VOLTAGE STABILITY ANALYSIS OF INTERCONNECTED POWER SYSTEM

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"VOLTAGE STABILITY ANALYSIS OF INTERCONNECTED POWER SYSTEM"

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(Electrical Power Systems)

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Certificate

This is to certify that the Major Project Report entitled **"Voltage Stability Analysis of Interconnected Power System"** submitted by **Mr. Shah Aagam Tushar (10MEEE14)**, towards the partial fulfillment of the requirements for the award of degree in **Master of Technology (Electrical Engineering)** in the field of **Electrical Power Systems** of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

Voltage control and stability problems are not new to the electric utility industry but are now receiving special attention in many systems. Once associated primarily with weak systems and long lines, voltage problems are now also a source of concern in highly developed networks as a result of heavier loadings. In recent years, voltage instability has been responsible for several major network collapses. As a consequence, the terms "voltage instability" and "voltage collapse" are appearing more frequently in literature and in discussions of system planning and operation.

Voltage stability is concerned with ability of a power system to maintain acceptable voltages at all buses in the system under normal conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable decline voltage. The main factor causing instability is the inability of the power system to meet the demand for reactive power.

This thesis illustrates the basic concepts related to voltage instability by firstly considering the characteristics of transmission systems and then examining how the phenomenon is influenced by the characteristics of generators, loads, and reactive power compensation devices.

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Abbreviations

ULTC . . . . Under Load Tap Changer
HVDC . . . . High Voltage Direct Current

Nomenclature

δ .... Load angle(Degrees)
P .... Active power (kW)
ΔP .... Change in Active Power(kW)
Q .... Reactive power (kVAR)
ΔQ .... Change in Reactive Power(kVAR)
$\Delta\theta$ .... Change in Load Angle(Degrees)
X .... Impedance (ohms-Ω)
V .... Receiving end voltage (Volts)
E .... Sending end voltage (Volts)
ΔV .... Change in Receiving end voltage(Volts)
J_R .... Reduced Jacobian Matrix of the system
ϕ .... Right eigenvector matrix of J_R
Γ .... Left eigenvector matrix of J_R
λ .... Diagonal eigenvalue matrix of J_R

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Chapter 1

Introduction

Voltage instability has been given much attention by power system researchers and planners in recent years, and is being regarded as one of the major sources of power system insecurity. Voltage instability phenomena are the ones in which the receiving end voltage decreases well below its normal value and does not come back even after setting restoring mechanisms such as VAR compensators, or continues to oscillate for lack of damping against the disturbances. Voltage collapse is the process by which the voltage falls to a low, unacceptable value as a result of an avalanche of events accompanying voltage instability. Once associated with weak systems and long lines, voltage problems are now also a source of concern in highly developed networks as a result of heavier loading.

1.1 Objective of project

The main factors causing voltage instability in a power system are now well explored and understood. A brief introduction to the basic concepts of voltage stability and some of the conventional methods of voltage stability analysis are presented in this report. Simulation results on test power systems are presented to illustrate the problem of voltage stability and the conventional methods to analyze the problem.

1.2 Problem Identification

- Voltage stability problems normally occur in heavily stressed systems.While the disturbance leading to voltage collapse may be initiated by a variety of causes, the underlying problem is an inherent weakness in the power system.
- In addition to the strength of transmission network and power transfer levels, the principal factors contributing to voltage collapse are the generator reactive power/voltage control limits,load characteristics, characteristics of reactive compensation devices, and the action of voltage control devices such as transformer under-load tap changers (ULTCs).
- This thesis will review basic concepts related to voltage stability and characterize the "voltage avalanche" phenomenon.The dynamic and static approaches to voltage stability analysis will be described, and methods identified for preventing voltage instability.

1.3 Literature Survey

Reference [1] features a complete account of equipment characteristics and modelling techniques. Included is detailed coverage of generators, excitation systems, prime movers, ac and dc transmission, principles of active and reactive power control, and models for control equipment. Different categories of power system stability are thoroughly covered with descriptions of numerous methods of analysis and control measures for mitigating the full spectrum of stability problems.

Reference [2] shows that voltage stability is a major concern in the planning and operation of electric power systems.It also provides a clear, in-depth explanation of voltage stability, covering both transient and longer-term phenomena and presenting proven solutions to instability problems. The book describes equipment characteristics for transmission, generation, and distribution/load subsystems of a power system, together with methods for the modelling of equipment.It also contains static and dynamic computer simulation examples for small equivalent power systems and for a very large power system, plus an account of voltage stability associated with HVDC links.lt also contains planning and operating guidelines, computer methods for power flow and dynamic simulation, and descriptions of actual voltage instability incidents.

The special publication [3] is the result of several years of work by many experts from all around the globe, and was written to explain in great detail a variety of topics associated with voltage stability analysis of power systems, from both theoretical and practical points of view. A large number of theoretical and practical examples are used to illustrate the concepts and methodologies presented in this document. This document covers various fundamental concepts regarding stability analysis of non linear power systems, concentrating in particular on voltage stability issues. The authors have tried to explain most of the material through words and illustrations, as well as with the help of some simple examples, staying away, on purpose, from lengthy and complex mathematical descriptions. This document also concentrates on describing the techniques and tools, as well as the related modelling and data requirements used for off-line studies of voltage stability problems in power systems. Several practical examples are used throughout this document to illustrate the material presented in the document.

Paper [4] discusses voltage stability analysis of power systems using static and dynamic techniques. Using a small test system, results of time domain simulations are presented to clarify the phenomena of voltage instability and to better understand modelling requirements. The same system is then analyzed using a static approach in which modal analysis is performed using system conditions, or snapshots, which approximate different stages along the time domain trajectory. The results obtained using the dynamic and static methods are compared and shown to be consistent.

Paper [5] deals with voltage stability phenomena in a large interconnected grid like Indian grid. The main purpose of work presented is to study the effects of different controllers like generator field current limiter and under load tap changing transformer on voltage stability of major load area of this grid. For the analysis of voltage stability of a system, dynamic simulation of entire power system is required which is in detail in this paper. For large interconnected grid all power system components are modeled in detail in SIMULINK toolbox of MATLAB platform. Critical buses from two major load area are simulated for voltage stability and the bus voltages and nearby generators field currents plots are presented here.

Paper [6] presents an in depth investigation of incident and the possibilities of static or dynamic voltage instability leading to collapse situation. For static stability assessment, the continuation power flow method has been utilized, where as for dynamic voltage stability assessment, an eigen value analysis and participation factor analysis program has been developed and utilized.

Paper [7] presents brief introduction to the topic of voltage stability, discusses few methods of analysis and certain control measures to enhance the voltage stability of the system.

Paper [8] describes the Power System Analysis Toolbox (PSAT), an open source Matlab and GNU/Octave-based software package for analysis and design of small to medium size electric power systems.

Paper [9] describes the results for a large practical model of South-Southeast Brazilian system. The operating point considered is intended to duplicate real system conditions of March-1993, when a black out, due to voltage collapse, took place in the Rio de Janerio area.

Reference [10] presents bifurcation and continuation based computational techniques for voltage stability assessment and control. It reviews various aspects of bifurcation phenomena and includes numerical techniques that can detect the bifurcation points. It also discusses the application of continuation methods to power system voltage stability and provides extensive coverage on continuation power flow. It presents general sensitivity techniques available in the literature that includes margin sensitivity and also includes voltage stability margin boundary tracing.

Reference [11] presents an approach based on the modal analysis of system reduced Jacobian matrix. It involves the calculation of a group of smallest eigenvalues and its associated eigenvectors of the reduced Jacobian matrix. Each eigenvalue and its associated eigenvector define a mode through which system may become voltage unstable. The magnitudes of the eigenvalues provide a relative measure of the proximity of the system to voltage instability. Eigenvectors, on the other hand, provide information regarding the mechanism of voltage stability.

Chapter 2

Basic Concepts of Power System Voltage Stability

At any point of time, a power system operating condition should be stable, meeting various operational criteria, and it should also be secure in the event of any credible contingency. Present day power systems are being operated closer to their stability limits due to economic and environmental constraints. Maintaining a stable and secure operation of a power system is therefore a very important and challenging issue. Power system stability can be classified as seen in Fig. 2.1:

2.1 Voltage Collapse Incidents

Carson Taylor in his book reported voltage collapse incidents up to the year 1987. Since then there have been additional incidents that are related to voltage collapse. On July 2 1996 western region(WECC) of the United States experienced voltage collapse. During May, 1997 the Chilean power system experienced blackout due to voltage collapse that resulted in loss of 80 percentage of its load. The Chilean power system is mainly radial with prevalent power flows in south north direction. On July 12, 2004 Athens experienced a voltage collapse that resulted in the blackout of the entire Athens and Peloponnese peninsula.

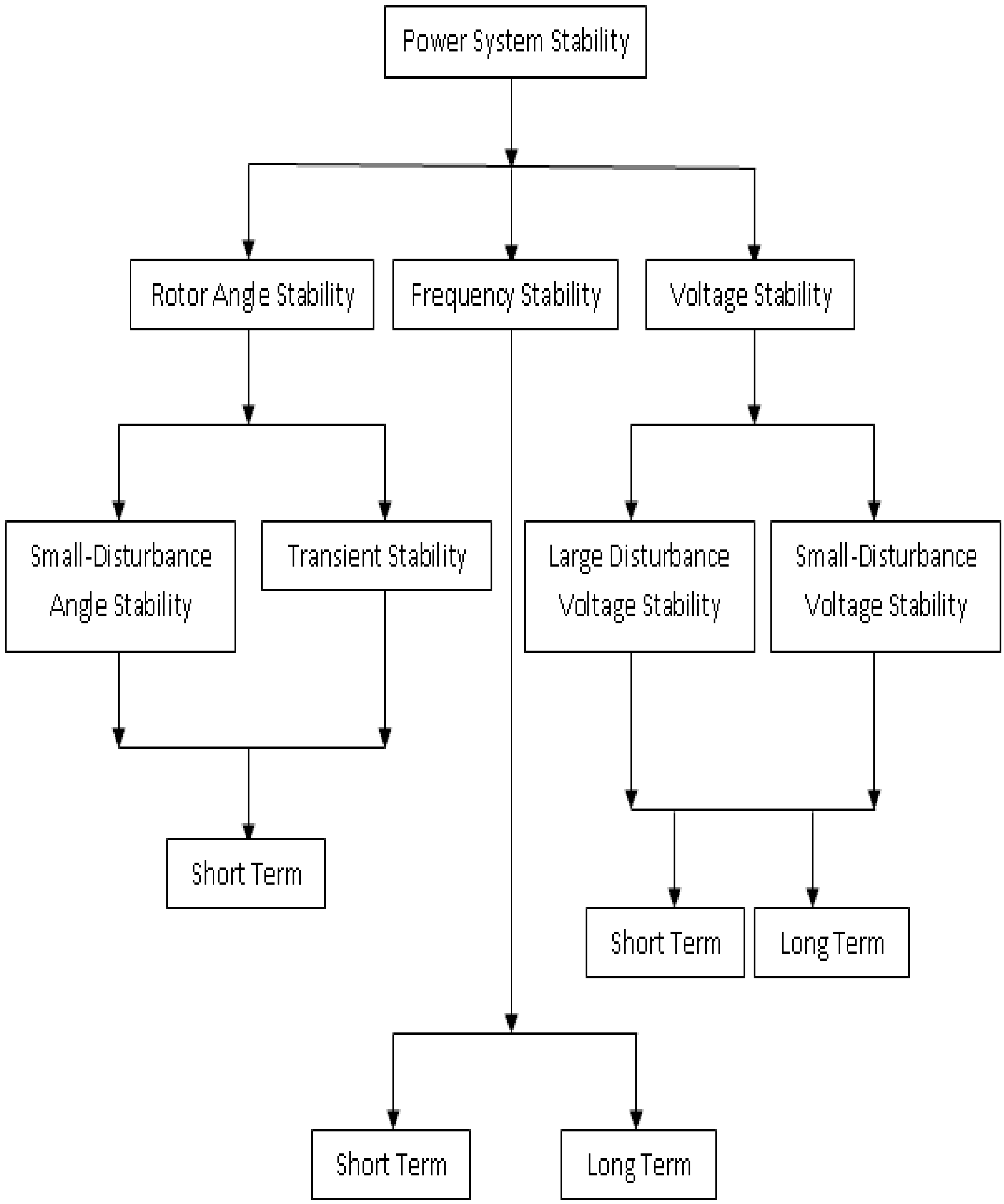

Figure 2.1: Classification of Power System Stability,Courtesy:Reference[10]

Date	Location	Time frame
11/30/86	SE Brazil, Paraguay	2 Seconds
5/17/85	South Florida	4 Seconds
8/22/87	Western Tennessee	10 Seconds
12/27/83	Sweden	50 Seconds
9/22/77	Jacksonville, Florida	Few Minutes
9/02/82	Florida	1-3 Minutes
11/26/82	Florida	1-3 Minutes
12/28/82	Florida	1-3 Minutes
12/30/82	Florida	2 Minutes
12/09/65	Brittany, France	?
11/20/76	Brittany, France	?
8/04/82	Belgium	4.5 Minutes
1/12/87	Western France	4-6 Minutes
7/23/87	Tokyo	20 Minutes
12/19/78	France	26 Minutes
8/22/70	Japan	30 Minutes
12/01/87	France	?

Figure 2.2: List of Voltage Collapse Incidents,Courtesy:Reference[10]

2.2 Introduction to Voltage Stability

In general terms, voltage stability is defined as ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. Instability that may result appears in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and the other elements by their protection leading to cascading outages that in turn may lead to loss of synchronism of some generators.

2.3 Classification of Voltage Stability

The time span of a disturbance in a power system, causing a potential voltage instability problem, can be classified into short-term and long-term. The corresponding voltage stability dynamics is called short term and long-term dynamics respectively. Automatic voltage regulators, excitation systems, turbine and governor dynamics fall in this short-term or 'transient' time scale, which is typically a few seconds. Induction motors, electronically operated loads and HVDC interconnections also fall in this category. If the system is stable, short-term disturbance dies out and the system enters a slow long-term dynamics. Components operating in the long-term time frame are transformer tap changers, limiters, boilers etc. Typically, this time frame is for a few minutes to tens of minutes. A voltage stability problem in the long-term time frame is mainly due to the large electrical distance between the generator and the load, and thus depends on the detailed topology of the power system.

Fig. 2.3 shows the components and controls that may affect the voltage stability of a power system, along with their time frame of operation. Examples of short-term or transient voltage instability can be found in the instability caused by rotor angle imbalance or loss of synchronism. Recent studies have shown that the integration of highly stressed HVDC links degrades the transient voltage stability of the system. There is not much scope for operator intervention in transient voltage instability. The transmission system operator (TSO) mainly relies on automatic emergency actions to avoid incumbent voltage instability. The automatic corrective actions are taken through protective devices to preserve operation of largest possible part of the power system by isolating the unstable part.

Long-term voltage instability (or mid-term or post-transient, as it is sometimes called) problems can occur in heavily loaded systems where the electrical distance is large between the generator and the load. The instability may be triggered by high power imports from remote generating stations, a sudden large disturbance, or a large load build up (such as morning or afternoon pickup). Operator intervention may be possible if the time scale is long enough. Timely application of reactive power compensation or load shedding may prevent this type of voltage instability.

From the point of view of techniques used to analyze the voltage stability, it is often useful to categorize the problem into small-disturbance and large-disturbance voltage stability. Small disturbance or steady state voltage stability deals with the situation when the system is subjected to a small perturbation, such that the system can be analyzed by linearizing around the pre-disturbance operating point. Steady state stability analysis is helpful in getting a qualitative picture of the system, i.e., how stressed the system is, or how close the system is, to the point of instability. Examples of steady state stability can be found in power systems experiencing gradual change in load.

Large-disturbance stability deals with larger disturbances such as loss of generation, loss of line etc. To analyze the large-disturbance stability, one has to capture the system dynamics for the whole time frame of the disturbance. A suitable model of the system has to be assumed and a detailed dynamic analysis has to be carried out in order to get a clear picture of the stability.

2.4 Voltage Stability of a Simple 2-Bus System

The basic concept of voltage stability can be explained with a simple 2-bus system shown in Fig. 2.4.The load is of constant power type. Real power transfer from bus 1 to 2 is given by,

$$P = \frac{EV}{X} \sin \delta \tag{2.1}$$

Reactive power transfer from bus 1 to 2 is given by,

$$Q = -\frac{V^2}{X} + \frac{EV}{X} \cos \delta \tag{2.2}$$

E = Voltage at Bus 1,

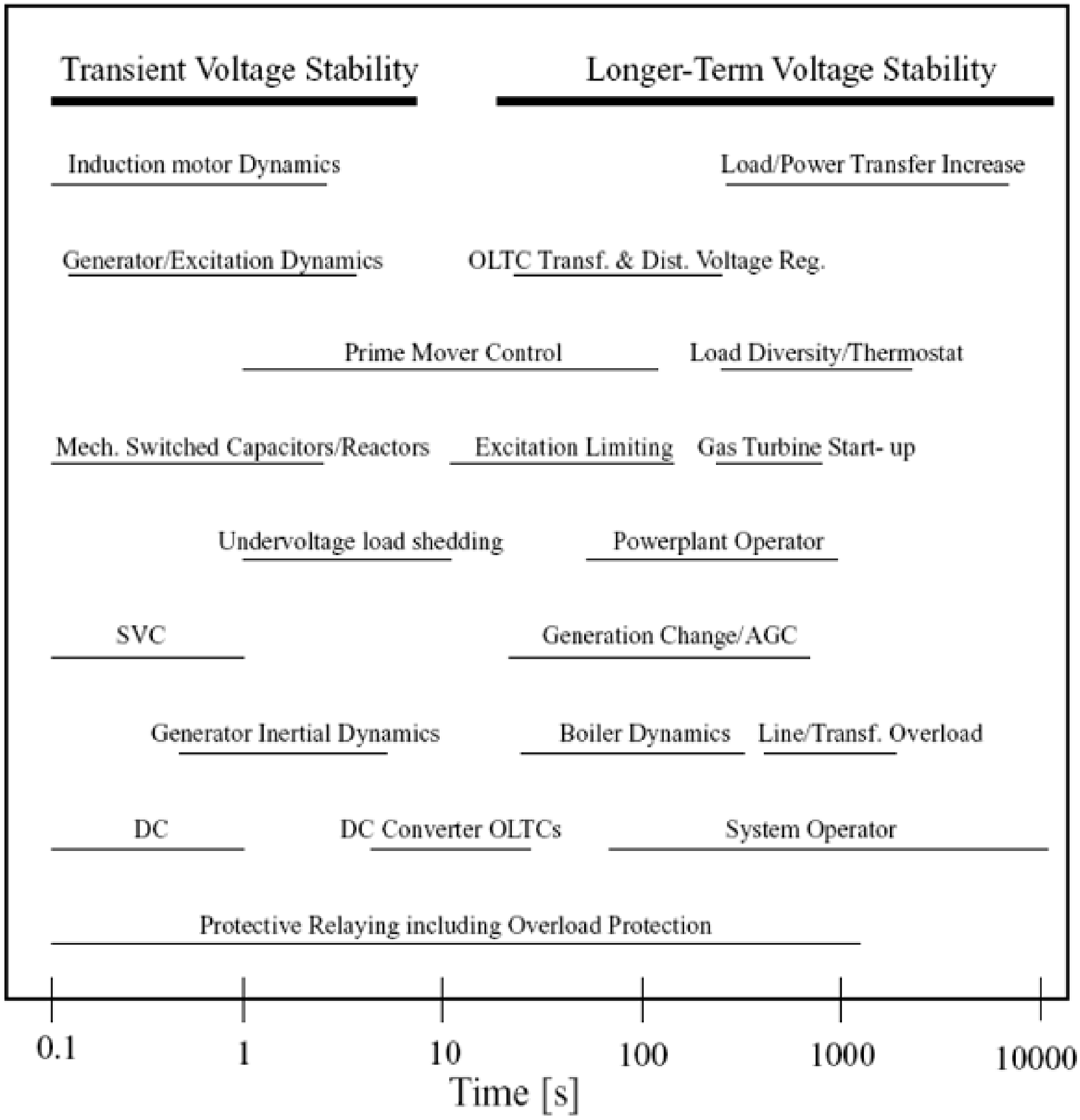

Figure 2.3: Classification of Power System Voltage Stability,Courtesy:Reference[12]

V = Voltage at Bus 2,

X = Impedance of the Line (neglecting resistance)

Normalizing the terms in (3.1) and (3.2) with $v = V/E$,$p = PX/E^2$,$q = QX/E^2$, one obtains,

$$p = v \sin \delta \tag{2.3}$$

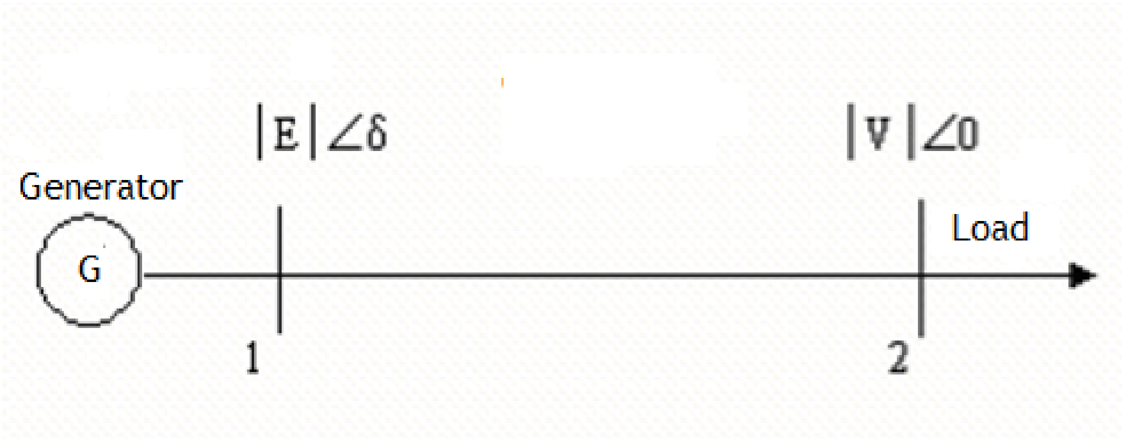

Figure 2.4: 2-Bus Test System,Courtesy:Reference[12]

$$q = -v^2 + v\cos\delta \tag{2.4}$$

Squaring the two equations above and rearranging,

$$v^4 + v^2(2q-1) + (p^2+q^2) = 0 \tag{2.5}$$

Positive real solutions of v from (1.5) are given by,

$$v = \sqrt{\frac{1}{2} - q \pm \sqrt{\frac{1}{4} - p^2 - q}} \tag{2.6}$$

A plot of v on the p-q-v plane is shown in Fig. 2.5. Corresponding to each point (p,q), there are two solutions for voltage, one is the high voltage or stable solution, which is the actual voltage at the bus, and the other one is the low voltage or unstable solution. The equator, along which the two solutions of v are equal, represents maximum power points. Starting from any operating point on the upper part of the surface, an increase in p or q or both brings the system closer to the maximum power point. An increase in p or q beyond the maximum power point makes the voltage unstable.

The preceding discussion illustrates voltage instability caused by an increase in

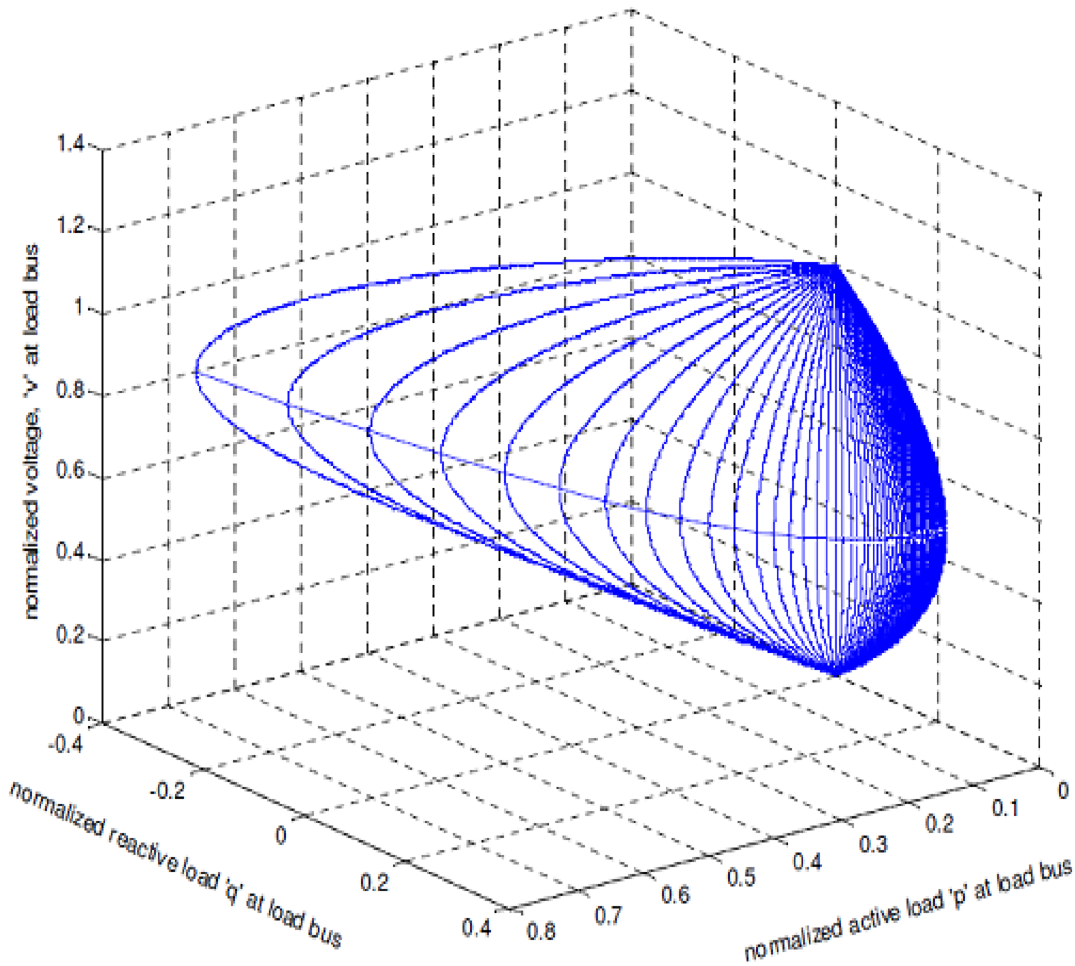

Figure 2.5: Variation of bus voltage with active and reactive loading for the 2-bus system,Courtesy:Reference[12]

system loading. In a real power system, voltage instability is caused by a combination of many additional factors which includes the transmission capability of the network, generator reactive power and voltage.

2.5 Tools for voltage stability analysis

Different methods exist in the literature for carrying out a steady state voltage stability analysis. The conventional methods can be broadly classified into the following types.

- P-V curve method.
- Q-V curve method and reactive power reserve.
- Methods based on sigularity of power flow Jacobian matrix at the point of voltage collapse.
- Continuation power flow method.

2.5.1 P-V curve method

This is one of the widely used methods of voltage stability analysis. This gives the available amount of active power margin before the point of voltage instability. For radial systems, the voltage of the critical bus is monitored against the changes in real power consumption. For large meshed networks, P can be the total active load in the load area and V can be the voltage of the critical representative bus. Real power transfer through a transmission interface or interconnection also can be studied by this method.

For a simple two-bus system as shown in Fig. 2.4,equation (3.6) gives real solutions of v^2,provided $(1 - 4q - 4p^2) \geq 0$.

Assuming a constant power factor load such that $q/p = k$ (constant), the inequality can be expressed as,

$$p \leq \frac{1}{2}((1 + k^2)^{\frac{1}{2}} - k) \tag{2.7}$$

For values of 'p' satisfying (3.7), there are two solutions of v as follows:

$$v_1 = (\frac{1}{2} - pk + (\frac{1}{4} - pk - p^2)^{\frac{1}{2}})^{\frac{1}{2}} \tag{2.8}$$

$$v_2 = (\frac{1}{2} - pk - (\frac{1}{4} - pk - p^2)^{\frac{1}{2}})^{\frac{1}{2}} \tag{2.9}$$

For real values of v_1 and v_2, the terms under the square roots should be positive. Hence, $(\frac{1}{2} - pk - (\frac{1}{4} - pk - p^2)^{\frac{1}{2}}) \geq 0$ or, $p^2(k^2 + 1) \geq 0$ which is always true.

Hence (3.7) is the inequality that determines the maximum value of p. Thus, representing the load as a constant power factor type, with a suitably chosen power factor, the active power margin can be computed from (1.7). For different values of load power factors, i.e., for different corresponding values of 'k', the normalized values of load active power are shown in Fig 2.6.

In practice, it is possible to find the Thevenin equivalent of any system with respect to the bus under consideration. It is to be noted that the generations are rescheduled at each step of change of the load. Some of the generators may hit the reactive power limit. The network topology may keep changing with respect to the critical bus, with change in the loading, thereby reducing the accuracy of the method. This method works well in the case of an infinite bus and isolated load scenario.

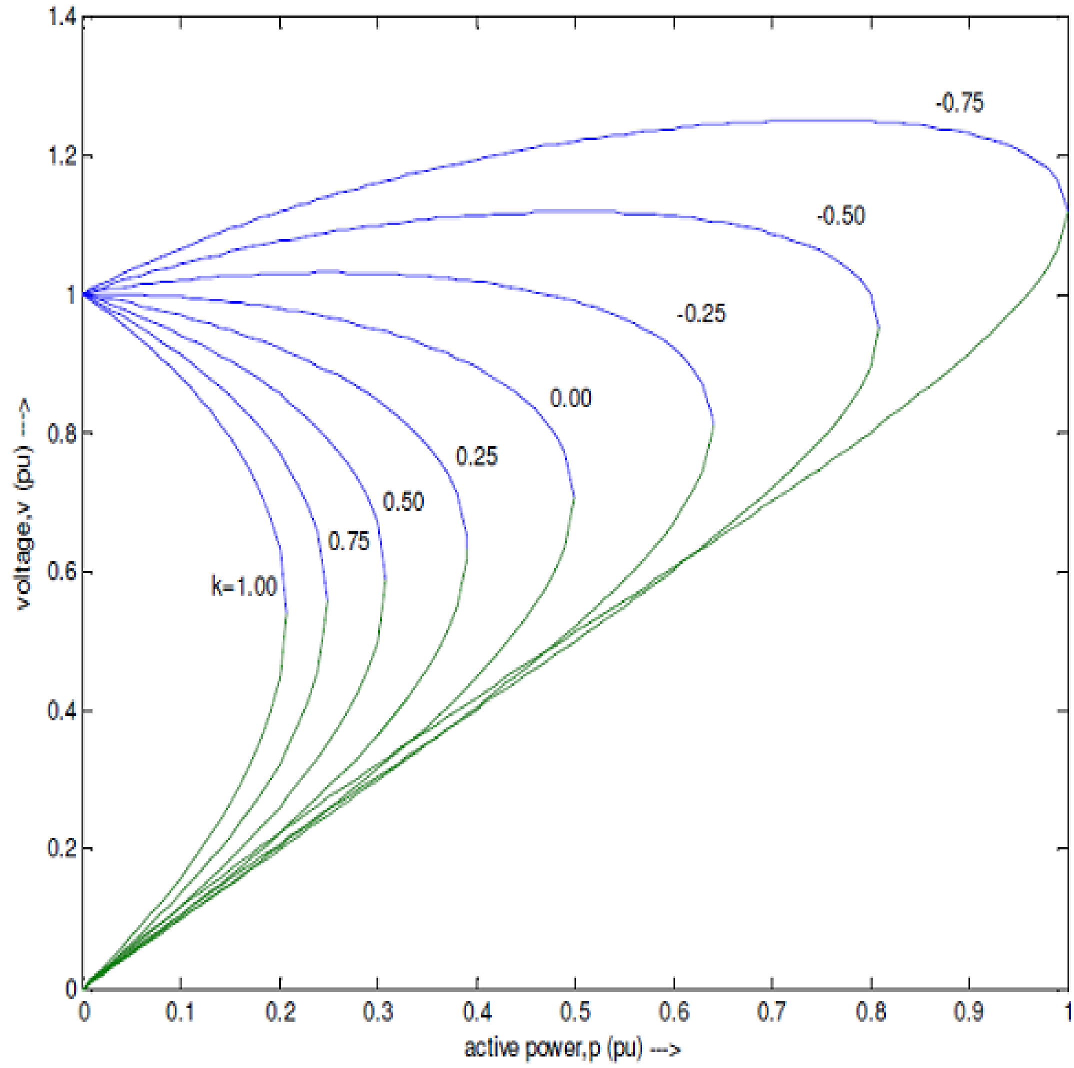

Figure 2.6: Normalized P-V curves for the 2-bus test system,Courtesy:Reference[12]

2.5.2 Q-V curve method and reactive power reserve

The Q-V curve method is one of the most popular ways to investigate voltage instability problems in power systems during the post transient period. Unlike the P-V curve method, it doesn't require the system to be represented as two-bus equivalent. Voltage at a test bus or critical bus is plotted against reactive power at that bus. A fictitious synchronous generator with zero active power and no reactive power limit is connected to the test bus. The power-flow program is run for a range of specified voltages with the test bus treated as the generator bus. Reactive power at the bus is noted from the power flow solutions and plotted against the specified voltage. The operating point corresponding to zero reactive power represents the condition when the fictitious reactive power source is removed from the test bus.

Voltage security of a bus is closely related to the available reactive power reserve, which can be easily found from the Q-V curve of the bus under consideration. The reactive power margin is the MVAR distance between the operating point and either the nose point of the Q-V curve or the point where capacitor characteristics at the bus are tangent to the Q-V curve. Stiffness of the bus can be qualitatively evaluated from the slope of the right portion of the Q-V curve. The greater the slope is, the less stiff is the bus, and therefore the more vulnerable to voltage collapse it is. Weak busses in the system can be determined from the slope of Q-V curve.

For the simple two-bus system shown in Fig 2.4, equations of Q-V curves for constant power loads can be derived as follows. From (3.3) the power angle is computed for specified active power and used in (3.4). For a range of values of voltage and different active power levels, normalized Q-V curves are shown in Figure 1.5. The critical point or nose point of the characteristics corresponds to the voltage where dQ/dV becomes zero. If the minimum point of the Q-V curve is above the horizontal axis, then the system is reactive power deficient. Additional reactive power sources are needed to prevent a voltage collapse. In Fig 2.7, curves for p=1.00 and p=0.75 signify reactive power deficient busses. Buses having Q-V curves below the horizontal axis have a positive reactive power margin. The system may still be called reactive power deficient, depending on the desired margin.

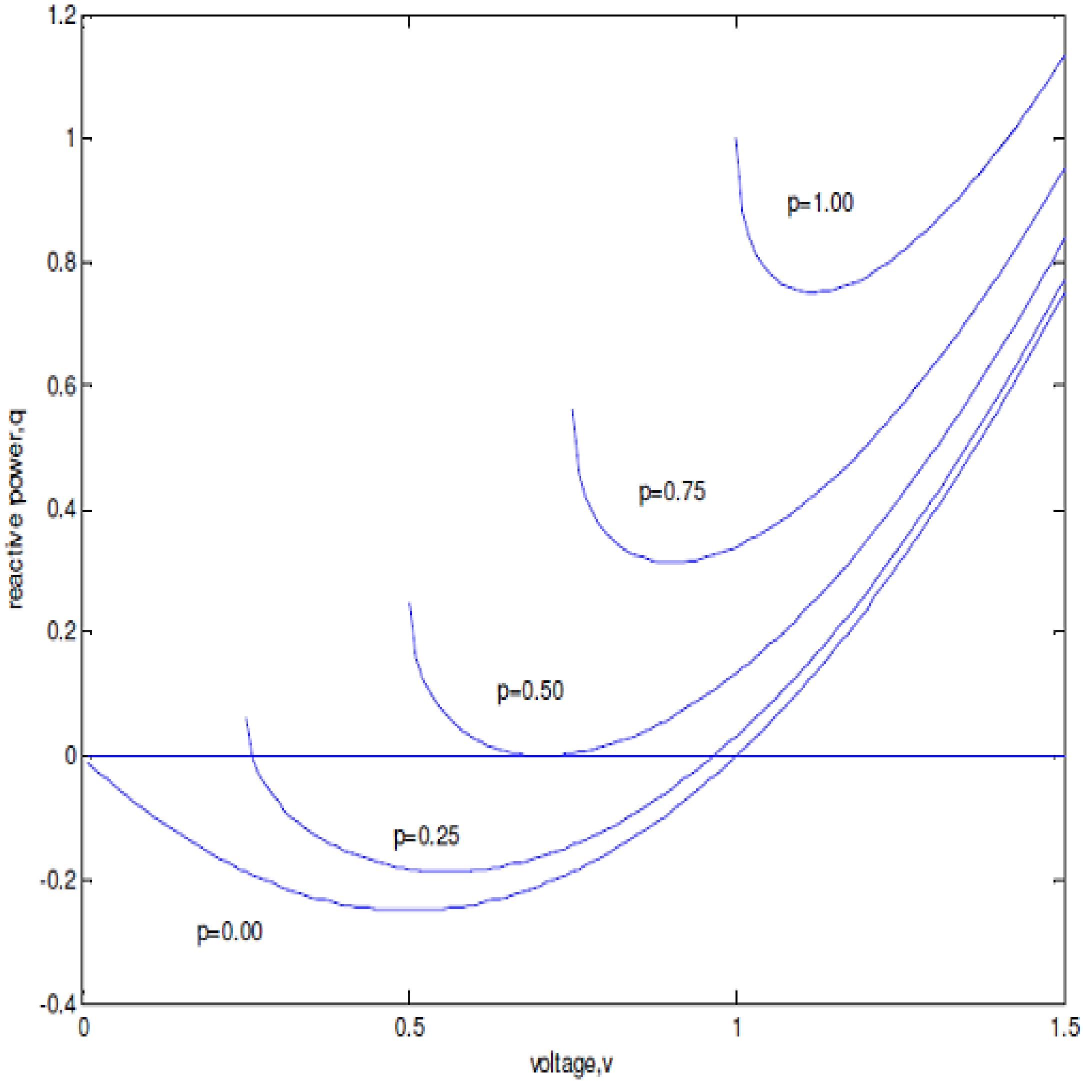

Figure 2.7: Normalized Q-V curves for the 2-bus test system,Courtesy:Refrence[12]

2.5.3 Methods based on singularity of power flow Jacobian matrix at the point of voltage collapse

A number of methods have been proposed in the literature that uses the fact that the power flow Jacobian matrix becomes singular at the point of voltage collapse. Modal analysis of the Jacobian matrix is one of the most popular methods.

This method involves the calculation of a group of smallest eigenvalues and associated eigenvectors of the reduced Jacobian matrix.Each eigenvalue and its associated eigenvector define a mode through which system may become voltage unstable.The magnitudes of the eigenvalues provide a relative measure of the proximity of the system to voltage instability.Eigenvectors, on the other hand, provide information regarding the mechanism of voltage instability.A detailed description of this method is given in further chapters.

2.5.4 Continuation power flow method

It is numerically difficult to obtain a power flow solution near the voltage collapse point, since the Jacobian matrix becomes singular. Continuation power flow is a technique by which the power flow solutions can be obtained near or at the voltage collapse point.A detailed description of this method is given in further chapters.

Chapter 3

Method of Analysis

3.1 Introduction

It is important to have an analytical method to predict the voltage collapse in the power system, particularly with a complex and large one. The modal analysis or eigenvalue analysis can be used effectively as a powerful analytical tool to verify both proximity and mechanism of voltage instability. It involves the calculation of a small number of eigenvalues and related eigenvectors of a reduced Jacobian matrix. However, by using the reduced Jacobian matrix the focus is on the voltage and the reactive power characteristics. The weak modes (weak buses) of the system can be identified from the system reactive power variation sensitivity to incremental change in bus voltage magnitude. The stability margin or distance to voltage collapse can be estimated by generating the Q-V curves for that particular bus.

3.2 Modal Analysis

The modal analysis mainly depends on the power-flow Jacobian matrix. An algorithm for the modal method analysis used in this study is shown in figure 3.1. Partitioned matrix equation can be rewritten as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \tag{3.1}$$

By letting $\Delta P = 0$ in Equation 3.1:

$$\Delta P = 0 = J_{11}\Delta\theta + J_{12}\Delta V, \Delta\theta = -J_{11}^{-1}J_{12}\Delta V \tag{3.2}$$

and

$$\Delta Q = J_{21}\Delta\theta + J_{22}\Delta V \tag{3.3}$$

Substituting Equation 3.2 in Equation 3.3:

$$\Delta Q = J_R \Delta V \tag{3.4}$$

where

$J_R = [J_{22} - J_{21}J_{11}^{-1}J_{12}]$, J_R is the reduced Jacobian matrix of the system. Equation 3.4 can be written as

$$\Delta V = J_R^{-1}\Delta Q \tag{3.5}$$

The matrix J_R represents the linearized relationship between the incremental changes in bus voltage (ΔV) and bus reactive power injection (ΔQ). The system voltage is affected by both real and reactive power variations. In order to focus the study of the reactive demand and supply problem of the system as well as minimize computational effort by reducing dimensions of the Jacobian matrix J the real power ($\Delta P = 0$) and angle part from the system in Equation 3.1 are eliminated.

The eigenvalues and eigenvectors of the reduced order Jacobian matrix J_R are used for the voltage stability characteristics analysis. Voltage instability can be detected by identifying modes of the eigenvalues matrix J_R. The magnitude of the eigenvalues provides a relative measure of proximity to instability. The eigenvectors on the other hand present information related to the mechanism of loss of voltage stability.

Eigenvalue analysis of J_R results in the following:

$$J_R = \phi \Lambda \Gamma \tag{3.6}$$

where

ϕ= right eigenvector matrix of J_R

Γ= left eigenvector matrix of J_R

Λ= diagonal eigenvalue matrix of J_R

Equation 3.6 can be written as:

$$J_R^{-1} = \phi \Lambda^{-1} \Gamma \tag{3.7}$$

Where $\phi\Gamma = I$

Substituting Equation 3.7 in Equation 3.5:

$\Delta V = \phi \Lambda^{-1} \Gamma \Delta Q$

or

$$\Delta V = \Sigma \frac{\phi_i \Gamma_i}{\lambda_i} \Delta Q \tag{3.8}$$

where λ_i is the i^{th} eigenvalue, ϕ_i is the i^{th} column right eigenvector and Γ_i is the i^{th} row left eigenvector of matrix J_R.

Each eigenvalue λ_i and corresponding right and left eigenvectors ϕ_i and Γ_i, define the i^{th} mode of the system.The i^{th} modal reactive power variation is defined as:

$$\Delta Q_{mi} = K_i \phi_i \tag{3.9}$$

where K_i is a scale factor to normalize vector ΔQ_i so that

$$K_i^2 \sum \phi_{ji}^2 = 1 \tag{3.10}$$

with ϕ_{ji} the j^{th} element of ϕ_i.

The corresponding i^{th} modal voltage variation is:

$$\Delta V_{mi} = \frac{1}{\lambda_i} \Delta Q_{mi} \tag{3.11}$$

Equation 3.11 can be summarized as follows:

a. If $\lambda_i = 0$, the i^{th} modal voltage will collapse because any change in that modal reactive power will cause infinite modal voltage variation.

b. If $\lambda_i > 0$, the i^{th} modal voltage and i^{th} reactive power variation are along the same direction,indicating that the system is voltage stable.

c. If $\lambda_i < 0$, the i^{th} modal voltage and the i^{th} reactive power variation are along the opposite directions, indicating that the system is voltage unstable.

In general it can be said that, a system is voltage stable if the eigenvalues of J_R are all positive. The relationship between system voltage stability and eigenvalues of the J_R matrix is best understood by relating the eigenvalues with the V-Q sensitivities of each bus (which must be positive for stability). J_R can be taken as a symmetric matrix and therefore the eigenvalues of J_R are close to being purely real. If all the eigenvalues are positive, J_R is positive definite and the V-Q sensitivities are also positive, indicating that the system is voltage stable.
The system is considered voltage unstable if at least one of the eigenvalues is negative. A zero eigenvalue of J_R means that the system is on the verge of voltage instability. Furthermore, small eigenvalues of J_R determine the proximity of the system to being voltage unstable.

There is no need to evaluate all the eigenvalues of J_R of a large power system because it is known that once the minimum eigenvalues becomes zeros the system Jacobian matrix becomes singular and voltage instability occurs. So the eigenvalues of importance are the critical eigenvalues of the reduced Jacobian matrix J_R. Thus, the smallest eigenvalues of J_R are taken to be the least stable modes of the system. The rest of the eigenvalues are neglected because they are considered to be strong enough modes. Once the minimum eigenvalues and the corresponding left and right eigenvectors have been calculated the participation factor can be used to identify the weakest node or bus in the system.

3.3 Identification of the Weak Load Buses

The minimum eigenvalues, which become close to instability, need to be observed more closely. The appropriate definition and determination as to which node or load bus participates in the selected modes become very important. This necessitates a tool, called the participation factor, for identifying the weakest nodes or load buses that are making significant contribution to the selected modes.
If ϕ_i and Γ_i represent the right- and left- hand eigenvectors, respectively, for the eigenvalue λ_i of the matrix J_R, then the participation factor measuring the participation of the k^{th} bus in i^{th} mode is defined as

$$P_{ki} = \phi_{ki}\Gamma_{ik} \tag{3.12}$$

Note that for all the small eigenvalues, bus participation factors determine the area close to voltage instability. Equation 3.12 implies that P_{ki} shows the participation of i^{th} eigenvalue to the V-Q sensitivity at bus k. The node or bus k with highest P_{ki} is the most contributing factor in determining the V-Q sensitivity at i^{th} mode. Therefore, the bus participation factor determines area close to voltage instability provided by the smallest eigenvalue of J_R.

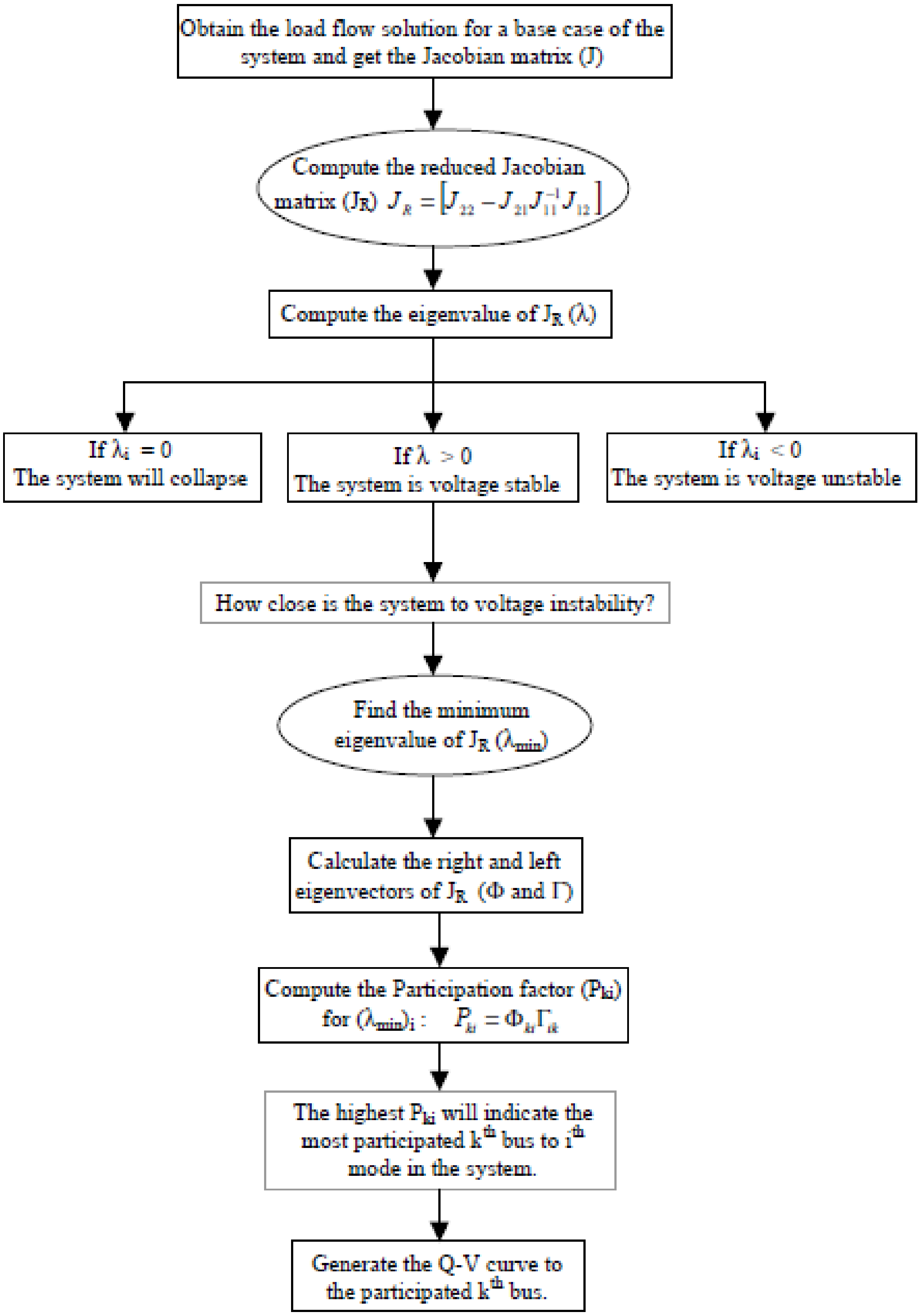

Figure 3.1: Algorithm for the voltage stability analysis

Chapter 4

IEEE 30 Bus System Simulation

4.1 Introduction

The Modal analysis method has been successfully applied to two different electric power systems. The Q-V cures will be generated for selected buses in order to monitor the voltage stability margin.

4.2 Test Systems Description

Two systems have been simulated and tested in this project to illustrate the proposed analysis methods:

- The IEEE 30 Bus Test Case represents a portion of the American Electric Power System (in the Midwestern US).
- Mumbai Grid

4.3 Analysis with Constant Impedance Load

The modal analysis method is applied to the two suggested test systems. The voltage profile of the buses is presented from the load flow simulation. Then, the minimum

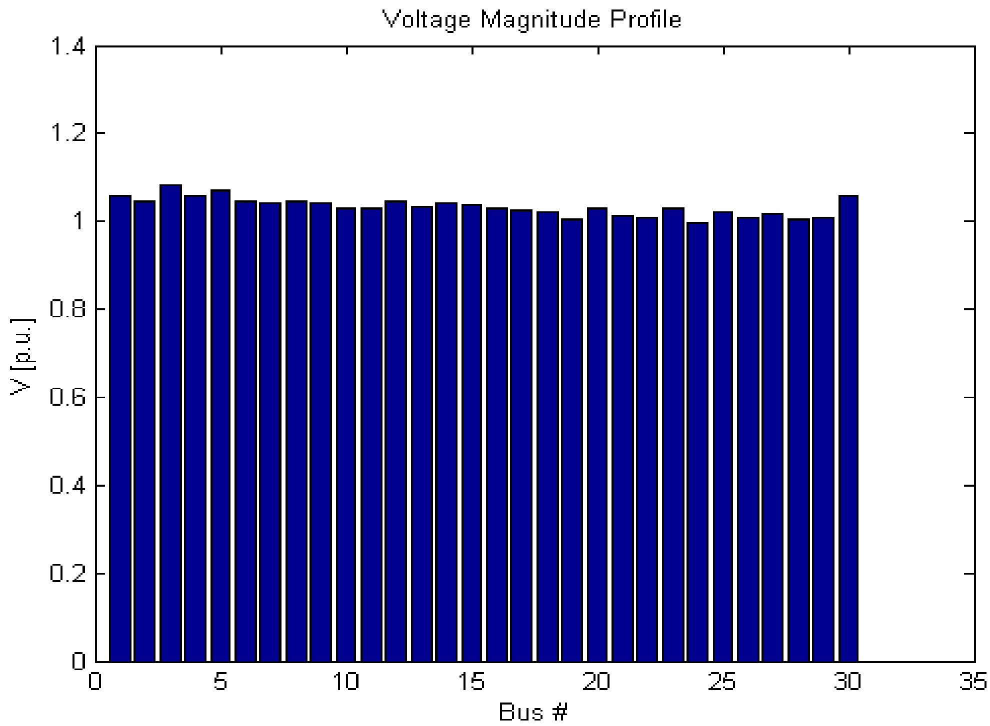

Figure 4.1: Voltage profiles of all buses of the IEEE 30 bus system

eigenvalue of the reduced Jacobian matrix is calculated. After that, the weakest load buses, which are subject to voltage collapse, are identified by computing the participating factors.

4.3.1 The IEEE 30 Bus System

Figure 4.1 shows the voltage profile of all buses of the IEEE 30 Bus system as obtained from the load flow. It can be seen that all the bus voltages are within the acceptable level except bus number 30, which is about 0.9975 p.u. The lowest voltage compared to the other buses can be noticed in bus number 30.

Note that all the eigenvalues are positive which means that the system voltage is stable. From Table 4.1, it can be noticed that the minimum eigenvalue $\lambda = 0.53692$ is the most critical mode. The participating factor for this mode has been calculated and the result is shown in Table 4.7.The largest participation factor value (0.22748)

Table 4.1: Eigenvalues of the standard power jacobian matrix

Eigevalue	Most associated bus	Real part	Imaginary part
Eig jlfr # 1	Bus6	124.92165	0.00000
Eig jlfr # 2	Bus21	115.11215	0.00000
Eig jlfr # 3	Bus4	71.47123	0.00000
Eig jlfr # 4	Bus10	69.46883	0.00000
Eig jlfr # 5	Bus6(twt)	40.20970	0.00000
Eig jlfr # 6	Bus19	38.15415	0.00000
Eig jlfr # 7	Bus12	35.57063	0.00000
Eig jlfr # 8	Bus15	23.69553	0.00000
Eig jlfr # 9	Bus28	23.29154	0.00000
Eig jlfr #10	Bus17	20.36595	0.00000
Eig jlfr #11	Bus7	19.04943	0.00000
Eig jlfr #12	Bus25	17.46951	0.00000
Eig jlfr #13	Bus24	14.31068	0.00000
Eig jlfr #14	Bus18	13.91223	0.00000
Eig jlfr #15	Bus3	11.93262	0.00000
Eig jlfr #16	Bus30	0.53692	0.00000
Eig jlfr #17	Bus19	1.11063	0.00000
Eig jlfr #18	Bus26	1.80866	0.00000
Eig jlfr #19	Bus16	9.20608	0.00000
Eig jlfr #20	Bus25	7.75015	0.00000
Eig jlfr #21	Bus19	3.79981	0.00000
Eig jlfr #22	Bus14	4.22907	0.00000
Eig jlfr #23	Bus30	6.34626	0.00000
Eig jlfr #24	Bus16	5.65455	0.00000
Eig jlfr #25	Bus1	999.00000	0.00000
Eig jlfr #26	Bus11	999.00000	0.00000
Eig jlfr #27	Bus13	999.00000	0.00000
Eig jlfr #28	Bus2	999.00000	0.00000
Eig jlfr #29	Bus5	999.00000	0.00000
Eig jlfr #30	Bus8	999.00000	0.00000

at bus 30 indicates the highest contribution of this bus to the voltage collapse.

The P-V curve was computed for the weakest bus of the critical mode in the IEEE 30 Bus system as expected by the modal analysis method. It can be seen clearly that bus 30 is the most critical bus compared the other buses.

Table 4.2: Eigenvalues of the standard power jacobian matrix

Eigevalue	Most associated bus	Real part	Imaginary part
Eig jlfr #1	Bus30	0.53692	0.00000

Table 4.3: Participation factors (euclidean norm)

	Bus1	Bus10	Bus11	Bus12	Bus13
Eig jlfr #1	0.00000	0.00880	0.00000	0.00306	0.00000

Table 4.4: Participation factors (euclidean norm)

	Bus14	Bus15	Bus16	Bus17	Bus18
Eig jlfr #1	0.00674	0.00923	0.00616	0.00853	0.01334

Table 4.5: Participation factors (euclidean norm)

	Bus19	Bus2	Bus20	Bus21	Bus22
Eig jlfr #1	0.01415	0.00000	0.01345	0.01160	0.01316

Table 4.6: Participation factors (euclidean norm)

	Bus23	Bus24	Bus25	Bus26	Bus27
Eig jlfr #1	0.02044	0.03409	0.10820	0.17828	0.11093

Table 4.7: Participation factors (euclidean norm)

	Bus28	Bus29	Bus3	Bus30	Bus4
Eig jlfr #1	0.00249	0.20813	0.00025	0.22748	0.00037

Table 4.8: Participation factors (euclidean norm)

	Bus5	Bus6	Bus7	Bus8	Bus6(twt)
Eig jlfr #1	0.00000	0.00041	0.00015	0.00000	0.00053

Table 4.9: Statistics

Number of buses	30.00000
# of eigs with re(μ) < 0	0.00000
# of eigs with re(μ) > 0	1.00000
# of real eigs	1.00000
# of complex pairs	0.00000
# of zero eigs	0.00000

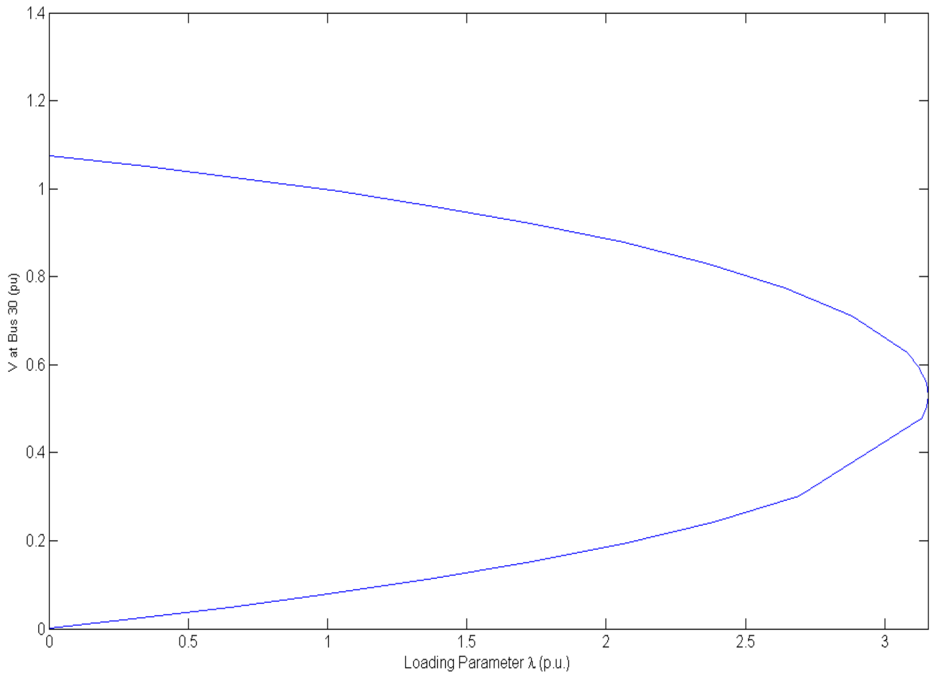

Figure 4.2: P-V Curve at bus 30 for the IEEE 30 bus system

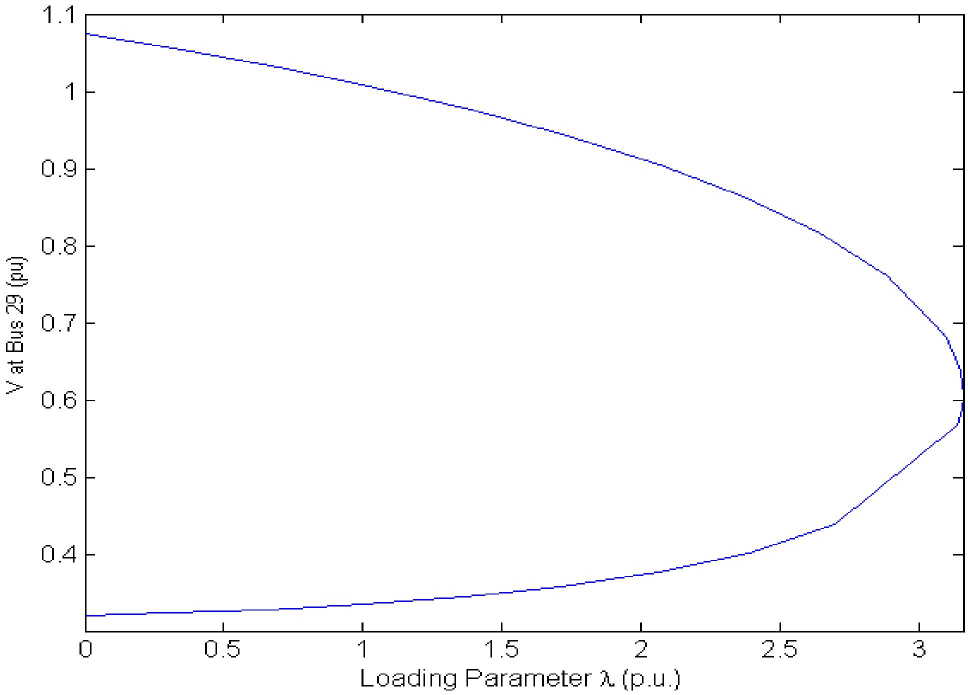

Figure 4.3: P-V Curve at bus 29 for the IEEE 30 bus system

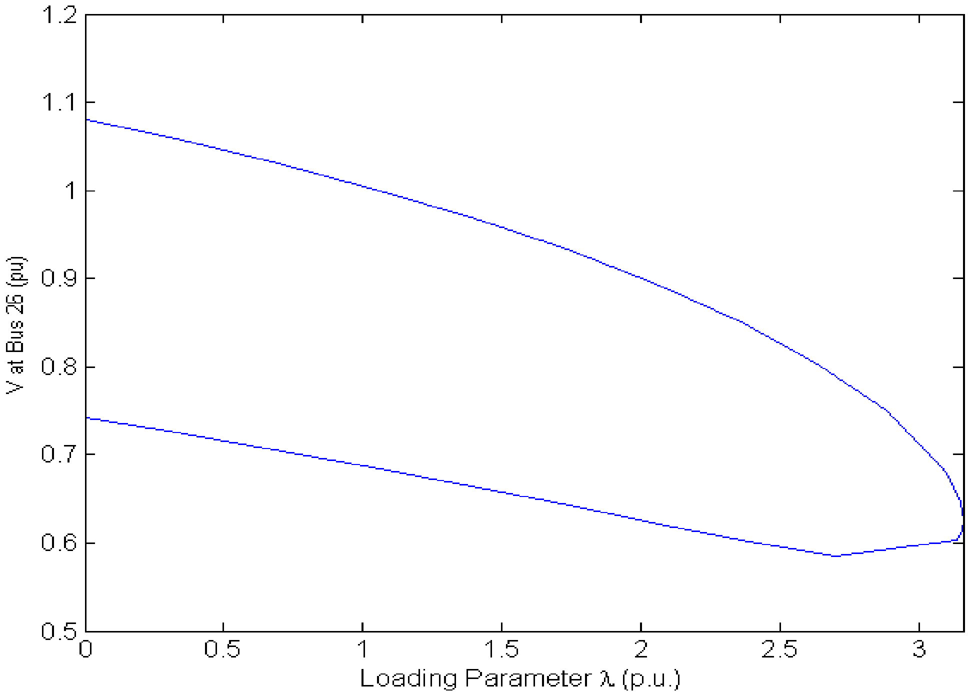

Figure 4.4: P-V Curve at bus 26 for the IEEE 30 bus system

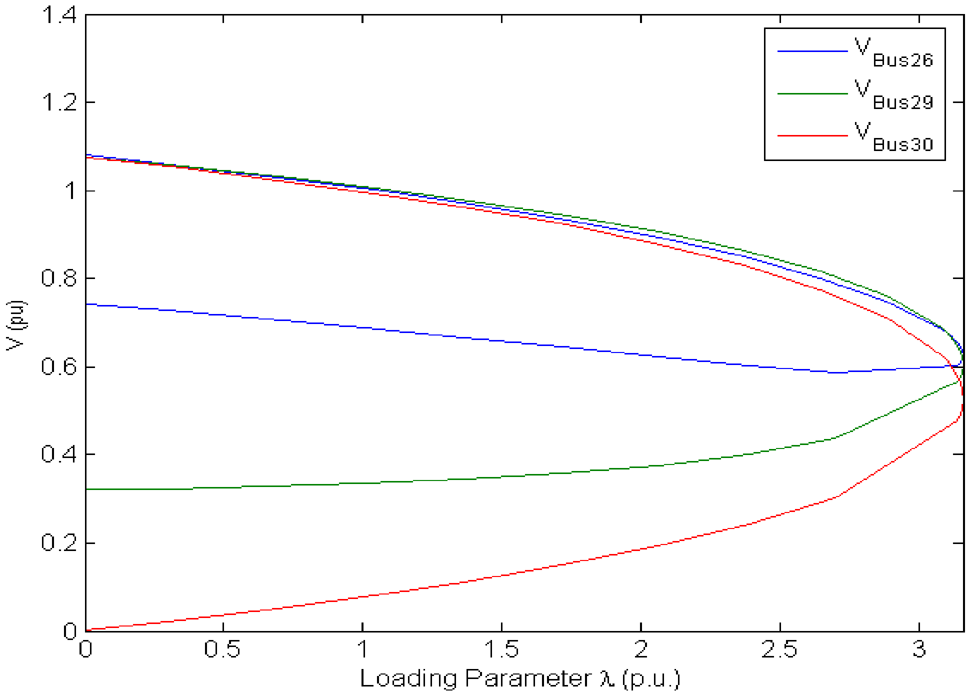

Figure 4.5: P-V Curves at bus 30,29 and 26 for the IEEE 30 bus system

Chapter 5

Mumbai Grid Simulation:Part A

5.1 Analysis with Constant Impedance Load

5.1.1 Mumbai Grid

Light Loading Condition

Figure 5.1 shows the voltage profile of all buses of the Mumbai Grid as obtained from the load flow. It can be seen that all the bus voltages are within the acceptable level except bus Chola 110, which is about 1.0082 p.u. The lowest voltage compared to the other buses can be noticed in bus Chola 110.

Table 5.1: Eigenvalues of the standard power jacobian matrix

Eigevalue	Most associated bus	Real part	Imaginary part
Eig jlfr #1	Chola_110	5.24553	0.00000

Note that all the eigenvalues are positive which means that the system voltage is stable. From Table 5.1, it can be noticed that the minimum eigenvalue $\lambda = 5.24553$ is the most critical mode. The participating factor for this mode has been calculated and the result is shown in Table 5.5.The largest participation factor value (0.09963) at bus Chola 110 indicates the highest contribution of this bus to the voltage collapse.

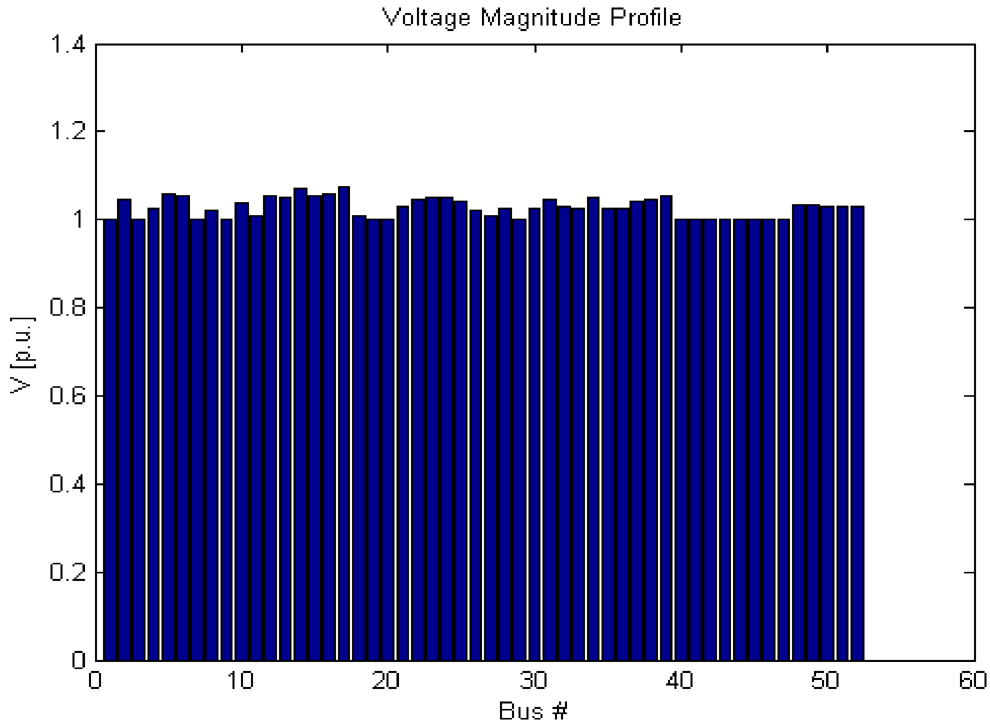

Figure 5.1: Voltage profiles of all buses of the Mumbai Grid

Table 5.2: Participation factors (euclidean norm)

	(53)_bhivpuri_5	A_trombay_100	Ambernath_110	Bmc_110	B_trombay_220
Eig jlfr #1	0.00000	0.00466	0.08788	0.05995	0.00000

Table 5.3: Participation factors (euclidean norm)

	Best_backbay_110	Bhira_11	Bhira_110	Bhira_11_2	Bhira_220
Eig jlfr #1	0.00724	0.00000	0.00243	0.00000	0.00133

Table 5.4: Participation factors (euclidean norm)

	Bhivpuri_110	Carnac_110	Carnac_110_2	Carnac_22	Carnac_220
Eig jlfr #1	0.02127	0.00734	0.00692	0.01503	0.00196

Table 5.5: Participation factors (euclidean norm)

	Carnac_220_2	Carnac_22_2	Chola_110	Dah_u1	Dah_u2
Eig jlfr #1	0.00208	0.01591	0.09963	0.00000	0.00000

Table 5.6: Participation factors (euclidean norm)

	Dahanu_220	Dharavi_110	Dharavi_220	Grant road	Kchembur
Eig jlfr #1	0.00590	0.00693	0.00171	0.00699	0.00582

Table 5.7: Participation factors (euclidean norm)

	Kalwa	Kalyan_110	Khopoli_110	Khopoli_5	Kolshet_110
Eig jlfr #1	0.07718	0.09510	0.00989	0.00000	0.06953

Table 5.8: Participation factors (euclidean norm)

	Maha_100	Malad_110	Mankhurd	Parel_110	Saki_110
Eig jlfr #1	0.00687	0.05149	0.01790	0.00676	0.06924

Table 5.9: Participation factors (euclidean norm)

	Salsette_110	Salsette_220	Tchembur	Tec_backbay_220	Tr_u1
Eig jlfr #1	0.06059	0.00576	0.00478	0.00672	0.00000

Table 5.10: Participation factors (euclidean norm)

	Tr_u2	Tr_u3	Tr_u44	Tr_u5	Tr_u6
Eig jlfr #1	0.00000	0.00000	0.00000	0.00000	0.00000

Table 5.11: Participation factors (euclidean norm)

	Tr_u7a	Tr_u_7b	T_borivli_110	T_borivli_220	Versova_110
Eig jlfr #1	0.00000	0.00000	0.03918	0.00852	0.05773

Table 5.12: Participation factors (euclidean norm)

	Versova_220	Vikhroli
Eig jlfr #1	0.00726	0.04456

Table 5.13: Statistics

Number of buses	52.00000
# of eigs with re(μ) < 0	0.00000
# of eigs with re(μ) > 0	1.00000
# of real eigs	1.00000
# of complex pairs	0.00000
# of zero eigs	0.00000

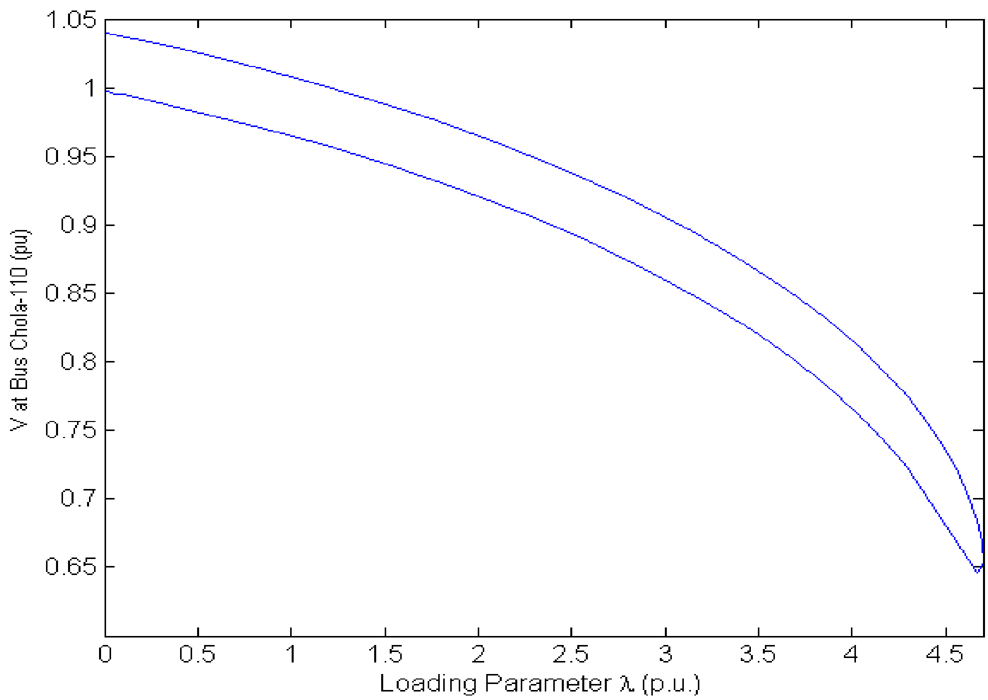

Figure 5.2: P-V Curve at bus Chola 110 for the Mumbai Grid

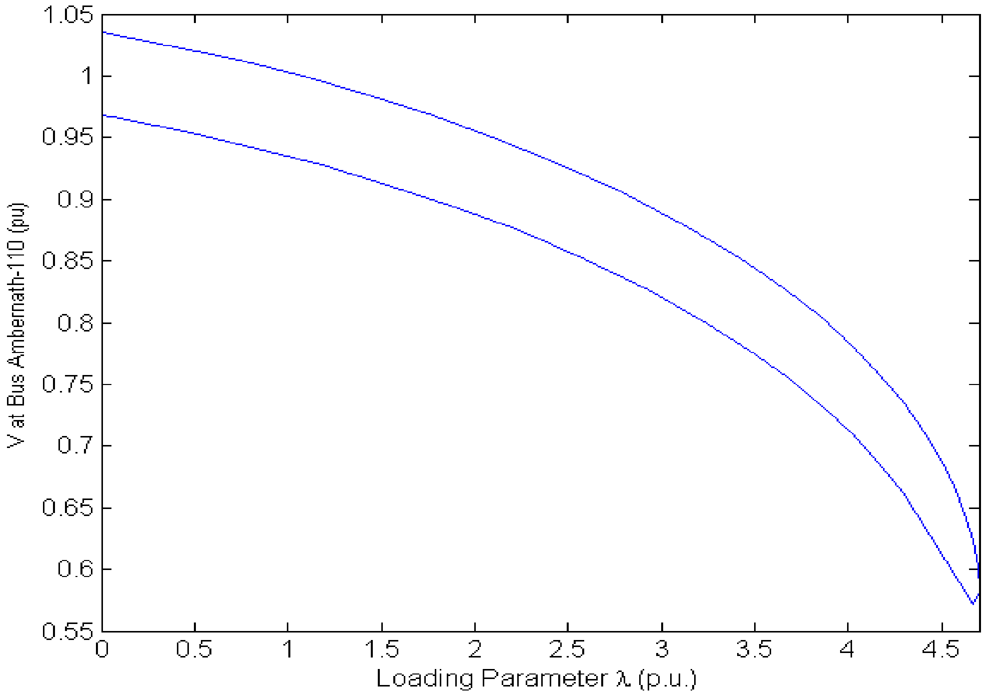

Figure 5.3: P-V Curve at bus Ambernath 110 for the Mumbai Grid

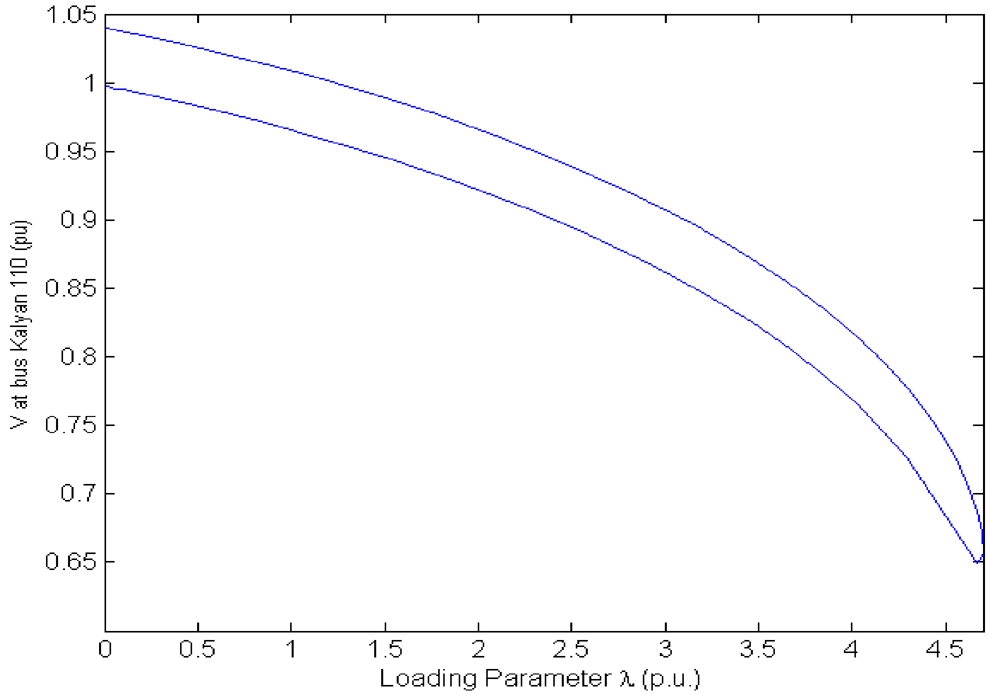

Figure 5.4: P-V Curve at bus Kalyan 110 for the Mumbai Grid

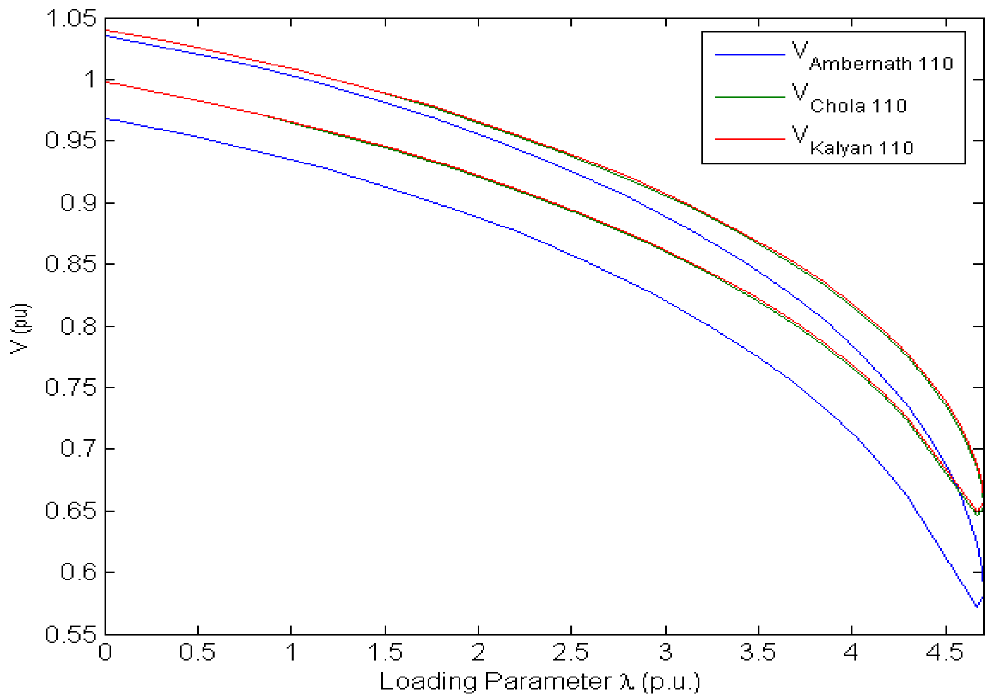

Figure 5.5: P-V Curve at buses Chola 110,Ambernath 110 and Kalyan 110 for the Mumbai Grid

Chapter 6

Mumbai Grid Simulation:Part B

6.1 Analysis with Constant Impedance Load

6.1.1 Mumbai Grid

Peak Loading Condition

Figure 5.1 shows the voltage profile of all buses of the Mumbai Grid as obtained from the load flow. It can be seen that all the bus voltages are within the acceptable level except bus Chola 110, which is about 0.99299 p.u. The lowest voltage compared to the other buses can be noticed in bus Chola 110.

Table 6.1: Eigenvalues of the standard power jacobian matrix

Eigevalue	Most associated bus	Real part	Imaginary part
Eig jlfr #1	Chola_110	5.07179	0.00000

Note that all the eigenvalues are positive which means that the system voltage is stable. From Table 6.1, it can be noticed that the minimum eigenvalue $\lambda = 5.07179$ is the most critical mode. The participating factor for this mode has been calculated and the result is shown in Table 6.5.The largest participation factor value (0.09599) at bus Chola 110 indicates the highest contribution of this bus to the voltage collapse.

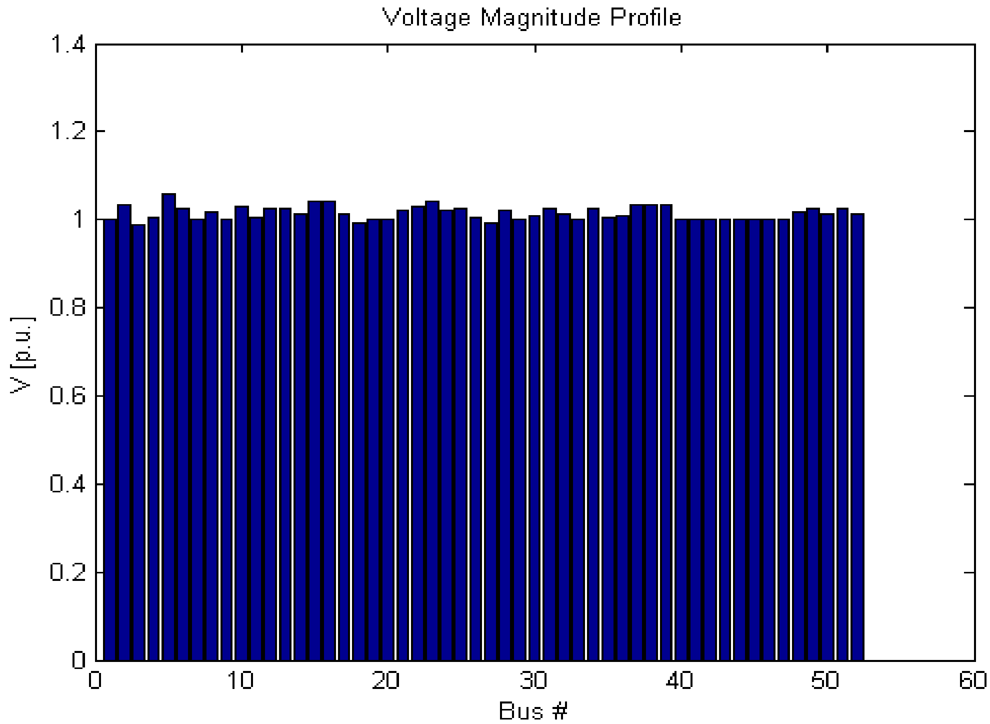

Figure 6.1: Voltage profiles of all buses of the Mumbai Grid

Table 6.2: Participation factors (euclidean norm)

	(53)_bhivpuri_5	A_trombay_100	Ambernath_110	Bmc_110	B_trombay_220
Eig jlfr #1	0.00000	0.00506	0.08419	0.05910	0.00000

Table 6.3: Participation factors (euclidean norm)

	Best_backbay_110	Bhira_11	Bhira_110	Bhira_11_2	Bhira_220
Eig jlfr #1	0.00839	0.00000	0.00238	0.00000	0.00138

Table 6.4: Participation factors (euclidean norm)

	Bhivpuri_110	Carnac_110	Carnac_110_2	Carnac_22	Carnac_220
Eig jlfr #1	0.02025	0.00864	0.00790	0.02022	0.00221

Table 6.5: Participation factors (euclidean norm)

	Carnac_220_2	Carnac_22_2	Chola_110	Dah_u1	Dah_u2
Eig jlfr #1	0.00242	0.02210	0.09599	0.00000	0.00000

Table 6.6: Participation factors (euclidean norm)

	Dahanu_220	Dharavi_110	Dharavi_220	Grant road	Kchembur
Eig jlfr #1	0.00572	0.00744	0.00183	0.00792	0.00626

Table 6.7: Participation factors (euclidean norm)

	Kalwa	Kalyan_110	Khopoli_110	Khopoli_5	Kolshet_110
Eig jlfr #1	0.07534	0.09173	0.00968	0.00000	0.06787

Table 6.8: Participation factors (euclidean norm)

	Maha_100	Malad_110	Mankhurd	Parel_110	Saki_110
Eig jlfr #1	0.00762	0.05010	0.01930	0.00755	0.06925

Table 6.9: Participation factors (euclidean norm)

	Salsette_110	Salsette_220	Tchembur	Tec_backbay_220	Tr_u1
Eig jlfr #1	0.05971	0.00560	0.00518	0.00761	0.00000

Table 6.10: Participation factors (euclidean norm)

	Tr_u2	Tr_u3	Tr_u44	Tr_u5	Tr_u6
Eig jlfr #1	0.00000	0.00000	0.00000	0.00000	0.00000

Table 6.11: Participation factors (euclidean norm)

	Tr_u7a	Tr_u_7b	T_borivli_110	T_borivli_220	Versova_110
Eig jlfr #1	0.00000	0.00000	0.03822	0.00828	0.05610

Table 6.12: Participation factors (euclidean norm)

	Versova_220	Vikhroli
Eig jlfr #1	0.00704	0.04444

Table 6.13: Statistics

Number of buses	52.00000
# of eigs with re(mu) ¡ 0	0.00000
# of eigs with re(mu) ¿ 0	1.00000
# of real eigs	1.00000
# of complex pairs	0.00000
# of zero eigs	0.00000

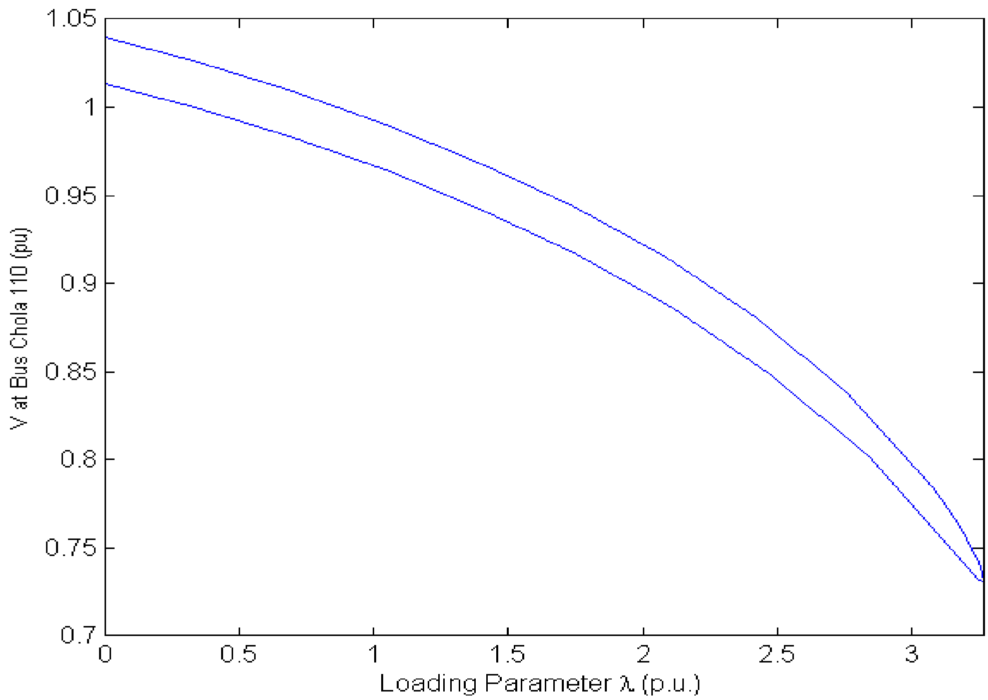

Figure 6.2: P-V Curve at bus Chola 110 for the Mumbai Grid

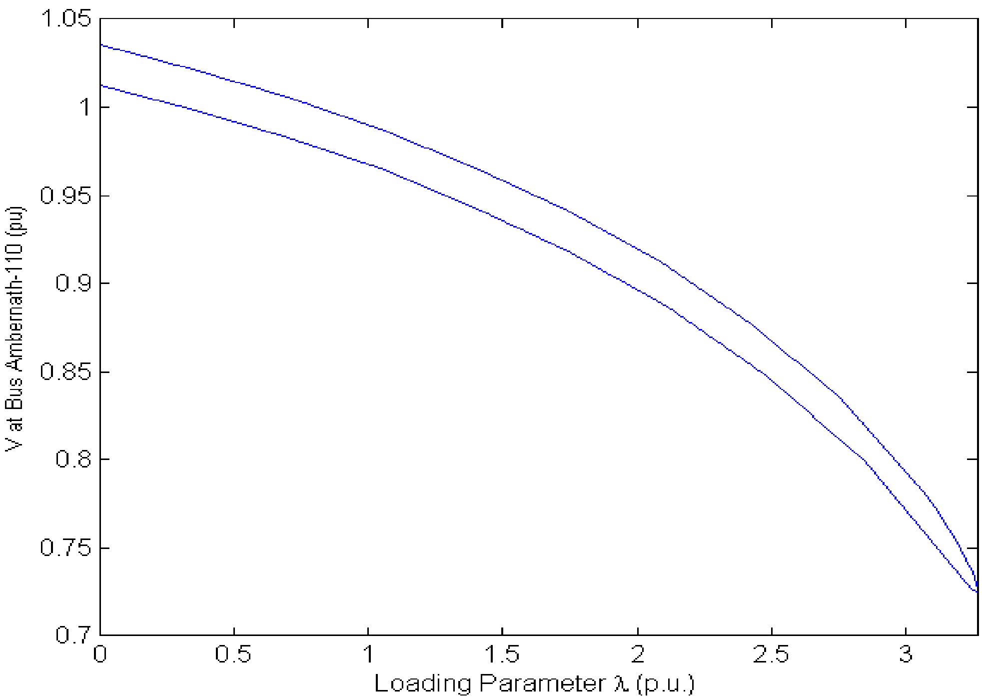

Figure 6.3: P-V Curve at bus Ambernath 110 for the Mumbai Grid

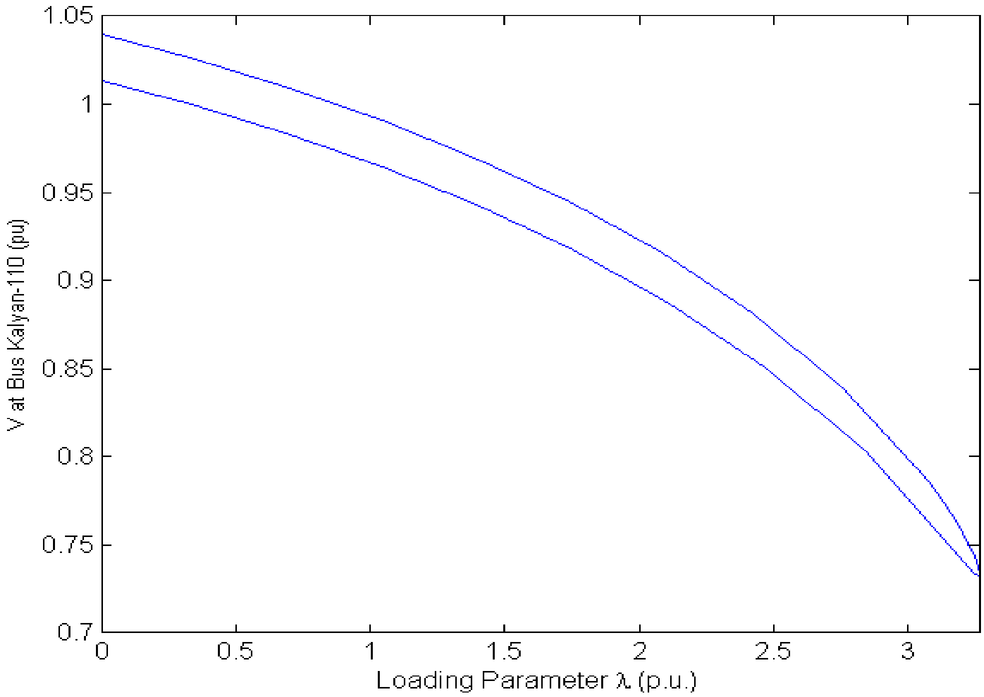

Figure 6.4: P-V Curve at bus Kalyan 110 for the Mumbai Grid

Chapter 7

Q-V Analysis

7.1 Objective

The Q-V curve is used to study a classical voltage collapse. Q-V curves are developed for specific critical buses in the power system. Each curve is a plot of the amount of reactive power that must be inserted at the critical bus to maintain a desired voltage level. The entire curve is produced with a constant active power transfer. Power flow studies are run to determine how much reactive support is needed to achieve a range of critical bus voltage levels.

7.2 Q-V Curves

Figure 7.1 is a typical of the Q-V curves that will be generated for a system that is stable at moderate loading and unstable at higher loadings.

The bottom of the Q-V curve, where the change of reactive power, Q, with respect to voltage, V (or derivative dQ/dV) is equal to zero, represents the voltage stability limit. Since all reactive power compensator devices are designed to operate satisfactorily when an increase in Q is accompanied by an increase in V, the operation on the right side of the Q-V curve is stable, whereas the operation on the left side is unstable. Also, voltage on the left side may be so low that the protective devices may be

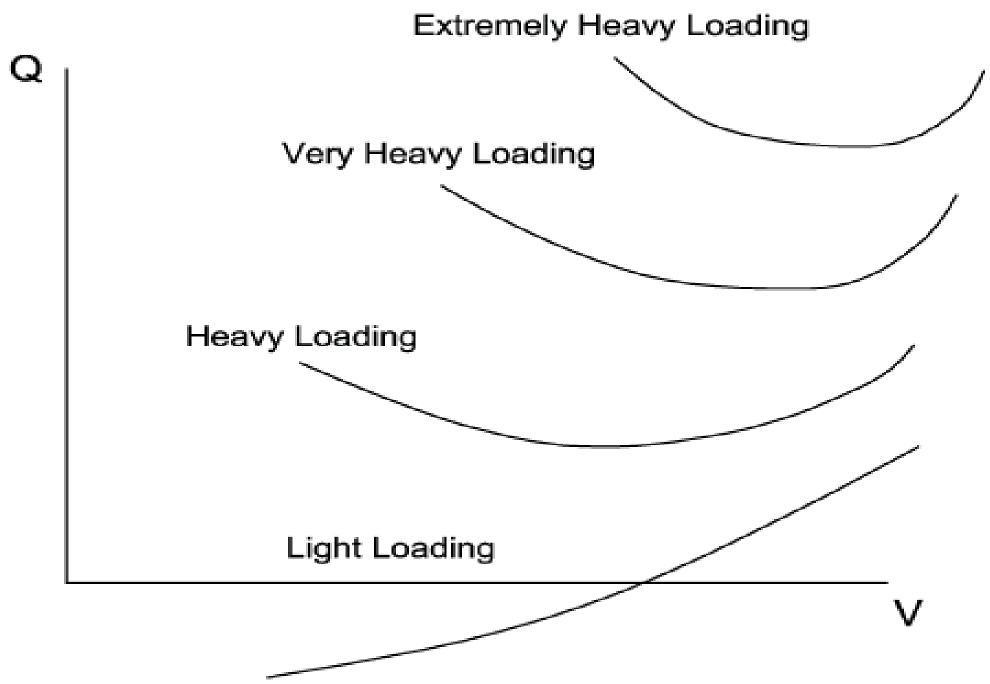

Figure 7.1: Q-V Curves for a Range of System Loading,Courtesy:Reference[13]

activated.The bottom of the Q-V curves, in addition to identifying the stability limit, defines the minimum reactive power requirement for the stable operation. Hence, the Q-V curve can be used to examine the type and size of compensation needed to provide voltage stability.

7.3 Use of P-V and Q-V Curves

Figure 7.2 contains a P-V curve and a Q-V curve. We will step through a simplified example of how a utility could use these two types of curves to determine a systems voltage stability related power transfer limits. First the utility produces many P-V curves by running numerous power flows. P-V curves are developed for all the critical buses in the system and for all critical outages. This must be done to ensure that all operating conditions and all areas of the system are checked and the most restrictive bus identified.

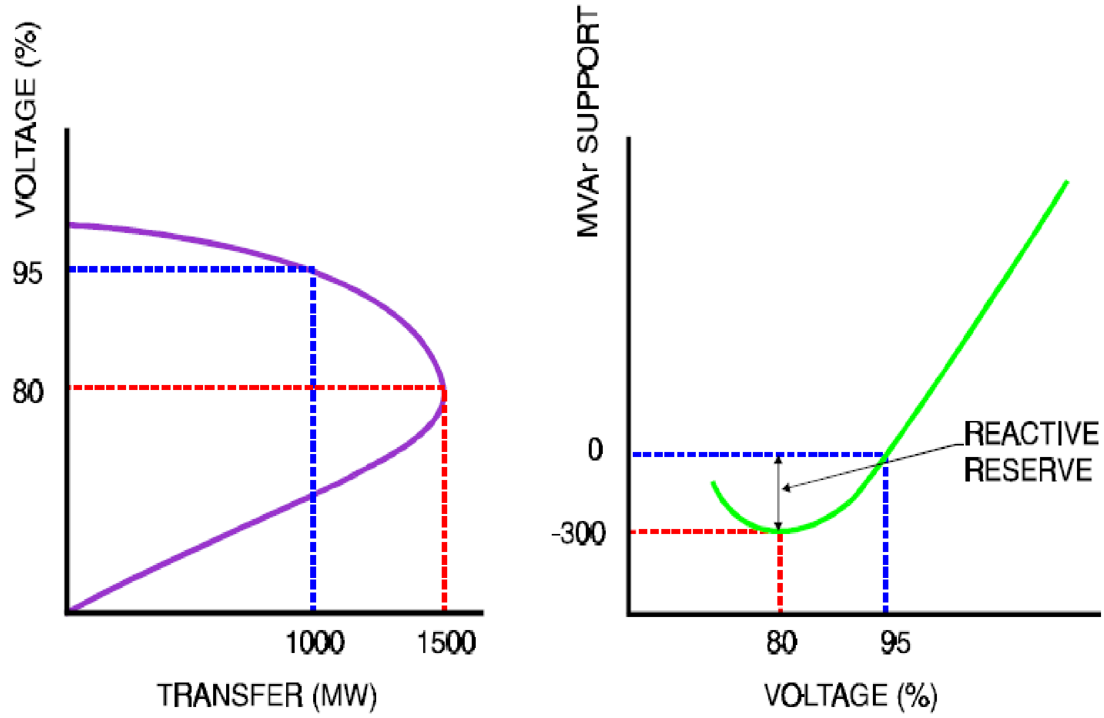

Figure 7.2: P-V and Q-V Curves,Courtesy:Reference[13]

Once the critical bus is identified a P-V curve as shown in the left side of Figure 7.2 is created. According to this P-V curve the maximum active power transfer before voltage instability is 1500 MW. The utility will not use 1500 MW but rather 1000 MW as their transfer limit to ensure it has a sufficient safety cushion.

Using a 1000 MW power transfer the utility produces a Q-V curve. The Q-V curve is also created using a power flow program. The power flow program is used to determine how many MVAr must be inserted at the critical bus to hold a range of bus voltages. Together the two curves give system operations a great deal of information. From the P-V curve the utility sets a transfer limit of 1000 MW and by looking at the Q-V curve the utility knows they have a 300 MVAr margin before voltage instability occurs at this transfer limit.

Figure 7.3 contains the same P-V and Q-V curves of Figure 7.2. The Q-V curve in Figure 7.3 is simply a rotation and mirror image of the Q-V in Figure 7.2. Note

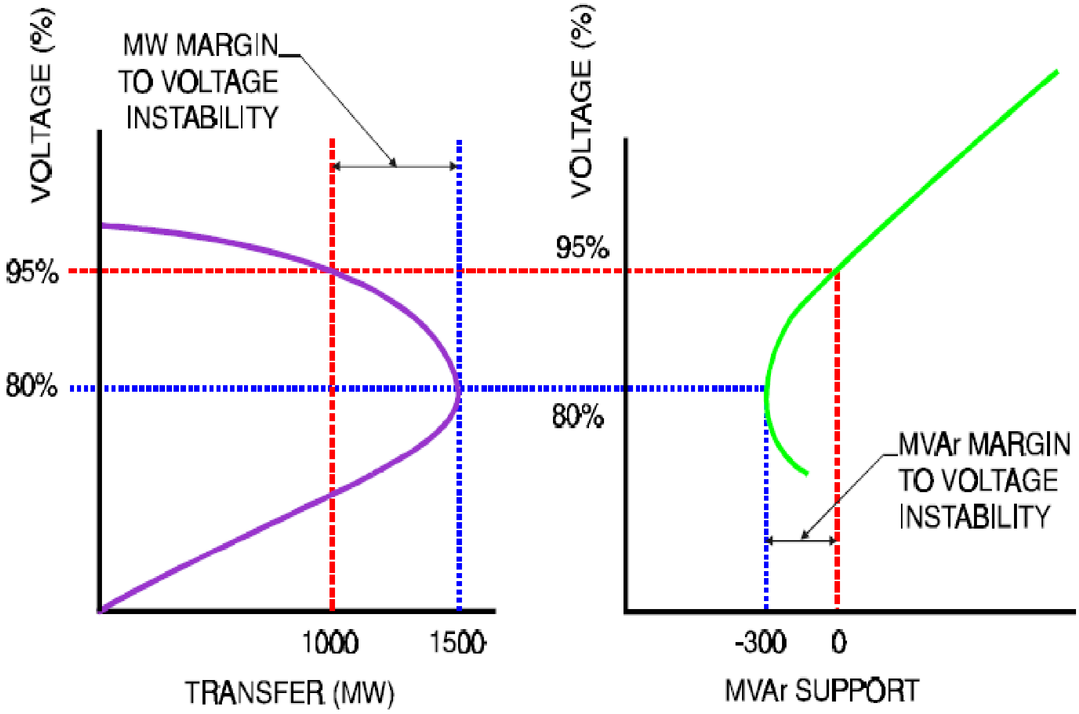

Figure 7.3: Margins to Voltage Instability,Courtesy:Reference[13]

The MW (500) and MVAr (300) margins to voltage instability occurs illustrated in Figure 7.3.

7.4 Method of Analysis

Here the Q-V curves are generated by artificially introducing a synchronous condenser, with high reactive power limits, at a bus to make this a P-V bus. As the scheduled voltage set point (bus voltage) of the P-V bus is varied in steps for a series of AC load flow calculations, the reactive power output from the condenser is monitored. When the reactive power is plotted as a function of the bus voltage a Q-V curves are obtained.

Q-V curves are commonly used to identify voltage stability issues and reactive power margin for specific locations in the power system under various loading and contingency conditions. The Q-V curves are also used as a method to size shunt reac-

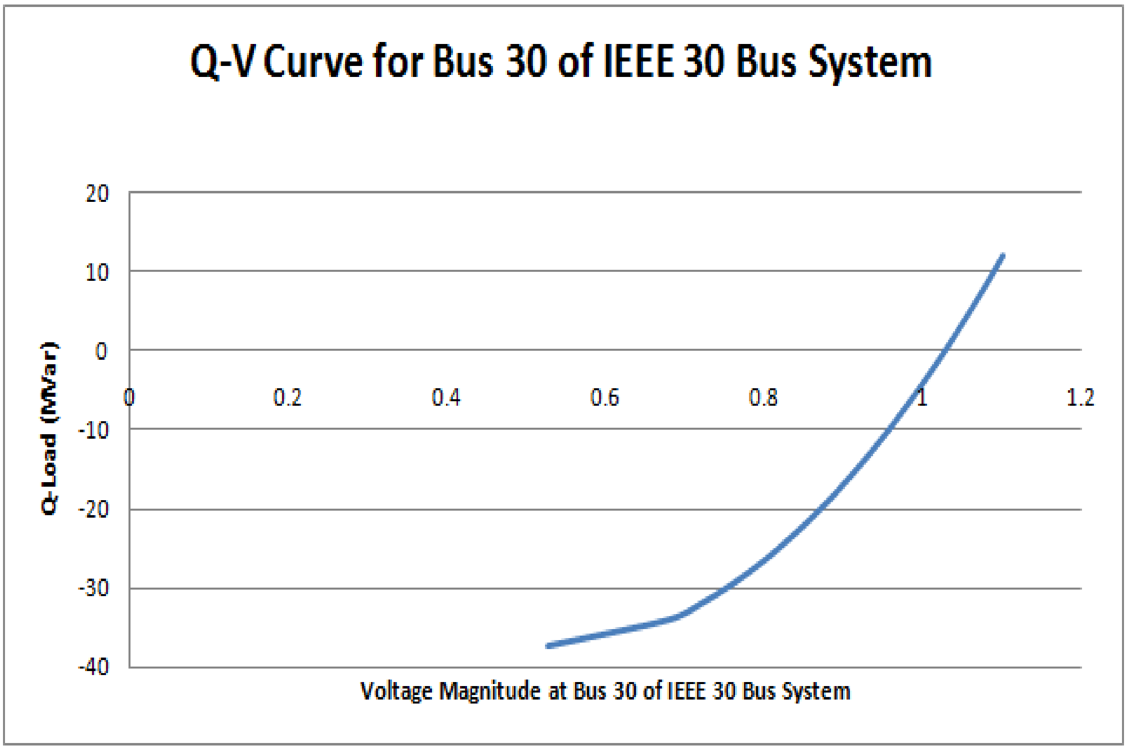

Figure 7.4: Q-V Curve of Bus 30 of IEEE-30 Bus System

tive compensation at any particular bus to maintain the required scheduled voltage.

7.5 Q-V Curves for the IEEE-30 Bus Test System

The following can be concluded from the Q-V Curves generated for 3 critical buses in the IEEE-30 bus test system:

- The amount of reactive power required by bus number 30 to maintain voltage stability is 20.4449 MVar
- The amount of reactive power required by bus number 29 to maintain voltage stability is 52.355 MVar
- The amount of reactive power required by bus number 26 to maintain voltage stability is 20.5737 MVar

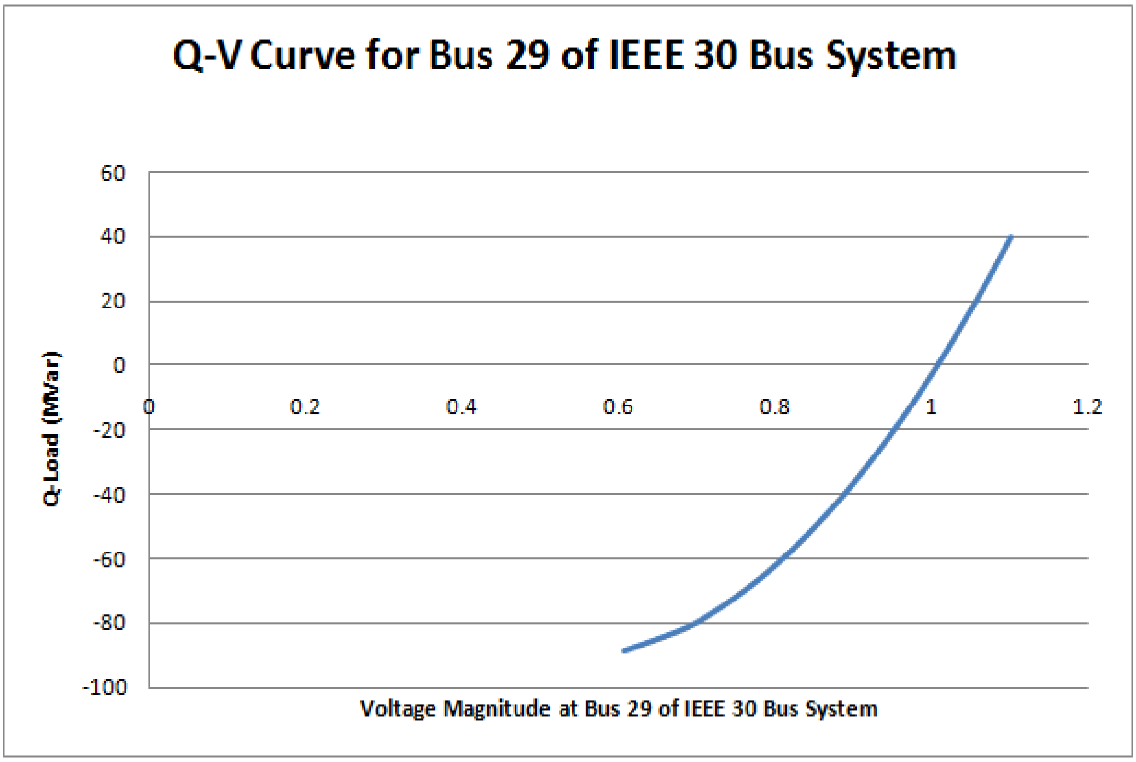

Figure 7.5: Q-V Curve of Bus 29 of IEEE-30 Bus System

7.6 Q-V Curves for the Mumbai Grid-Light Loading Condition

The following can be concluded from the Q-V Curves generated for 3 critical buses in the Mumbai Grid:

- The amount of reactive power required by bus Chola 110 to maintain voltage stability is 368 MVar
- The amount of reactive power required by bus Kalyan 110 to maintain voltage stability is 429.08 MVar
- The amount of reactive power required by bus Ambernath 110 to maintain voltage stability is 350.0758 MVar

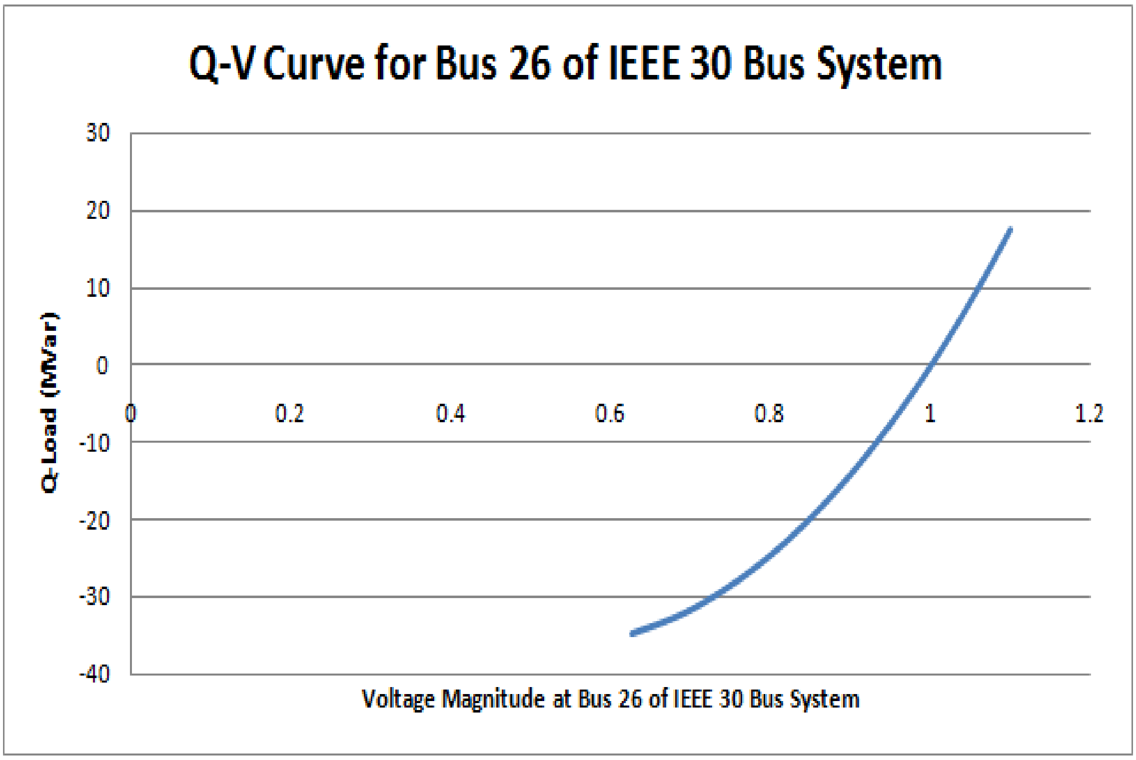

Figure 7.6: Q-V Curve of Bus 26 of IEEE-30 Bus System

7.7 Q-V Curves for the Mumbai Grid-Peak Loading Condition

The following can be concluded from the Q-V Curves generated for 3 critical buses in the Mumbai Grid:

- The amount of reactive power required by bus Chola 110 to maintain voltage stability is 305.2565 MVar
- The amount of reactive power required by bus Kalyan 110 to maintain voltage stability is 346.0087 MVar
- The amount of reactive power required by bus Ambernath 110 to maintain voltage stability is 257.2597 MVar

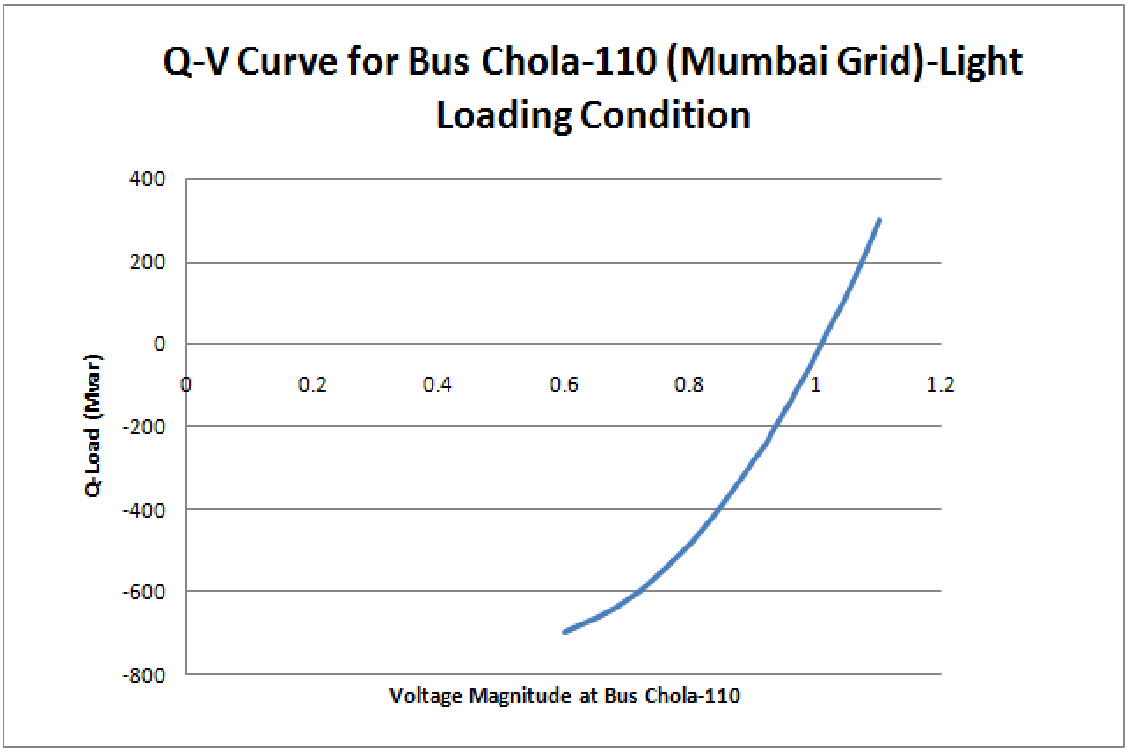

Figure 7.7: Q-V Curve of bus Chola 110 of the Mumbai Grid

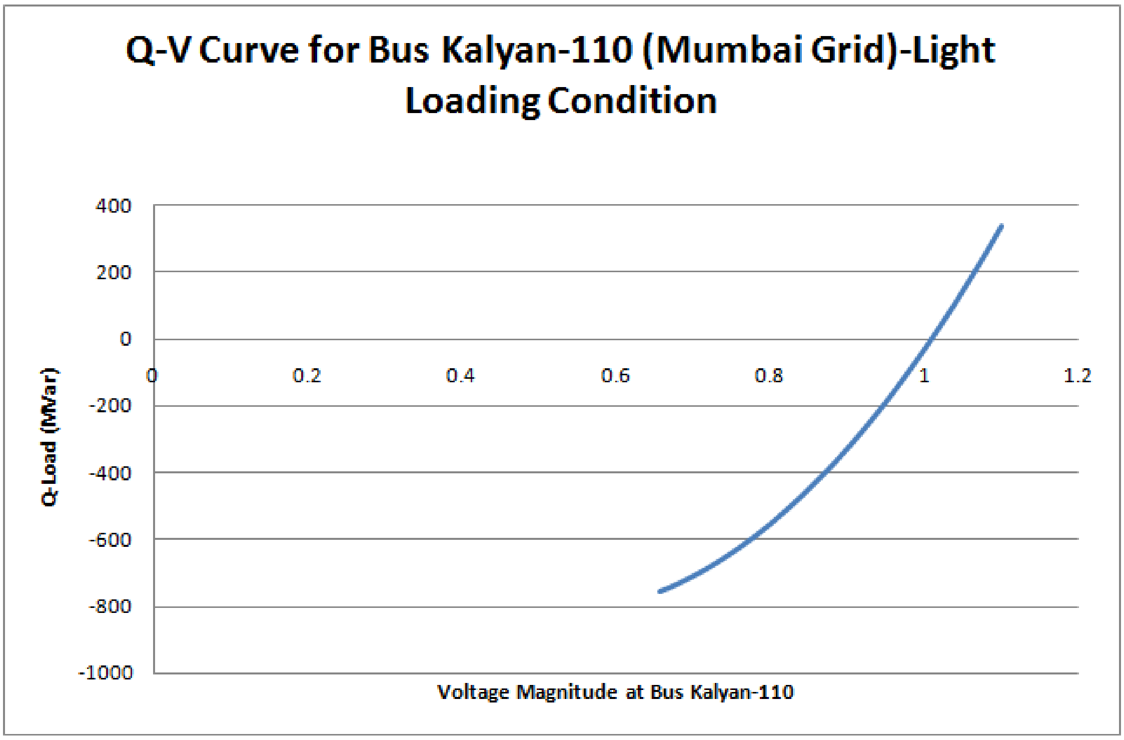

Figure 7.8: Q-V Curve of bus Kalyan 110 of the Mumbai Grid

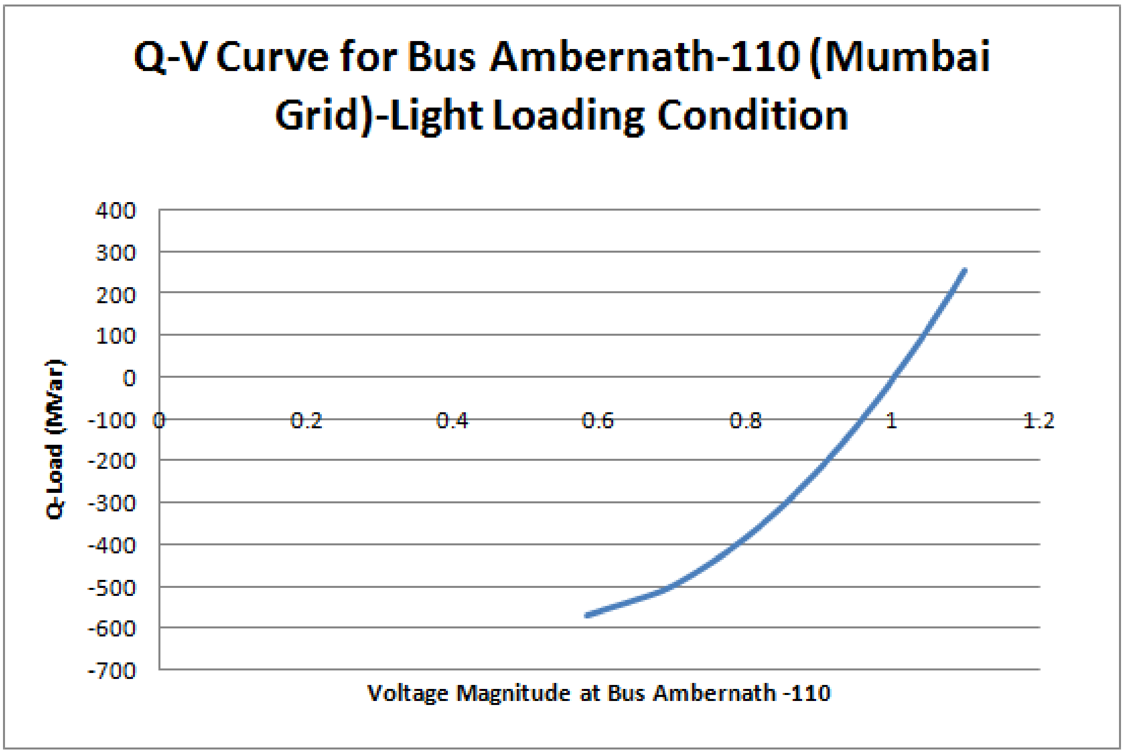

Figure 7.9: Q-V Curve of bus Ambernath 110 of the Mumbai Grid

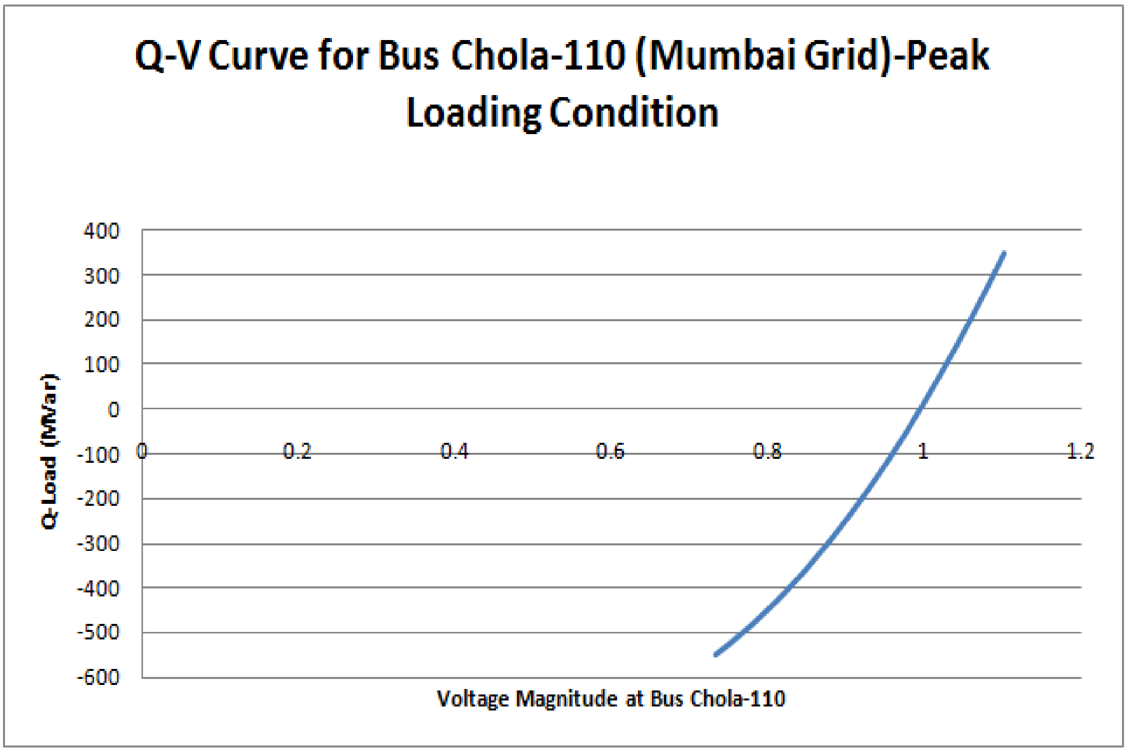

Figure 7.10: Q-V Curve of bus Chola 110 of the Mumbai Grid

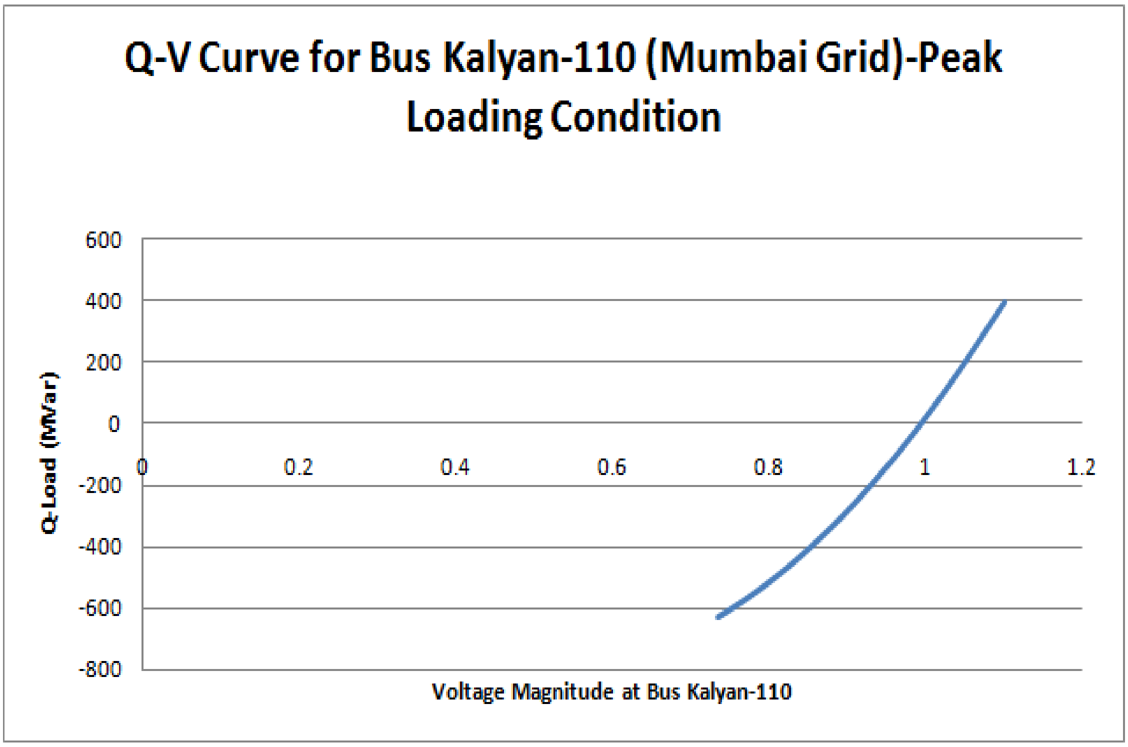

Figure 7.11: Q-V Curve of bus Kalyan 110 of the Mumbai Grid

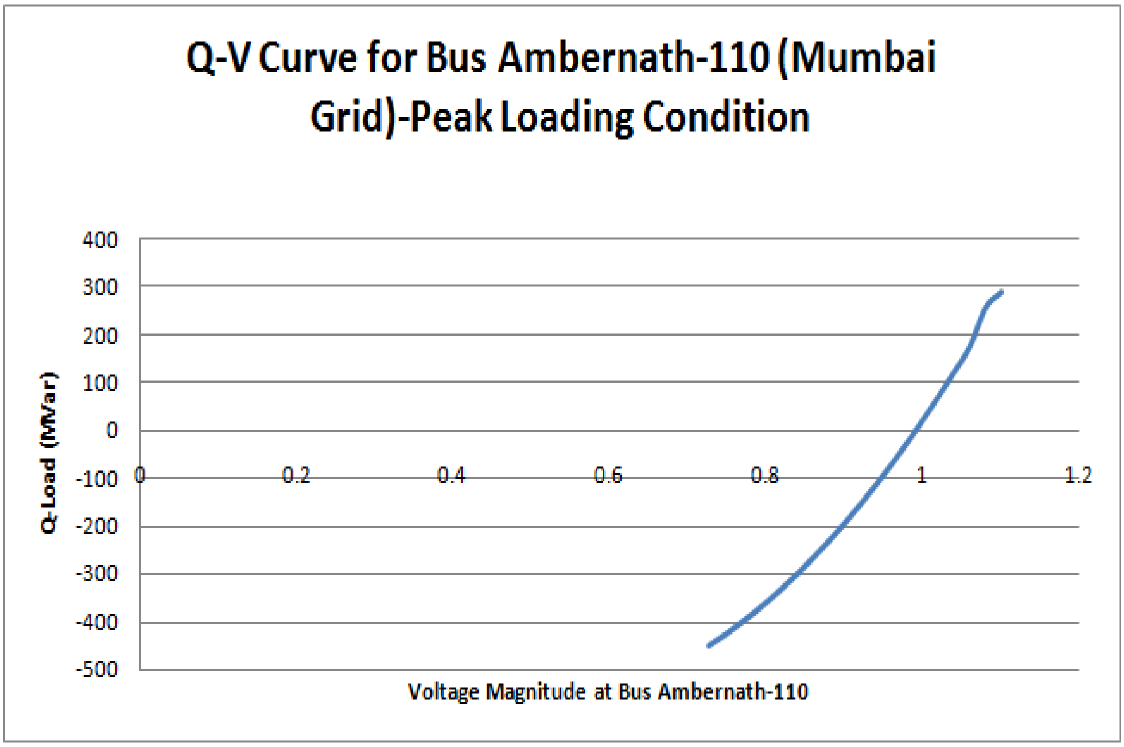

Figure 7.12: Q-V Curve of bus Ambernath 110 of the Mumbai Grid

Chapter 8

Voltage Collapse Prevention

8.1 Preventing Voltage Collapse

8.1.1 Dynamic Reactive Reserves

Dynamic reactive reserves are automatically controlled reactive reserves that respond rapidly to voltage deviations. Dynamic reactive reserves are typically carried in synchronous generators, synchronous condensers, or SVCs. Manually switched shunt capacitors and most automatically switched shunt capacitors do not qualify as dynamic reactive reserves due to their slow response speed and other control limitations. To ensure an ability to respond to events that may lead to voltage collapse it is important that utilities carry sufficient dynamic reactive reserves. These dynamic reserves should be strategically placed throughout the power system. It is difficult to transmit reactive power so the location of the dynamic reactive reserves is very important. The reactive reserves should be carried in the areas they most likely will be needed.

8.1.2 Voltage Control Zones

Active power reserve requirements are typically carried by individual utilities with few stipulations placed on their locations. This is usually acceptable for active power reserves as it is comparatively easy to transmit active power.

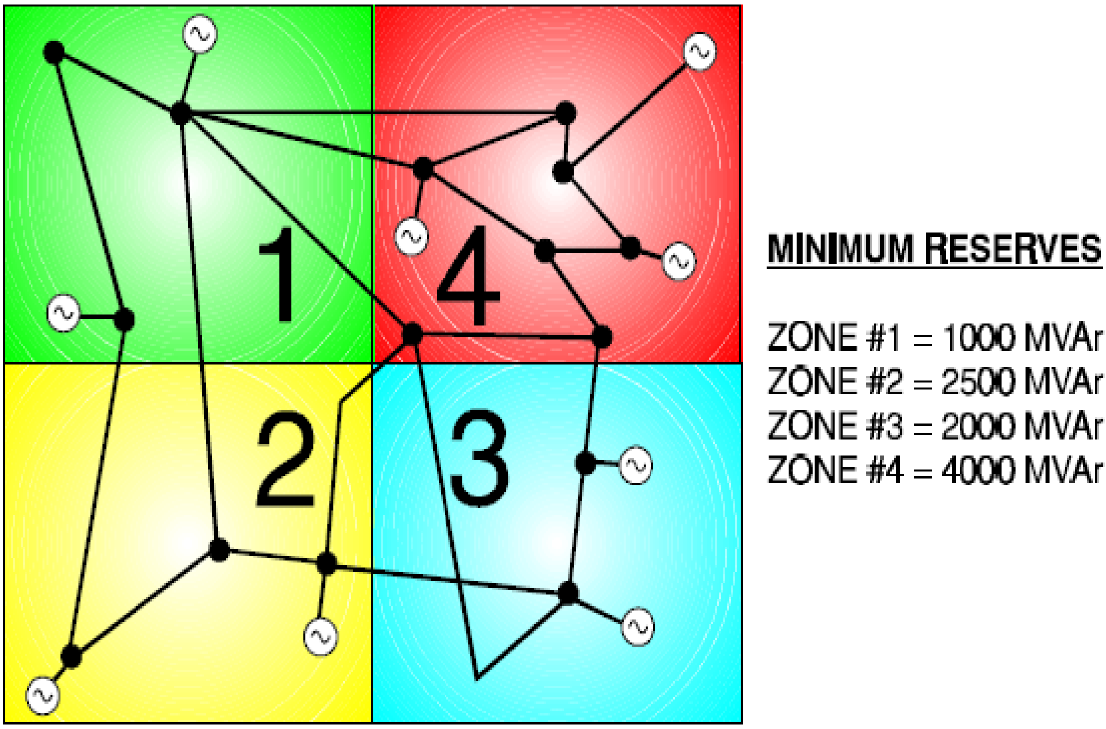

Figure 8.1: Voltage Control Zones

Dynamic reactive power reserves are a different story. It is difficult to transmit reactive power so the locations of the dynamic reactive reserves are critical. The concept of voltage control zones was created to address the importance of the location of reactive reserves. A voltage control zone is a physical section of the power system that responds as a cohesive unit to voltage deviations within that zone. For example, given a voltage deviation within a voltage control zone the reactive sources within that zone will respond together to restore the zones voltages.

Figure 8.1 illustrates the concept of voltage control zones for a simple power system. This particular system has been divided into four voltage control zones. The reactive reserves within each zone will strongly respond to voltage deviations within that particular zone. As long as minimum levels of reactive reserves are held in each zone the likelihood of a voltage collapse is minimized within each zone.

Voltage control zones are not a new concept but are only used by a few utilities.

As the incidence of voltage collapse increases it is likely that many power systems will implement variations of the voltage control zone theme.

8.1.3 Load Shedding

Assuming that sufficient reactive reserves cannot be made available the primary means to avoid a voltage collapse is to shed load. The ideal load to shed is heavily inductive load. When heavily inductive load is shed, such as uncompensated induction motor load, both the system active and reactive power loads are reduced.

Manual Load Shedding

Manual load shedding may be an option if the voltage collapse develops slowly. (If the voltage collapse develops rapidly a system operator may not be able to shed load quickly enough to arrest the voltage collapse process.) If manual load shedding is to be used to avoid voltage collapse, clear operating procedures must be made available to the system operators. These operating procedures should:

- Provide assistance to the system operator to help identify voltage collapse prone conditions.
- Describe the conditions in which manual load shedding may be used.
- Clearly identify which loads are available for shedding and which loads should be shed for different system conditions.

Automatic Load Shedding

Undervoltage load shedding (UVLS) systems should be implemented in the grid systems.A UVLS system will automatically trip selected customer loads when voltage falls below a trigger level. The voltage normally must remain below the trigger level for a specified time delay before tripping is allowed.For example, the utilities should install three stages of UVLS relays within their system. The UVLS settings are:

- 5 percent of load is tripped if voltage falls below 92 percent of nominal for a minimum of 5 seconds.

- An additional 5 percent of load is tripped if voltage falls below 92 percent of nominal for a minimum of 8 seconds.

- An additional 5 percent of load is tripped if voltage falls below 90 percent of nominal for a minimum of 3.5 seconds.

8.2 Role of the System Operator

This section provides information and suggestions to the system operator in detecting and responding to a voltage collapse.

8.2.1 Detecting a Voltage Collapse

An important function of the system operator is to monitor and respond to unusual power system events before the events proceed to a point at which they cannot be controlled. As a system operator you can prevent some types of voltage collapse if you can detect the conditions that may indicate a pending voltage collapse. In general, the response of a system operator is limited to a long term voltage collapse. Transient voltage collapse occurs too rapidly for system operator action. Classical voltage collapse that lasts for several minutes may be impacted by a system operators response if actions are performed quickly. The following power system events may indicate a pending voltage collapse.

- System voltage levels are unusually low. This may be due to heavy loads or heavy power transfer. Voltage levels should be continuously monitored. If a problem can be corrected before the voltages fall too far, voltage collapse may be avoided.

- Unusual magnitudes and directions for reactive power flows. If unusually large amounts of reactive power are flowing to one area of the system it may point to a pending voltage collapse in that area.

- Heavy reactive power generation at key area generators. If key area generators are at their reactive power limit, they will not be available if further reactive power is required. Avoid entering a heavy load period with low dynamic reactive power reserves.

- ULTC adjustments fail to move the voltage. This may indicate a reactive power shortage.

8.2.2 Responding to a Voltage Collapse

The best response to a voltage collapse is to prevent a collapse from occurring in the first place. This will not always be possible. The following methods of response are given as general guidelines. The guidelines are divided according to our three types of voltage collapse.

Long Term Voltage Collapse

Generating resources are often found in remote locations, far removed from any major load centers. Radial power systems are constructed to connect these economical generating plants to the major load centers. Hopefully, the power system designers will have planned for enough reactive power reserves to withstand the tremendous reactive power losses associated with heavily loaded, long radial power systems. The following precautions can be taken to prevent a long term voltage collapse in a radial power system:

- Ensure that the power plants at the sending end of the power system have sufficient reactive power reserves to support the system and the loads. These dynamic reserves must meet the requirements of the heaviest possible load period.

- All available reactive power sources at the receiving end, such as shunt capacitors, should be in-service and in proper working order. (Shunt reactors should also be out-of-service.)

- If series capacitors are available in the radial system they should be in service. Series capacitors lower line reactance. When series capacitors are in-service the systems reactive losses will decrease.

- If voltages are low in the transmission system a conservative rule of thumb is to avoid the use of area ULTCs. ULTC operation can impact a voltage collapse in two ways. System load naturally decreases with decreasing voltage. When an ULTC operates to raise voltage it also increases load magnitude. In addition, when ULTCs raise low side voltage they often depress high side voltage. ULTC operation may increase the chances of a voltage collapse.

- As a last resort a system operator should consider manually dropping load. If all possibilities to control the voltage collapse are exhausted, it is better to drop load in a controlled manner than to let the system collapse in an uncontrolled manner. Systems may have automatic undervoltage relay schemes installed to trip load during low voltage periods. It is critical that these schemes are in operation during the voltage collapse prone periods of the year.

Classical Voltage Collapse

A classical voltage collapse follows a severe system disturbance. As a result of the disturbance there is insufficient reactive power to satisfy the demands of the system and the customer load. The solution is simple; supply more reactive power where it is needed. The means to achieve this solution may be very difficult. To prevent a classical voltage collapse, a system operator (if time allows) can do the following:

- Maintain transfer limits within established guidelines. As active power transfer increases, reactive power losses escalate. If conditions are ripe for a voltage collapse consider reducing system transfers to limit reactive power losses.
- Ensure that all available static reactive power sources, such as shunt capacitors, are in-service. In addition, make sure that all shunt reactors are out-of-service.
- Ensure that sufficient dynamic reactive reserves exist to handle any probable contingency. The amount of dynamic reactive reserve is typically determined by planning and operating engineers. System operators must ensure these amounts actually are held.
- Ensure that the plant operators are providing all possible reactive power. This may mean a need to re-dispatch generation.
- Generating plants in the effected area that are normally not run due to economic factors may be run to increase active and reactive power supply.
- Shift system generation patterns to unload heavily loaded lines. This will reduce reactive power losses since they are a function of the current squared.
- Consider blocking operation of the effected areas ULTCs to prevent further drops in transmission voltages.
- Request reactive power support from neighboring power systems. Neighboring systems can raise voltage at common buses. This may help raise voltages throughout the effected area.
- As a last resort consider manually dropping load. (Also be sure all automatic undervoltage load shedding schemes, if they exist, are in service.)

Transient Voltage Collapse

A transient voltage collapse is a rapid event from the perspective of a system operator. Once the process has begun a system operator has little role in the final outcome.

There is little a system operator can do to avoid an induction motor type collapse. One suggestion is to ensure protective systems are in place and functioning properly. However, if collapse of this type does occur, restoration can proceed quickly if the cause of the collapse is quickly identified.

To prevent the loss of synchronism type voltage collapse, the conditions that lead to the loss of synchronism must be avoided. Among the actions that would help to prevent a loss of synchronism are:

- Maintain system transfer limits within acceptable margins. The larger the power transfer, the larger the power angle. If power transfers are limited, the power angle increase following a disturbance will be reduced.

- Keep power system voltage levels as high as allowed by system voltage schedules. The higher the voltage levels, the lower the power angles necessary to transmit a given amount of power. Voltage control equipment should be in-service and in proper working order.

- Generators are the primary means to control normal system voltage levels. In addition, a generator has further voltage control capability during a system disturbance. Many generators have high speed excitation systems that can respond rapidly to increase system voltage levels. For example, during a disturbance that depresses system voltages, such as during a fault, an excitation system can help maintain angle stability. A power system could go unstable because available high speed excitation systems have been intentionally disabled.

- Out-of-step protective relay systems are designed to detect the low voltages that occur during a loss of synchronism. These protective relay systems will detect the out-of-step conditions and initiate a controlled separation of the power system. Be sure these systems are in-service as stated by utility policy. It is better to separate in a controlled manner then to let the system separate in whatever manner it chooses.

Chapter 9

Conclusion and Future scope

9.1 Conclusion

In this research, the voltage collapse problem is studied. The following can be concluded:

- The Modal analysis technique is applied to investigate the stability of a well-known power system. The method computes the smallest eigenvalue and the associated eigenvectors of the reduced Jacobian matrix using the steady state system model. The magnitude of the smallest eigenvalue gives us a measure of how close the system is to the voltage collapse. Then, the participating factor can be used to identify the weakest node or bus in the system associated to the minimum eigenvalue.

- The Q-V curves are used successfully to confirm the result obtained by Modal analysis technique, where the same buses are found to be the weakest and contributing to voltage collapse.

- Using the Q-V curves, the stability margin or the distance to voltage collapse is identified based on voltage and reactive power variation. Furthermore, the result can be used to evaluate the reactive power compensation.

9.2 Future Scope

- Modeling of the other power system devices such as generators and static var compensators.
- Consideration of suitable solutions for the voltage collapse problem in the analyzed system.

References

[1] P. Kundur, Power System Stability and Control, McGraw-Hill, 1993.

[2] C.W.Taylor, Power System Voltage Stability, McGraw-Hill, 1994.

[3] IEEE/PES Power System Stability Subcommittee Special Publication, Voltage Stability Assessment: Concepts, Practices and Tools, Final Document, August 2002.

[4] G.K.Morrison, B.Gao and P.Kundur, "Voltage Stability Analysis Using Static and Dynamic Approaches", IEEE Transactions on Power Systems, Vol. 8, No. 3, August 1993, pp. 1159-1171.

[5] A.K.Panchal, "Voltage Stability of a Large Grid", Power Engineering Conference, 2005, IPEC 2005, The 7th International.

[6] N.Mithulananthan, S.C.Srivastava, "Investigation of a Voltage Collapse Incident in Sri Lankan Power System Network", 10th National Power Systems Conference (NPSC)-Proceedings, October- 1998, Vadodara, India, pp. 90-96.

[7] S.C.Srivastava, "Power System Voltage Stability Analysis and Control", 10th National Power Systems Conference (NPSC), Tutorial, 13th October 1998, Vadodara, India.

[8] F.Milano, "An Open Source Power System Analysis Toolbox", IEEE Transactions on Power Systems, Vol. 20, No. 3, August 2005, pp. 1199-1206.

[9] H.J.C.P.Pinto, N.Martins, X.Vieira F, A.Bianco, P.Gomes, M.G. dos Santos, "Modal Analysis for Voltage Stability: Application at Base Case and Point of Collapse", Bulk Power System Voltage Phenomena-3 Voltage Stability, Security and Control, Davos, Switzerland, 22-26 August 1994.

[10] V.Ajjarapu, "Computational Techniques for Voltage Stability Assessment and Control", Springer Publications, 2006.

[11] B. Gao, "Voltage Stability Analysis of Large Power Systems", Ph.D. thesis, University of Toronto,1992.

[12] S.Chakrabarti , Dept of Electrical Engineering-IIT-Kanpur, "Notes on Power System Voltage Stability".

[13] J.Bucciero, M.Terbrueggen,"Interconnected Power System Dynamics Tutorial", Final Report-January 1998, Electric Power Research Institute.

List of Publications

[1] Aagam.T.Shah, Sarika.S.Kanojia , "Voltage Stability Analysis of Interconnected Power Systems", National Conference on Emerging Technologies in Renewable Energy and Electrical Electrical Engineering, ETREEE- 2012.

Appendix A

The IEEE-30 Bus Test System

Appendix B

The Mumbai Grid