Synchro-Phasor Based Voltage Stability Analysis of Electrical Power System

Major Project Report

Submitted in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING
(ELECTRICAL POWER SYSTEMS)

By

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Undertaking For Originality of the Work

I, **Darshan B Mehta** (Roll No.14MEEE09), give undertaking that the Major Project entitled **"Synchro-Phasor Based Voltage Stability Analysis of Electrical Power System"** submitted by me, towards the partial fulfillment of the requirement for the degree of Master of Technology in Electrical Engineering (Energy System), under Institute of Technology, Nirma University, Ahmedabad is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in event of any similarity found subsequently with any published work or any Dissertation work elsewhere; it will result in severe disciplinary action.

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CERTIFICATE

This is to certify that the Major Project Report entitled **" Synchro-Phasor based voltage stability analysis of electrical power system"** submitted by **Mr. Darshan B. Mehta (14MEEE09)**, towards the partial fulfillment of the requirements for degree of Master of Technology (Electrical Engineering) in the field of Power Systems of Nirma University is the record of work carried out by him under my supervision and guidance. The work submitted has in my opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of my knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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- Darshan B. Mehta

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Abstract

With the growth in generation sector and demand electrical transmission network systems have to continuously being operated in the stressed condition, which lead this to near its stability limit. Under such condition if the reactive power reserves operate inadequately then it will initiate sequence of points of voltage instability and can lead the system towards voltage collapse. In this condition by usage of synchrophasor based measurement of power system lead to continuously updated state of power system. Which will lead to a robust protection system and better performance. The application synchro phasor based measurements will be utilized for the purpose of monitoring of voltages an each buses of typical power network. Based on same the system voltage stability will be analyzed.

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Chapter 1

Introduction

With growth in electrical energy sector, the problems of voltage instability becomes more serious..

A deregulation of electricity market has resulted in increased bulk power across interconnected systems. In some utilities, the amount of transactions previously purchased in a year is now managed in one day.

If power system run in such condition where there is inadequate reactive power reserve will initiate the voltage instability points and can lead to the voltage collapse.

1.1 Problem Identification

Voltage analysis can be done by PV and QV graphical methods ,also this analysis should done by power flow analysis method.Actually these methods does not give proper voltage analysis because when these methods are in process they use old data but some error could generate in this analysis .For reducing this error might be using the synchro phasor method.In synchro phasor method real time data used.

1.2 Objective of The Work

a. To stable the voltage of the taken system using the hezien matrix and error generated because of the usage of it.

b. This stability analysis will be done on taken system using taken from (Phasor Measurement Unit)PMUs,present in the PSAT(MATLAB tool)simulation tool.

1.3 Literature Survey

The literature survey is carried out to know about basic conceptualization of power system voltage stability analysis method and synchro phasor is used for measurement of voltage stability .

Paper Allan Agatep,"Voltage Stability Analysis Using Simulated Synchro phasor Measurement",A Thesis presented to California Polytechnic State University,May 2013.

In this thesis how to carry out the voltage stability of electrical network and there are two technic of analysis like PV and QV graphical and Power flow analysis method

Paper Ranjana Sodhi,"Synchro phasor Assisted State Estimation and Voltage Stability Monitoring Including Optimal PMU Placement",A Thesis presented to IIT Kanpur,November 2010.

In this thesis to carry out knowledge about the various state estimation and how it will be using for finding voltage stability.Also finding where synchro phasor will be putting for each node of bus.

1.4 Outline of Thesis

- **Chapter 1** Introduce with why we are doing synchro phasor technique for voltage stability.
- **Chapter 2** Power system stability.
- **Chapter 3** Introduction of phasor measurement unit(PMUs).
- **Chapter 4** State Estimation

Chapter 2

Power System Stability

2.1 Introduction

Power system stability is know as the system to maintain an operating equilibrium point after being subjected to a disturbance for given initial operating conditions. Power system stability is categorized based on the following considerations:

- The nature of the resulting instability mode indicated by the observed instability on certain system variables.
- The size of the disturbance which consequently inuences the tool used to assess the system stability.
- The time margin needed to assess system stability.

The stability of any system defines by it's ability to return back to steady state condition when it hits by any disturbance. As the power system runs only if there is synchronism in the terms of voltage and phase sequence only when both side has equal frequency. So we can define it as the ability of the power system to return back to its steady state condition without losing synchronism.

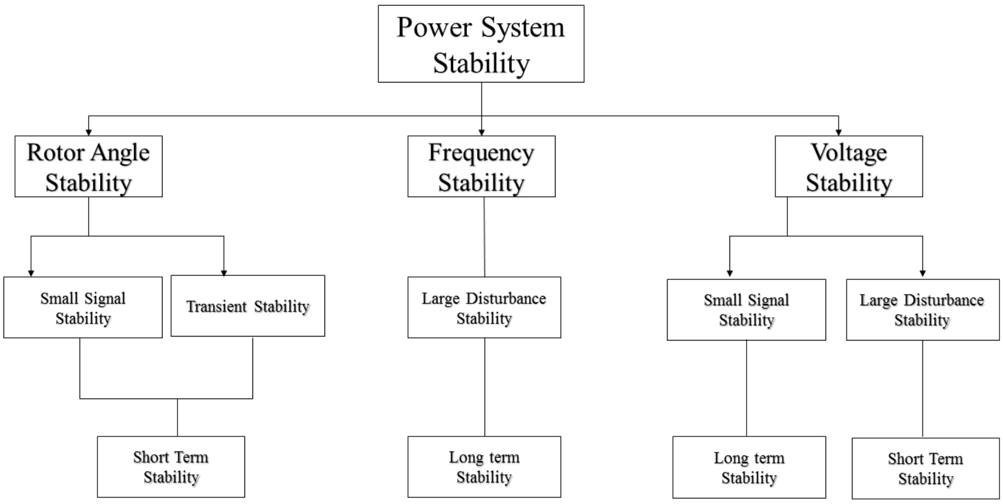


Figure 2.1: Classification Of Power System Stability

2.1.1 Rotor Angle Stability

The stability of rotor angel is stated as the capability of interconnected synchronous machines to kept in synchronism in stable operating situation and after being subjected to a disturbance. Load and generation balance associate with below parameter.

- Generator input or input torque (Mechanical output torque)
- Output of generator or output torque (The electrical torque)

The system's interruption can interrupts equilibrium, which result in generator rotor being acceleration or decelerate. In a case of two generator , if from two generator one generator rotor is running faster than another for a temporary period of time then the angular position of faster one will relatively increase than the slower one.

2.1.2 Frequency Stability

Stability of frequency refers to the ability of the electrical power system to maintain the frequency steady following a severe system upset , resulting in significant load and generation imbalance stability of frequency depends on the ability of the electrical power system to restore or maintain equilibrium between load and generation system, with less unintentional load loss. Which will result in stability by sustained swing of frequency.

2.1.3 Voltage Stability

The third power system stability problem is the voltage stability and is elaborated in section 1.2. Further analysis and method of the voltage stability of network.

2.2 Voltage Stability

Overall power system stability defined as the voltage stability. Maintaining steady voltages at all buses in the system after being affected by contingency from a given initial operating condition.
The voltage stability definitions according to as followed.

- A power system at a given operating point is small-disturbance voltage stable if, after a small disturbance, voltages near loads are similar or identical to pre-disturbance values.[1]

- A power system at a given operating point and subject to a given disturbance is voltage stable if voltages near loads approach post disturbance equilibrium values.[1]

- A power system at a given operating point and subject to a given disturbance undergoes voltage collapse if post-disturbance equilibrium voltages are below acceptable limits.Voltage collapse may be system wide or partial.[1]

Main factor affecting the voltage stability is voltage drop , inductive reactance across each elements of power system and associated with transmission network respectively. Increment in reactive losses due to increase in line currents during the various power flow conditions increase. Increase in reactive losses results into decrement in voltage magnitude. Increment in real power flow results into decrement in voltage magnitude. Due to this at some instant system doesnt support the power flow on the lines and maintain stable voltage. Results in voltage collapse..

2.2.1 Classification Of Voltage Stability

According to the time limit of interruption in electrical power system, cause problem of voltage instability, which classified as short and long term. In short term at a scale of transient , these things falls which are Automatic Voltage Regulation (AVR), excitation system, turbine and governor dynamics, which falls in time scale of seconds. In this category HVDC(High voltage Direct Current) interconnections, Induction motor, electronic based load can be considered.

If the electrical power system is stable, interruption time out is of short term and the system enter in slow long term dynamics Equipment operated in time frame of long term are transformer tap changers, limiters, boilers etc. typically the time limit is for a few minutes to terms of minutes. In long term time limit is mainly due to large interruption between the generator and load depends on detailed topology of system.

2.3 Voltage Stability

Various system plays a role for voltage stability. Some of them are Generators, transmission lines , loads. Crucial role for providing reactive power to the power systems are played by Generators. Generation of reactive power is due to generators and is being restricted by present rating of field , coil windings.

Since the higher than limit of current increasing , heat increasing exciter winding will take before the winding becomes broken, the utmost reactive power output is ready as over excitation clipper (OEL). once OEL over the limit, the terminal voltage will be modified. Transmission networks also are one necessary parameter for voltage

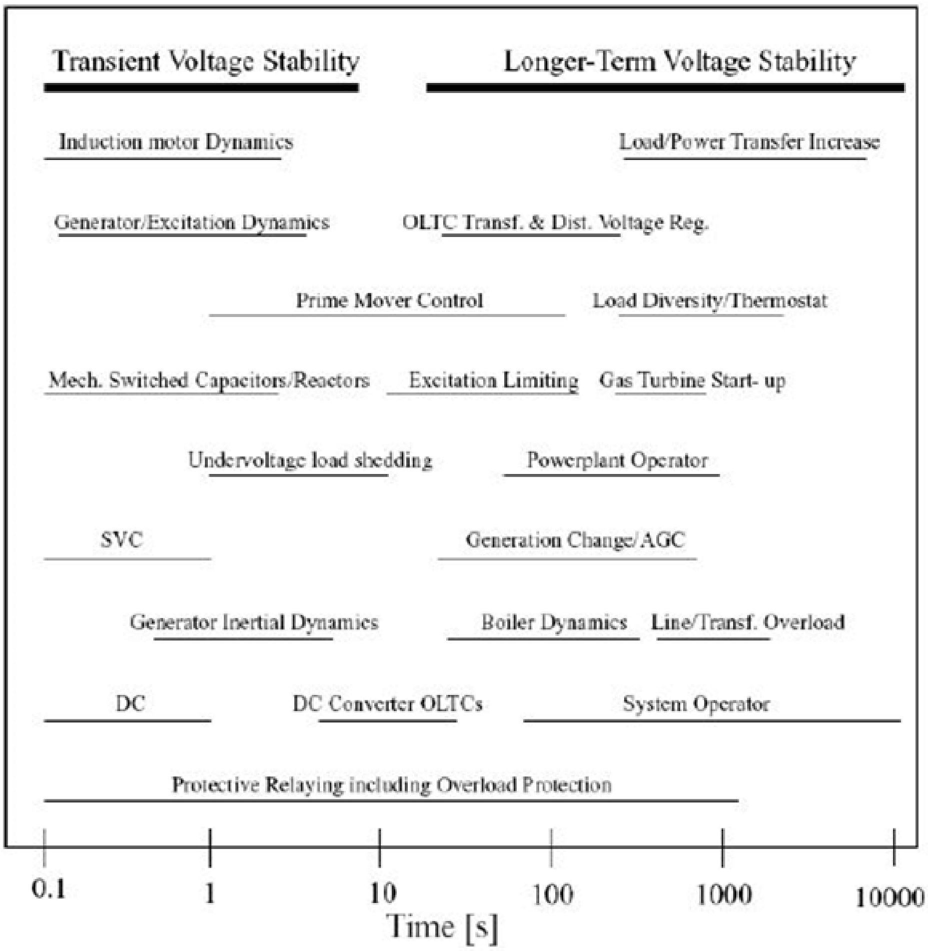


Figure 2.2: Time Responses Of Different Controls And Components To Voltage Stability

stability. underneath a release atmosphere wherever a lot of power is transport across long distances, the utmost gave power is restricted by the gear characteristics. Power on the far side the limit transmission capability determined by thermal or stability concerns can not be delivered.

Major third issue is that result voltage instability in system hundreds. Voltage instability is load driven. Following a modification within the demand, the load can initially modification consistent with its fast characteristic like, constant electrical phenomenon or current.It will then change this drawn from the system till the load provided by the system satisfies the demand at the ultimate system voltage. equally once there's a sharp modification in system voltage, such as, following a disturbance, the load can modification momentarily. it'll then change this and draw from the system, no matter current is important so as to satisfy the demand.

2.4 Voltage Stability Analysis

Most commonly used technique in large complex meshed network is power flow analysis.In this section contains an introduction about power flow analysis,load flow analysis . Its application of voltage stability will be giving in order to understand the voltage stability indices.

2.4.1 Power Flow Analysis

A balanced three phase is assumed for carrying out the load flow study, and thus only network of positive sequence is being used.As per the study each bus having four variables associated with are voltage, real and reactive power , phase angle supplied to each bus. While from these four variables according to the type of bus there will be two variables specified while other two variables unspecified:
which ,typically per unit, is the input data. The network equations in terms of the bus admittance matrix can be written as follows:

$$\begin{pmatrix} \overline{I}_1 \\ \overline{I}_2 \\ . \\ . \\ \overline{I}_n \end{pmatrix} = \begin{pmatrix} Y_{11} & -Y_{12} & -Y_{13} & ... & -Y1n \\ -Y_{21} & Y_{22} & -Y_{23} & ... & -Y2n \\ . & . & . & ... & . \\ . & . & . & ... & . \\ . & . & . & ... & . \\ -Y_{n1} & -Y_{n2} & -Y_{n3} & ... & Y_{nn} \end{pmatrix} * \begin{pmatrix} \overline{V}_1 \\ \overline{V}_2 \\ . \\ . \\ \overline{v}_n \end{pmatrix} \tag{2.1}$$

Where , n is no. of buses,
Y_{ii} is self admittance at node i,
Y_{ij} is mutual admittance between buses,

$\overline{V}_i$ is the phasor voltage.

$\overline{I}_i$ is the phasor current.

The current at any node k is related to P, Q and V as follows:

$$\overline{Y} = \frac{P_k + jQ_k}{\overline{V}_k^*} \tag{2.2}$$

The relations between P, Q, V and I are defined by the characteristics of the devices connected to the buses, this depended makes the problem nonlinear and therefore have to be solved iteratively using techniques such as Gauss-Seidel or Newton-Raphson.

2.4.2 PV and QV Curves

PV and QV are the simplex method for analysis of voltage stability and that will using for two power flow.

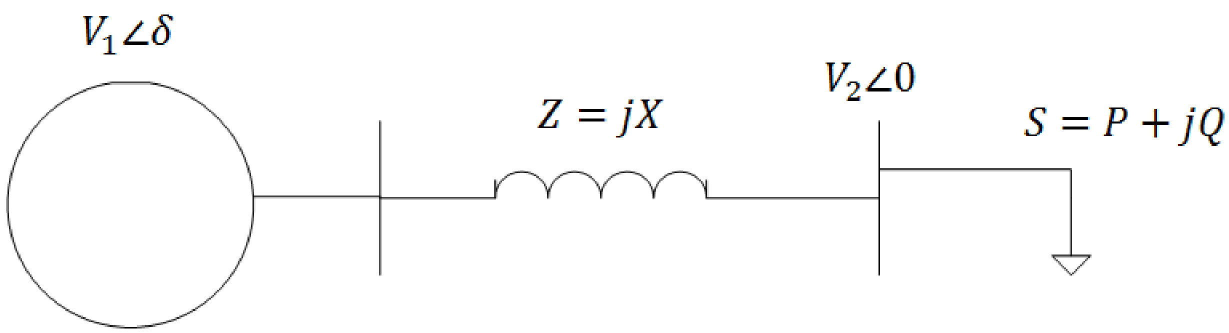


Figure 2.3: Time Responses Of Different Controls And Components To Voltage Stability

Where V is voltage at the load bus δ and is the phase difference between the load and generator θ and is the line impedance angle. The power delivered to the load given by equations:

$$P = \frac{V_1 V_2}{X} * sin(\delta) \tag{2.3}$$

$$Q = \frac{V_1 V_2}{X} * cos(\delta) - \frac{V_2^2}{X} \quad (2.4)$$

Using equations (2.3) and (2.4) to eliminate ,δ the following equation is obtained

$$V_2 = \sqrt{(V_1^2/2) - Q_L X \pm X * \sqrt{(V_1^2/4X^2) - P_L^2 - Q * (V_1^2/X)}} \quad (2.5)$$

As shown in Equation (2.5), the load voltage V_2 depends on the sending end voltage V_1 , line impedance X, and load demand values, P and Q.

For every PV curve there are two stable points, one at high voltage and so low cur-

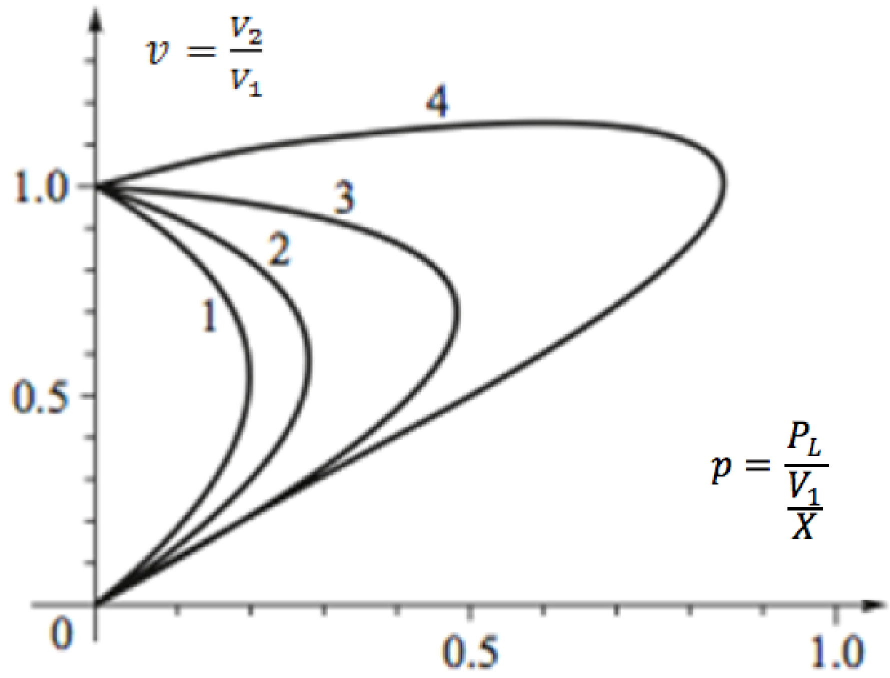


Figure 2.4: 3 PV curves for corresponding power factors: (1) ϕ=45 lagging, (2) ϕ=30 lagging, (3) ϕ=0, (4) ϕ=30 leading

rent, and the other at low voltage at high current. Now same circuit is using for QV graph plotting. QV curve is represented reactive power versus voltage at bus.

In order to create a QV curve, a constant real power load is assumed and a fictitious synchronous condenser with infinite reactive capability is placed on the test bus. The voltage of the synchronous condenser is then varied, and the VAR output is allowed to be any value to meet the scheduled voltage. Reactive power demand is plotted for various voltage schedules as shown in figure 4.

From figure 2.4, the from x-intercept represent the curve on the positive slope rep-

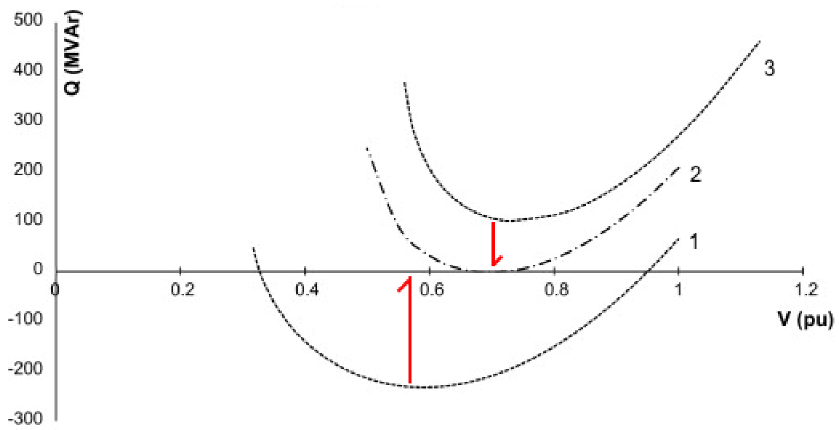


Figure 2.5: QV curves for various load levels

resents the base case operating point. Downward the curve represents an increase in MVAr load along with a corresponding decrease in voltage.The positive slope of the QV curve,

where ,dQ/dV> 0,is the stable region and the negative slope of the QV curve where dQ/dV< 0, is the unstable region. The bottom of the curve where dQ/dV= 0 shows the minimum reactive power required for stable operation, as well as the minimum voltage that the bus can withstand.

For the figure (2.4) Curve 1 shows a positive reactive margin, and thus is more stable in terms of voltage stability. Curve 2 has less or no margin, and is so marginally stable. Any increasing in demand will result in voltage collapse. Curve 3, represent that no x-intercept that means a negative margin and so the system has collapsed. As a result the system has required additional MVAr in order to take out of the collapse. This method is used as it provides the reactive power margin with respect to reactive power injections at the test bus. In conjunction to PV-curves, these two methods are useful for study voltage stability for small network, specially for radial systems., it is not efficient for large systems. It is require extensive computation and may contain more than one critical bus to be analysis.

2.4.3 Voltage

For quantification purpose of voltage stability problem as a perspective index voltage is being used. As a remedial action to initialization for voltage instability problem voltage magnitude monitoring is the widely accepted index. To prevent voltage collapse under voltage load shedding is used in such scenario. 85%-90% of its nominal voltage is set typically for it. As at that point relay will be tripping to cut off such load in order to prevent voltage collapse.

2.4.4 Analysis Methods

For the purpose of Voltage stability analysis be classified as Dynamic Analysis and Static Analysis. This methods are being specified according to the problems as per the particular problem specific analysis method is being used while each method has its own advantage and disadvantage as well.
Dynamic Analysis applied over a system gives information about it's performance in relation with time. Dynamic analysis can conduct on coordination of elements where time overlaps, e.g. generator controls, load shedding and switched capacitor banks. By using dynamic simulation one can find the system performance when such case happens like stalling of motor, changes happening in load and recovery happening in case of voltage collapse or stability. Static analysis are slower forms of voltage stability. In instability phenomenon indices are very helpful as the generated indices for a system defines the voltage instable area and indicate such elements. These methods are computationally less intensive as it suitable for online and offline applications.

Chapter 3

Introduction of Phasor measurement unit

3.1 Introduction

Phasor represents the signal with quantity like magnitude and phase angle in sinusoidal signal. Phasor measurement technology enables the measurement of quantity like voltage and current phasors with respect to a reference signal to be synchronized with satellite clock.

PMUs given time-synchronized data and its applicable are:

a. Wide area monitoring,

b. Real time dynamics and stability monitoring,

c. Dynamic system ratings,

d. Improvements in state estimation, protection, and controls.

This technology gives the ability to visualize the wide area. Which facilitates the ability for distributed sensing and control the control action in coordinated manner. PMUs gives directly the phase angles as per the state estimation which is slow and may be error one due to out of date or not accurate models which are require for

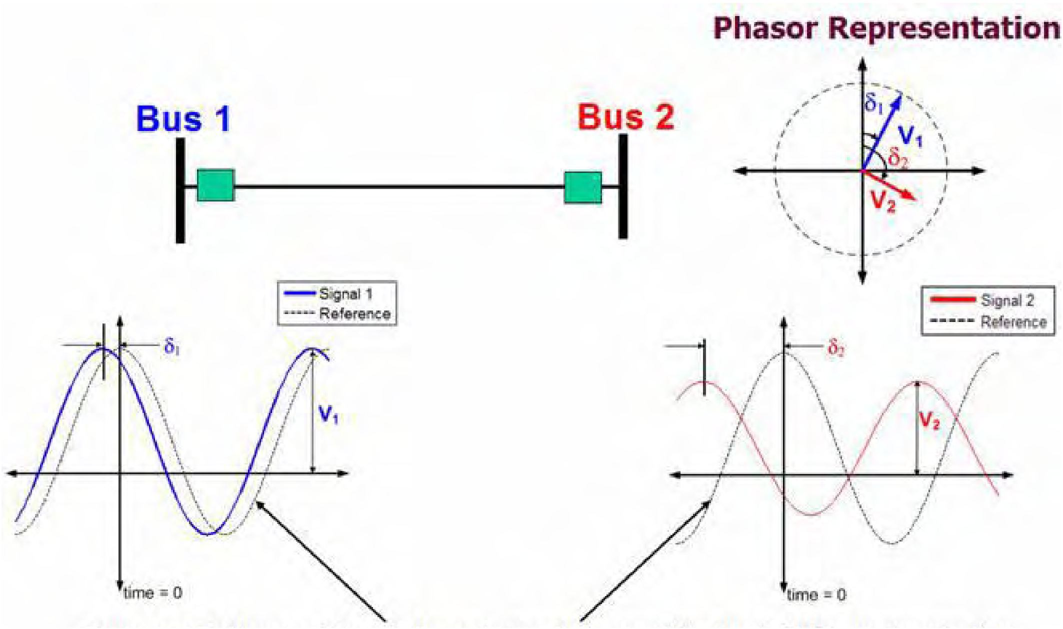


Figure 3.1: common Reference Signal at remote locations possible due to GPS synchronization

state estimation.

3.2 Synchro Phasor

Measurement through PMUs are being synchronized with satellite to synchronize the data of each and every location in widely sprea network. As the improvement of the transmission network becomes more complex, the need for faster clearing times, pilot protection schemes and more wide-area protection and control systems are being most utilized, has increased.

Protection and control systems must be constant changes in the network.The changeability on both the supply and demand side increases the importance of having wide area protection, control and monitoring systems that are secure, reliable, and simple as possible.

Phasor representation of sinusoidal signals is commonly used in ac power system analysis. The sinusoidal waveform defined in equation.

$$x(t) = X_m \cos(\omega t + \phi) \tag{3.1}$$

The synchro phasor representation X of a signal x(t) is the complex value given by.

$$X = \frac{X_m}{\sqrt{2}}\theta^{j\phi} = \frac{X_m}{\sqrt{2}}(\cos\phi + j\sin\phi) = X_r + jX_i \tag{3.2}$$

Where, The magnitude is the root-mean-square (rms) value, $X_m/\sqrt{2}$, of the waveform, and the subscripts r and i signify real and imaginary parts of a complex value in rectangular components. In power systems it is common to represent X in phasor

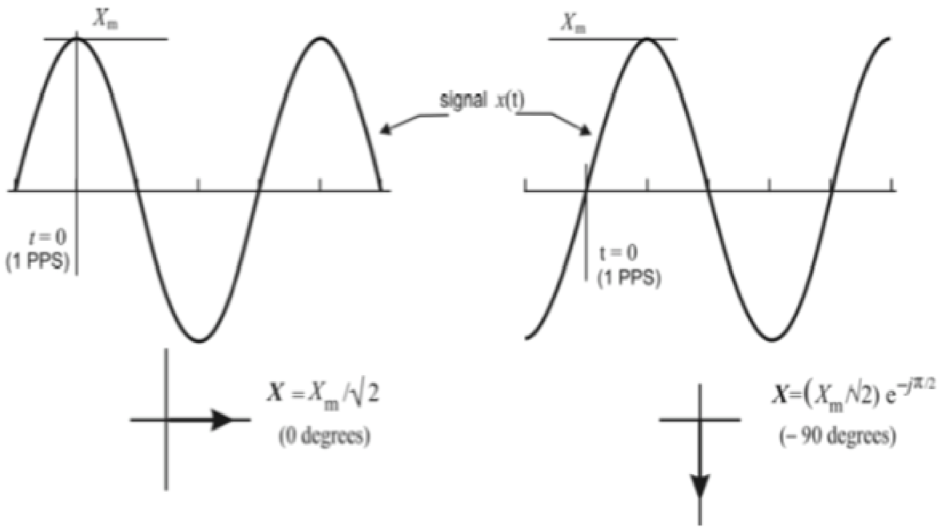


Figure 3.2: Synchro phasor measurement

notation:x=X_m ϕ phase angleϕ depends on the time scale, particularly where t = 0. It is important to note this phasor is defined for the angular frequency ω given by 2Πf where, f is the frequency.

The representation of a synchro phasor is shown in figure (3.1). IEEE Standard C37.118.1 defines synchro phasors as actual time-synchronized measurements of certain parameters on the electricity grid from phasor measurement units (PMUs). Phasor data is calculated phasor in the time synchonized grid condition data by measurements of PMU which contains voltage, current and frequency.

Each phasor measurement is in time domain against Global Positioning System universal time. This allows measurements taken by PMUs in different locations or by different owners, to be transmitted over standard communication systems using Ethernet, phone modem, or just an EIA-232 cable from the PMU, then to be synchronized with computer at every end of the line.

Chapter 4

State Estimation

Power system state estimation is the estimation of voltage and angel which are power system state . Before direct measurement provided to system operator or telemetered to the EMS (energy management system) one should make sure data id correct efficient and accurate.
If any input is in accurate or not provided ,one cannot decide system operating point at given time and cannot take decision to operate system within the predefine limits. A state estimator provides o/p like bus voltage angle, measurement error etc. for all metered and unmetered quantity in order to maintain power system in normal and secure state. State estimation type static refers to the procedure to obtain the voltage phasor at every buses at a given point of time.

4.1 State Estimation Problems

a. State observation

   No unknown input model known (L/NL)initial state unknown ,no measurement error exact state computation.

b. State estimation / Kalman filtering

   Input statistical properties known model(L)know, properties of initial state of measurement error known MMSE(Minimum mean square error) estimation computation.

c. Extended estimation problem

- Non linear observers
- Unknown input observers
- Extended Kalman filter
- Adaptive observers

A system is observable if we can uniquely determine the vector X(r) given the input and output requires of u(i) and y(i) for i $\geq$ R.

a. Least squares:-

The terms least squares and weighted least squares have with the criterion for selecting a solution to the over defined equation produced when more measurement than states are represented in the estimation problem. Suppose the equation are linear and in the form.

$$y=Ax$$

where
X is the state.
y is the measurements.
A is a matrix with more rows than columns.

$$y=Ax+\varepsilon$$

where
ε represents errors in the measurement.

4.2 Different Methods for State Estimation

a. Weighted Least Square [W.L.S]

b. Orthogonal Transformation

c. Hybrid Method

Different methods for state estimation are compared typically on several criteria such as,

- Numerical Stability
- Computational Efficiency
- Implementation Complexity

4.2.1 Comparison of Different methods

Orthogonal Transformation vs Normal Equation

- The QR Factorization H requires more computation[1]

$$\begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix} H = \begin{bmatrix} R \\ 0 \end{bmatrix} \tag{4.1}$$

$$R\Delta x = Q_1 W^{1/2} \Delta z \tag{4.2}$$

- Where in N.E triangular factorization of G requires less computation[1]

$$G = H^T W H \tag{4.3}$$

$$G = U^T U \tag{4.4}$$

$$(U^T U)\Delta x = H^T W \Delta Z \tag{4.5}$$

Major drawback of orthogonal factorization is that it is not able to take advantage of efficient implementation using decoupling property.

whereas fast decouple version of W.L.S has been very efficient and effective.
And major advantage of W.L.S is its Intensive computation of G is performed once at beginning.
Also as Q of Ortho. can be stored and compute again when we require but it is non-sparse and has higher dimension so require large space.[1]

Hybrid vs Orthogonal Transformation

Hybrid method solves the normal equation using the orthogonal factorization.

$$R\Delta x = Q_1 W^{1/2} \Delta z \tag{4.6}$$

So, hybrid method is less stable than the Ortho. because it uses two measurement in given equation one is telemetered and second is virtual. When it multiplied by r(residual) second term will dominates and RHS will become zero. Hybrid method does not require the storage of the matrix Q and can be efficient fast decouple.[1]

4.2.2 Summary

After performing different method in[1] author has concluded that Ortho. is mathematically most stable with heaviest computation and cannot be applied by decoupled version. Thereby normal equation is efficient, stable, and requires less heavy computation as computation of gain matrix is not require in every step or iteration.

4.3 WLS State Estimation

Weighted least square(WLS) method often used in practice of power system state estimation.

4.3.1 Introduction

It refers procedure of obtaining voltage and angle at all of the system buses at a given point of time. One can use state estimation to filter out error and find optimal state by use of set of redundant measurement.

4.3.2 Assumptions in Method

- System is operating in steady state under balance condition i.e. power flow is balanced three phase,transmission line is fully transposed, all series and shunt devices are symmetrical, Which allows to use single phase positive equivalent circuit for modeling entire power system.all data and variable expressed in P.U.
- As starting to initiate WLS all bus voltage at 1.0 P.U and in phase with each other.

a. Least squares:-

The terms least squares and weighted least squares have with the criterion for selecting a solution to the over defined equation produced when more measurement than states are represented in the estimation problem. Suppose the equation are linear and in the form.

$$y=Ax$$

where

X is the state.

y is the measurements.

A is a matrix with more rows than columns.

$$y=Ax+\varepsilon$$

where

ε represents errors in the measurement.

The least squares solution is based on assuming the error are independent and identically distributed with mean zero and variance.

$$E\varepsilon = 0, \ E\{ \varepsilon \, \varepsilon^{T} \} = I$$

The optimization problem is to find the estimate

4.3.3 WLS State Estimation Algorithm

- **STEP 1:**

  Start the iteration, Set the iteration index k=0

- **STEP 2:**

  Initialize the state vector x^k, Flat Start.

- **STEP 3:**

  Calculate the gain matrix(G).

$$G = H^T W H \tag{4.7}$$

$$W = R^{-1} = \begin{bmatrix} \frac{1}{\sigma_1^2} & & \\ & . & \\ & & \frac{1}{\sigma_n^2} \end{bmatrix} \tag{4.8}$$

- **STEP 4:**

  Decompose G and solve Δx^k

$$\Delta x = Z - \hat{Z} \tag{4.9}$$

$$\hat{Z} = H\hat{x} \tag{4.10}$$

$$\hat{x} = G^{-1} H^T W Z \tag{4.11}$$

- **STEP 5:**
  Check convergence $\mid \Delta x \mid \leqslant \varepsilon$?

- **STEP 6:**
  If no then update $x^{k+1} = x^k + \Delta x^k$ and repeat from step 3 else stop.

As G is not inverted. Instade of that decompose into it's triangular factors and following sparse linear set of equation are solved by forward and backwards substitution at each iteration k:

$$[G(x^k)]\Delta x^{k+1} = H^T(x^k)R^{-1}[z - h(x^k)] \tag{4.12}$$

In each iteration of above algorithm calculation given bellow is essential:

1. Calculation of righthand side of equation(2.17)

   a. Calculate the measurement function,h(x^k)

   b. Built the measurement jacobian, H(x^k)

2. Calculation of G(x^k) and solution of Equation(2.17)

   a. Building the Gain Matrix,G(x^k)

   b. Decomposing the G(x^k) into cholesky factors.

   c. Performing forward/backward substitution to solve Δx^{k+1}

Measurement Function,h(x^k)

The most commonly measurements are line power flow, bus power injection, bus voltage magnitudes, and can be shown in the form of state variable using polar or rectangular forms. The state vector will be (2N-1) elements when using polar coordinate for N bus system. The state vector will be like following with assumption of bus no.1 as reference bus.

$$x^T = [\Theta_2, \Theta_3..., \Theta_n V_1, V_2..., V_n] \tag{4.13}$$

Assuming two port Π-model for network branches: **1**.Real and Reactive power injection at bus i:

$$P_i = V_i \sum_{j \in N_i} V_j (G_{ij} \cos \Theta_{ij} + B_{ij \sin \Theta_{ij}}) \tag{4.14}$$

$$Q_i = V_i \sum_{j \in N_i} V_j (G_{ij} \sin \Theta_{ij} + B_{ij \cos \Theta_{ij}}) \tag{4.15}$$

2.Power flow of real and reactive terms from i to j bus:

$$P_{ij} = V_i^2 (g_{si} + g_{ij}) - V_i V_j (g_{ij} \cos \Theta_{ij} + b_{ij} \sin \Theta_{ij}) \tag{4.16}$$

$$Q_{ij} = -V_i^2 (b_{si} + b_{ij}) - V_i V_j (g_{ij} \sin \Theta_{ij} - b_{ij} \cos \Theta_{ij}) \tag{4.17}$$

Where

V_i, Θ_i are Voltage Magnitude and phase angle at bus i

$\Theta_{ij} = \Theta_i - \Theta_j$

$G_{ij} + jB_{ij} = ij_{th}$ element of complex bus admittance matrix

$g_{ij} + jb_{ij}$=admittance of series branch connecting buses i and j

$g_{si} + jb_{si}$=shunt admittance at bus i

N_i=set of bus numbers directly connected to bus i.

The Measurement Jacobian,H

The structure of matrix H (Jacobian) is as follows:

$$H = \begin{bmatrix} 0 & \frac{\delta V_{mag}}{\delta V} \\ \frac{\delta P_{inj}}{\delta \Theta} & \frac{\delta P_{inj}}{\delta V} \\ \frac{\delta Q_{inj}}{\delta \Theta} & \frac{\delta Q_{inj}}{\delta V} \\ \frac{\delta P_{flow}}{\delta \Theta} & \frac{\delta P_{flow}}{\delta V} \\ \frac{\delta Q_{flow}}{\delta \Theta} & \frac{\delta Q_{flow}}{\delta V} \end{bmatrix} \tag{4.18}$$

1. Elements of real power injection measurements:

- $\frac{\delta P_i}{\delta \Theta_i} = \sum_{j=1}^{N} V_i V_j(-G_{ij} \sin\Theta_{ij} + B_{ij}\cos\Theta_{ij}) - V_i^2 B_{ii}$
- $\frac{\delta P_i}{\delta \Theta_j} = V_i V_j(G_{ij} \sin\Theta_{ij} - B_{ij}\cos\Theta_{ij})$
- $\frac{\delta P_i}{\delta V_i} = \sum_{j=1}^{N} V_j(G_{ij} \cos\Theta_{ij} + B_{ij}\sin\Theta_{ij}) + V_i^2 G_{ii}$
- $\frac{\delta P_i}{\delta V_j} = V_i(G_{ij} \cos\Theta_{ij} + B_{ij}\sin\Theta_{ij})$

2. Elements corresponding to reactive power injection measurements:

- $\frac{\delta Q_i}{\delta \Theta_i} = \sum_{j=1}^{N} V_i V_j(G_{ij} \cos\Theta_{ij} + B_{ij}\sin\Theta_{ij}) - V_i^2 G_{ii}$
- $\frac{\delta Q_i}{\delta \Theta_j} = V_i V_j(-G_{ij} \cos\Theta_{ij} - B_{ij}\sin\Theta_{ij})$
- $\frac{\delta Q_i}{\delta V_i} = \sum_{j=1}^{N} V_j(G_{ij} \sin\Theta_{ij} - B_{ij}\cos\Theta_{ij}) + V_i^2 B_{ii}$
- $\frac{\delta Q_i}{\delta V_j} = V_i(G_{ij} \sin\Theta_{ij} + B_{ij}\cos\Theta_{ij})$

3. Elements corresponding to real power flow measurement:

- $\frac{\delta P_{ij}}{\delta \Theta_i} = V_i V_j(g_{ij} \sin\Theta_{ij} - b_{ij}\cos\Theta_{ij})$
- $\frac{\delta P_{ij}}{\delta \Theta_j} = -V_i V_j(g_{ij} \sin\Theta_{ij} - b_{ij}\cos\Theta_{ij})$
- $\frac{\delta P_{ij}}{\delta V_i} = -V_j(g_{ij} \cos\Theta_{ij} + b_{ij}\sin\Theta_{ij}) + 2(g_{ij} + g_{si})V_i$
- $\frac{\delta P_{ij}}{\delta V_j} = -V_j(g_{ij} \cos\Theta_{ij} + b_{ij}\sin\Theta_{ij})$

4. Reactive power flow measurements corresponded by these elements:

- $\frac{\delta Q_{ij}}{\delta \Theta_i} = -V_i V_j(g_{ij} \cos\Theta_{ij} + b_{ij}\sin\Theta_{ij})$
- $\frac{\delta Q_{ij}}{\delta \Theta_j} = V_i V_j(g_{ij} \cos\Theta_{ij} + b_{ij}\sin\Theta_{ij})$
- $\frac{\delta Q_{ij}}{\delta V_i} = -V_j(g_{ij} \sin\Theta_{ij} - b_{ij}\cos\Theta_{ij}) - 2(b_{ij} + b_{si})V_i$

- $\frac{\delta Q_{ij}}{\delta V_j} = -V_j(g_{ij}\sin\Theta_{ij} - b_{ij}\cos\Theta_{ij})$

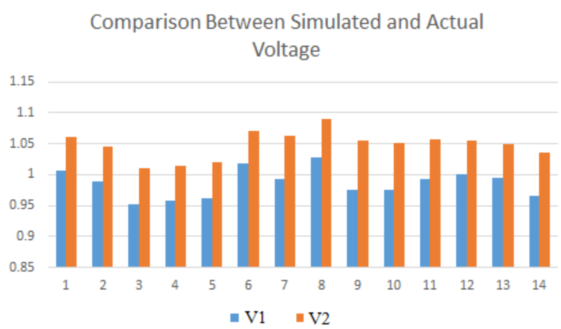
5. Voltage magnitude measurement corresponded by these elements:

- $\frac{\delta V_i}{\delta V_i}$=1
- $\frac{\delta V_i}{\delta V_j}$=0
- $\frac{\delta V_i}{\delta \Theta_i}$=0
- $\frac{\delta V_i}{\delta \Theta_j}$=0

Power system of small scale is monitored through seven measurements, errors of each are independent which distributed independently according to normal distribution with zero mean and variance as given below:

Sate Estimation Result of IEEE 3-Machine, 14-Bus System

Comparing results shown in below table with the standard voltage and phase angle table given in one can conclude that output of the WLS state estimation is nearer to standard results. The results shown in table 4.1



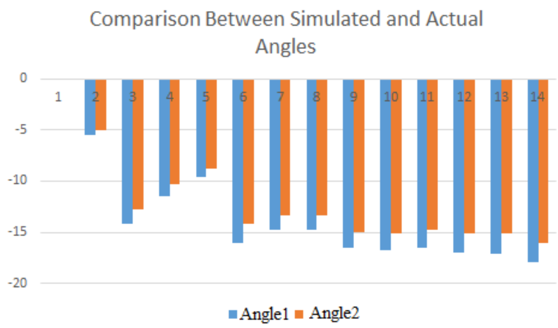


Table 4.1: Comparison between simulated and actual data

NO.	Bus NO.	Bus Type	Simulation Results		Actual Data	
			Voltage (p.u.)	Angles (Deg.)	Voltage (p.u.)	Angles (Deg.)
1	1	Slack	1.0068	0.00	1.060	0.00
2	2	P-V	0.9899	-5.5265	1.045	-4.98
3	3	P-V	0.9518	-14.2039	1.010	-12.72
4	4	P-Q	0.9579	-11.4146	1.014	-10.33
5	5	P-Q	0.9615	-9.57583	1.020	-8.78
6	6	P-Q	1.0185	-16.0798	1.070	-14.22
7	7	P-Q	0.9919	-14.7510	1.062	-13.37
8	8	P-Q	1.0287	-14.7500	1.090	-13.56
9	9	P-Q	0.9758	-16.5125	1.056	-14.94
10	10	P-Q	0.9758	-16.7476	1.051	-15.10
11	11	P-Q	0.9932	-16.5397	1.057	-14.74
12	12	P-Q	1.0009	-17.0203	1.055	-15.07
13	13	P-Q	0.9940	-17.0583	1.050	-15.16
14	14	P-Q	0.9647	-17.8967	1.036	-16.04

Chapter 5

Analysis of Voltage stability

There are some methods which are used to calculating for voltage stability. It is given below.

- Continuation Power flow
- Minimum Singular value
- Point of Collapse method
- Optimization method

A brief explanation of these processes is the in the next sections, with particular emphasis in continuation power flow, or continuation method, which is the method developed in this study.

5.1 Continuation Power flow

This is the most commonly used method to calculate the power flow and its given the system response to load variation in order to eliminating system collapse and to ensure the security economy and control of electrical energy distribution. All parameterizations has necessary to guarantee the non-singularity of Jacobian matrix in power flow equations, the continuation equations of the corrector step can be shown nonsingular at the collapse point

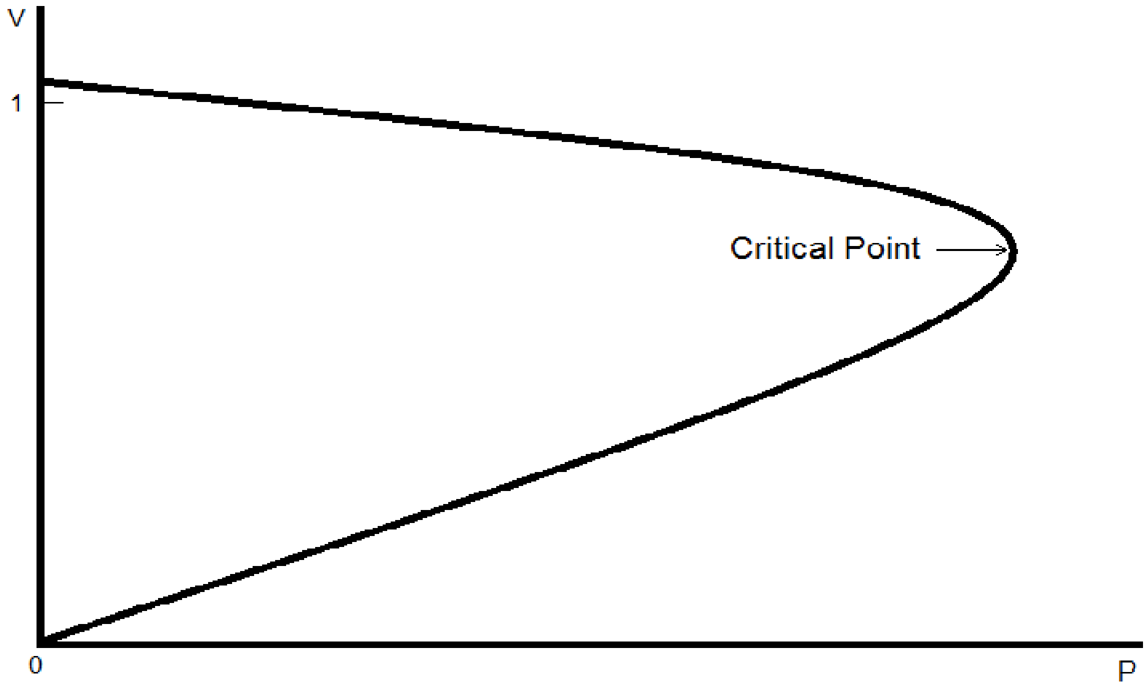


Figure 5.1: Typical PV curve

The conventional power flow calculating with Gauss-Seidel method.Then it is overcome with Newton-Raphson method in which the continuation method is based on the latest faster convergence method.

In this strategy, continuation power flow is connected without changing continuation parameter. Load parameter W is chosen as continuation parameter in all expectation and rectification steps. The non-peculiarity of Jacobian in this strategy can be gotten by decreasing stride size d as the arrangement ways to deal with basic point. In this study, continuation power stream strategy without parameterizations is used to break down the voltage solidness of frameworks since it gives acceptable results.

5.1.1 Newton-Raphson method

In this method

$$f(x_1, ..., x_n) = y \tag{5.1}$$

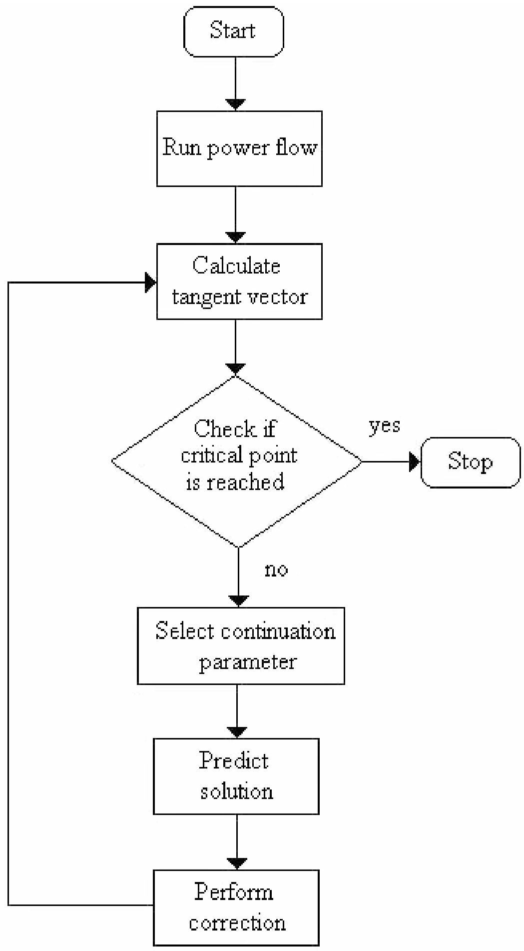


Figure 5.2: Flow chart for continuation power flow

where the vector f,is composed by differential funtions of variables x_1,......,x_n and y stands for vector of constant. for the initial guessx^0 we have,

$$f(x^0 + \triangle x^0) = y \quad (5.2)$$

$$f(x^0) + [J^0]\triangle x^0 = y \quad (5.3)$$

$$[J^0]\triangle x^0 = \triangle y^0 \quad (5.4)$$

At iteration k the Jacobian matrix $[J^k]$ is given by

$$[J^k] = \begin{pmatrix} \frac{\partial f_1(x^k}{\partial x_1} & .... & \frac{\partial f_1(x^k}{\partial x_n} \\ . & . & . \\ \frac{\partial f_n(x^k}{\partial x_1} & . & \frac{\partial f_n(x^k}{\partial x_n} \end{pmatrix} \tag{5.5}$$

$$\triangle x^k = [J^k]^{-1} \triangle y^k \tag{5.6}$$

finally expressing the equation as function

$$x^{k+1} = x^k + \triangle x^k \tag{5.7}$$

$$x^{k+1} = x^k + [J^k]^{-1} \triangle y^k \tag{5.8}$$

The new obtained values of x are then introduced in expression $f(x_1, ..., x_n) =$ y. The produce is repeated until $f(x_1, ..., x_n - y)$ is less then a specified acuracy.

5.1.2 Application of Newton-Raphson method to power flow

Applied this procedure to the power flow problem, the state variable for state estimation are voltage phase angle and magnitude.
Thus the equation are

$$\theta^{k+1} = \theta^k + [J^k]^{-1} \triangle f^k \tag{5.9}$$

$$V^{k+1} = V^k + [J^k]^{-1} \triangle f^k \tag{5.10}$$

And,

$$f(x_1, ..., xn) = [P_i(\theta_1, ..., \theta_n), Q_i(\theta_1, ..., \theta_n)] \tag{5.11}$$

The jacobian matrix is defined as,

$$[J] = \begin{pmatrix} \frac{\partial P_1}{\partial \theta_1} & \cdots & \frac{\partial P_1}{\partial \theta_n} & \frac{\partial P_n}{\partial V_1} & \cdots & \frac{\partial P_1}{\partial V_n} \\ . & \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{\partial P_n}{\partial \theta_1} & \cdots & \frac{\partial P_n}{\partial \theta_n} & \frac{\partial P_n}{\partial V_1} & \cdots & \frac{\partial P_n}{\partial V_n} \\ \frac{\partial Q_1}{\partial \theta_1} & \cdots & \frac{\partial Q_1}{\partial \theta_n} & \frac{\partial Q_1}{\partial V_1} & \cdots & \frac{\partial Q_1}{\partial V_n} \\ . & \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{\partial Q_n}{\partial \theta_1} & . & \frac{\partial Q_n}{\partial \theta_n} & \frac{\partial Q_n}{\partial V_1} & \cdots & \frac{\partial Q_n}{\partial V_n} \end{pmatrix} \tag{5.12}$$

5.2 Result

By using the above equations finding out the Jacobian matrix and P-V and Q-V curve .This P-V and Q-V curve are given below.

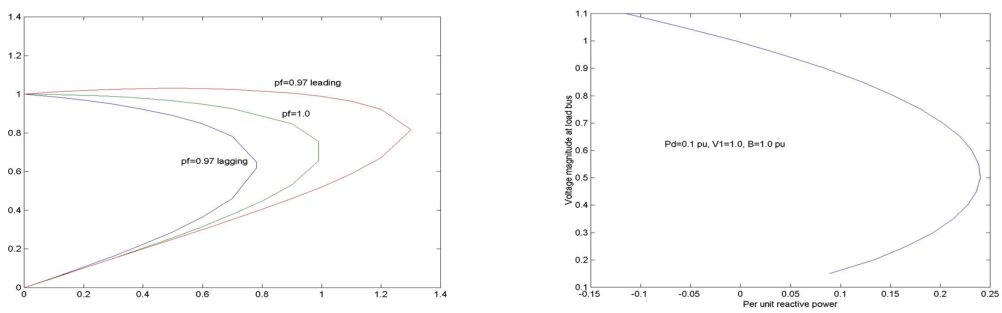


Figure 5.3: Left:PV Curve Right:QV curve

In IEEE-14 bus system there will be critical buses bus no 4,5,7,9,10,14 are the critical bus will be shown below :-

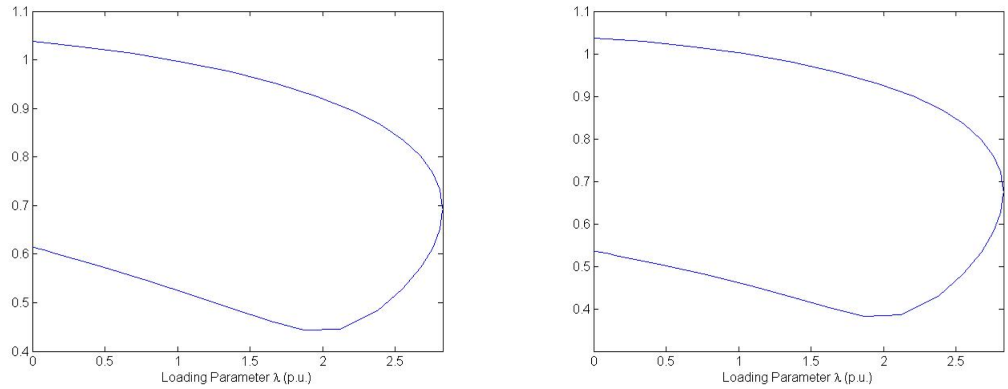


Figure 5.4: Left:Bus4 Voltage vs Loading parameter λ (p.u) Right:Bus5 Voltage vs Loading parameter λ (p.u)

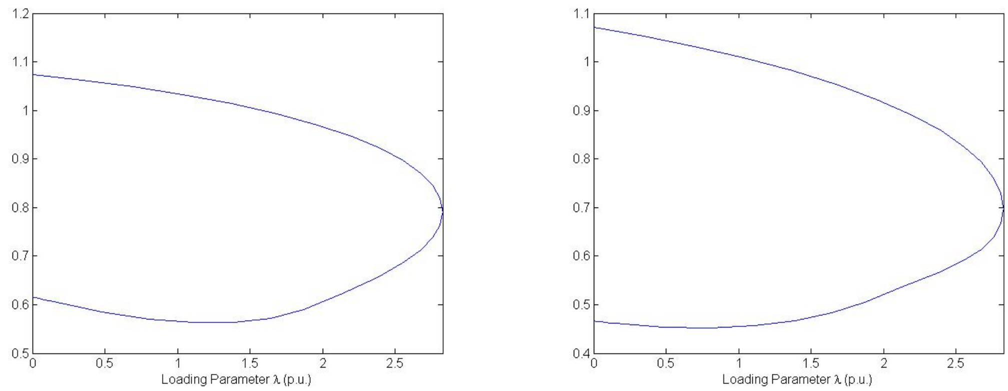


Figure 5.5: Left:Bus7 Voltage vs Loading parameter λ (p.u) Right:Bus9 Voltage vs Loading parameter λ (p.u)

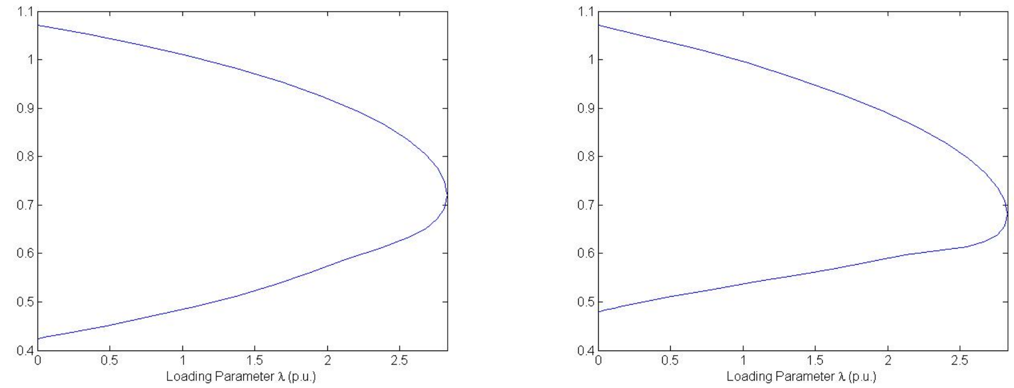


Figure 5.6: Left:Bus10 Voltage vs Loading parameter λ (p.u) Right:Bus14 Voltage vs Loading parameter λ (p.u)

Also the bus voltages a has been given that Fig.,after connecting shunt capacitor will be connected at the bus no 4

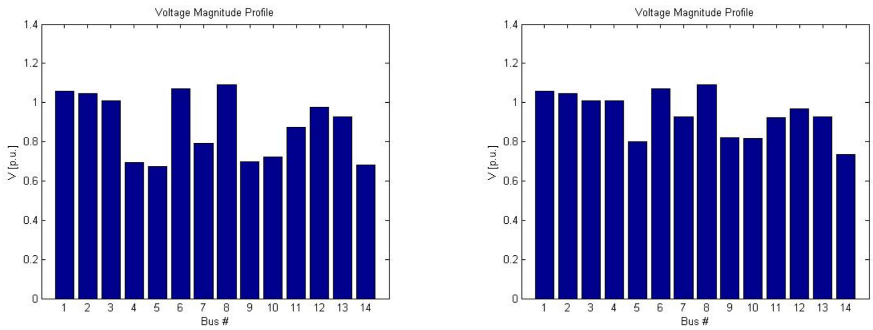


Figure 5.7: Left:Bus voltage profile without shunt capacitor Right:Bus voltage profile with shunt capacitor

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The extract of the work can be concluded as follows-

- From the IEEE-14 bus data finding out H matrix,also getting error of between actual data and simulated data from that control of reactive power.By using Continuation Power Flow(CPF) method finding out P-V and Q-V curve.

- That H matrix will be finding out from the WLS method of State estimation and also load flow analysis,and also load flow analysis. From the load flow analysis by using N-R method and found out Jacobian matrix.

6.2 Future Work

- From the simulated results, P-V and Q-V curve can found out for reaming other buses.

- Contingency analysis of IEEE 14 bus can be carried out.

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