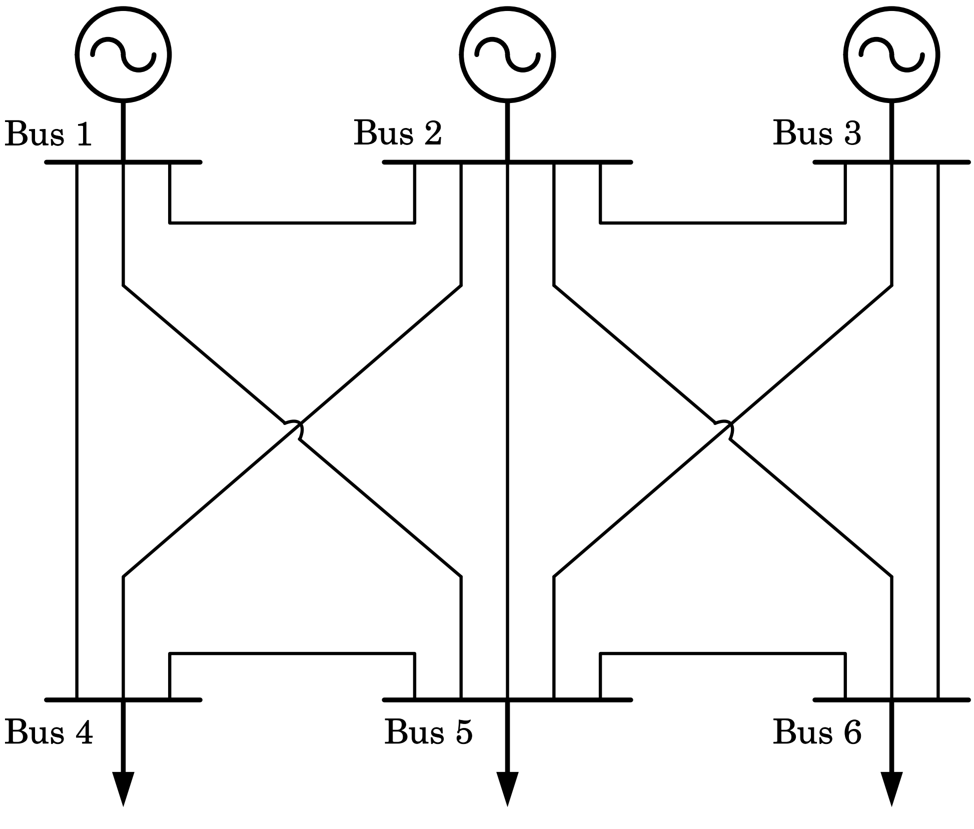

Fig. A.1: Single Line Diagram of IEEE 6-BUS System

A.2 Bus Data

Table A.1: Bus data for IEEE 6-BUS system

Bus number	Type	P_g	Q_g	P_d	Q_d	V_m	V_{min}	V_{max}
1	slack	0	0	0	0	1.05	0.9	1.1
2	PV	0.5	0	0	0	1.05	0.9	1.1
3	PV	0.6	0	0	0	1.07	0.9	1.1
4	PQ	0	0	0.7	0.7	1	0.9	1.1
5	PQ	0	0	0.7	0.7	1	0.9	1.1
6	PQ	0	0	0.7	0.7	1	0.9	1.1

A.3 Line Data

Table A.2: Line data for IEEE 6-BUS system

From Bus	To Bus	R	X	B
1	2	0.10	0.20	0.02
1	4	0.05	0.20	0.02
1	5	0.08	0.30	0.03
2	3	0.05	0.25	0.03
2	4	0.05	0.10	0.01
2	5	0.10	0.30	0.02
2	6	0.07	0.20	0.025
3	5	0.12	0.26	0.025
3	6	0.02	0.10	0.01
4	5	0.20	0.40	0.04
5	6	0.10	0.30	0.03

APPENDIX B

IEEE 30-BUS SYSTEM DATA

The single line diagram of the stranded IEEE 30-Bus system is shown in Fig. B.1. It consists of 6 generator buses, 24 load buses, 41 transmission lines and 4 tap changing transformers.The bust data and line data are given in tables B.1 and B.2, respectively. The values given in tables are the pu values. Here in bus data table B.1 Q_{min} and Q_{max} are the minimum and maximum reactive power limits respectively, that can be generated by the corresponding generator. The base power is 100 MVA .

B.1 Single Line Diagram of IEEE 30-BUS System

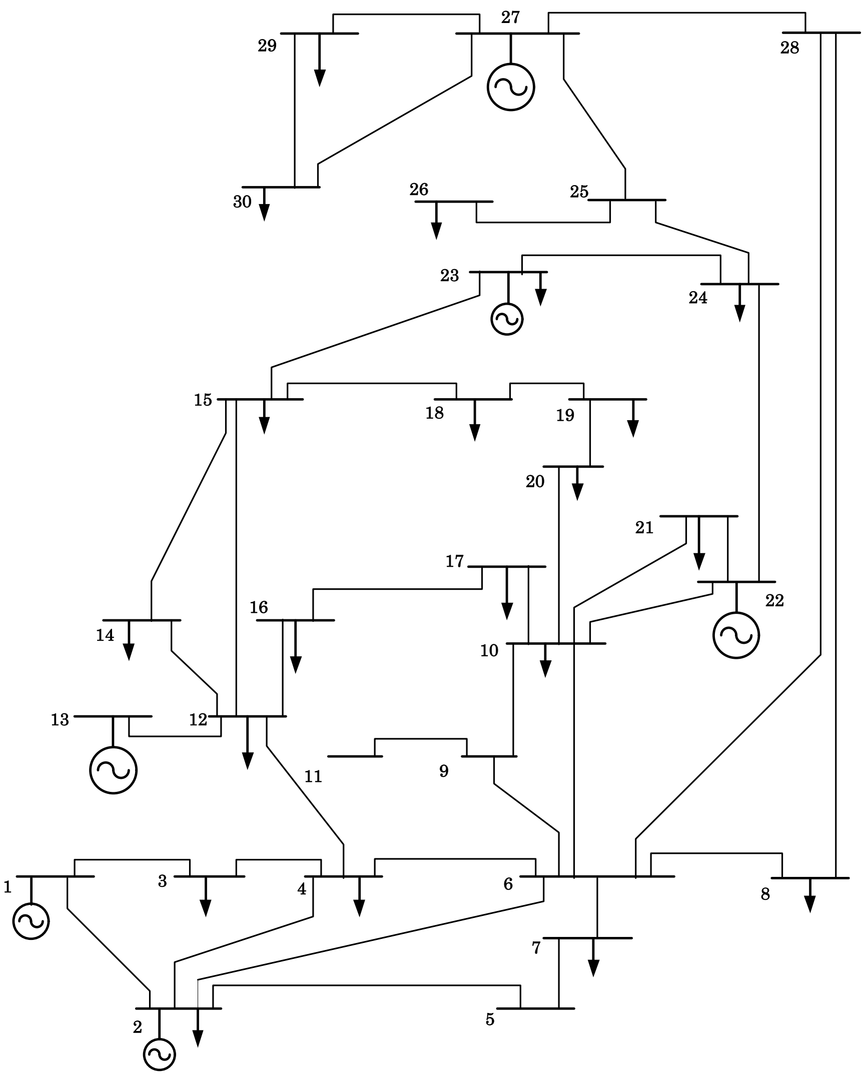

Fig. B.1: Single Line Diagram of IEEE 30-BUS System

B.2 Bus Data

Table B.1: Bus data for IEEE 30-BUS system

Bus number	Type	P_g	Q_g	P_d	Q_d	V_m	Q_{min}	Q_{max}	V_{min}	V_{max}
1	slack	0	0	0	0	1.06	0	0	0.9	1.1
2	PV	0.4	0	0.217	0.127	1.045	-0.4	0.5	0.9	1.1
3	PV	0.2	0	0	0.3	1.01	-0.1	0.4	0.9	1.1
4	PV	0	0	0.3	0	1.082	-0.06	0.24	0.9	1.1
5	PV	0	0	0.942	0.19	1.01	-0.4	0.4	0.9	1.1
6	PV	0	0	0	0	1.071	-0.06	0.24	0.9	1.1
7	PQ	0	0	0	0	1	0	0	0.9	1.1
8	PQ	0	0	0.058	0.02	1	0	0	0.9	1.1
9	PQ	0	0	0.112	0.075	1	0	0	0.9	1.1
10	PQ	0	0	0	0	1	0	0	0.9	1.1
11	PQ	0	0	0.076	0.016	1	0	0	0.9	1.1
12	PQ	0	0	0.228	0.109	1	0	0	0.9	1.1
13	PQ	0	0	0	0	1	0	0	0.9	1.1
14	PQ	0	0	0.062	0.016	1	0	0	0.9	1.1
15	PQ	0	0	0.082	0.025	1	0	0	0.9	1.1
16	PQ	0	0	0.035	0.018	1	0	0	0.9	1.1
17	PQ	0	0	0.09	0.058	1	0	0	0.9	1.1
18	PQ	0	0	0.032	0.009	1	0	0	0.9	1.1
19	PQ	0	0	0.095	0.034	1	0	0	0.9	1.1
20	PQ	0	0	0.022	0.007	1	0	0	0.9	1.1
21	PQ	0	0	0.175	0.112	1	0	0	0.9	1.1
22	PQ	0	0	0	0	1	0	0	0.9	1.1
23	PQ	0	0	0.032	0.016	1	0	0	0.9	1.1
24	PQ	0	0	0.087	0.067	1	0	0	0.9	1.1
25	PQ	0	0	0	0	1	0	0	0.9	1.1
26	PQ	0	0	0.035	0.023	1	0	0	0.9	1.1
27	PQ	0	0	0.024	0	1	0	0	0.9	1.1
28	PQ	0	0	0	0	1	0	0	0.9	1.1
29	PQ	0	0	0.024	0.009	1	0	0	0.9	1.1
30	PQ	0	0	0.106	0.019	1	0	0	0.9	1.1

B.3 Line Data

Table B.2: Line data for IEEE 30-BUS system

From Bus	To Bus	R	X	B
1	2	0.0192	0.0575	0.0264
1	3	0.0452	0.1652	0.0204

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Table B.2 – Continued

From Bus	To Bus	*R*	*X*	*B*
2	4	0.057	0.1737	0.0184
3	4	0.0132	0.0379	0.0042
2	5	0.0472	0.1983	0.0209
2	6	0.0581	0.1763	0.0187
4	6	0.0119	0.0414	0.0045
5	7	0.046	0.116	0.0102
6	7	0.0267	0.082	0.0085
6	8	0.012	0.042	0.0045
6	9	0	0.208	0
6	10	0	0.556	0
9	11	0	0.208	0
9	10	0	0.11	0
4	12	0	0.256	0
12	13	0	0.14	0
12	14	0.1231	0.2559	0
12	15	0.0662	0.1304	0
12	16	0.0945	0.1987	0
14	15	0.221	0.1997	0
16	17	0.0824	0.1923	0
15	18	0.1073	0.2185	0
18	19	0.0639	0.1292	0
19	20	0.034	0.068	0
10	20	0.0936	0.209	0
10	17	0.0324	0.0845	0
10	21	0.0348	0.0749	0
10	22	0.0727	0.1499	0
21	23	0.0116	0.0236	0
15	23	0.1	0.202	0
22	24	0.115	0.179	0
23	24	0.132	0.27	0
24	25	0.1885	0.3292	0
25	26	0.2544	0.38	0
25	27	0.1093	0.2087	0
28	27	0	0.396	0
27	29	0.2198	0.4153	0
27	30	0.3202	0.6027	0
29	30	0.2399	0.4533	0
8	28	0.0636	0.2	0.0214
6	28	0.0169	0.0599	0.065

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