Voltage Stability Improvement Using FACTS Devices

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the Degree of

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IN

ELECTRICAL ENGINEERING

(Electrical Power Systems)

By

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CERTIFICATE

This is to certify that the Major Project Report entitled **"Voltage Stability Improvement Using FACTS Devices"** submitted by **Mr. Krunal A. Patel (16MEEE23)**, 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

Electrical Power system is confronting few new difficulties now a days as the present system is threaten to several stressed conditions. Voltage strength is very imperative issue of electrical power system which can reduce the power system performance under such intractable condition. To intercept the blackouts voltage stability of the system must be examined for an extensive variety of working conditions.

Target of this work is to determine the critical bus utilizing a few voltage stability analysis methods and executing the FACTS devices to recover the voltage stability on IEEE-14 bus system. The proposed work introduces an approach to analyze the voltage stability of the system and finding out the particular stressed bus/line as an optimal location of FACTS using several voltage stability analysis methods. For voltage stability assessment several methods have been introduced so far. Methods used for analysis are voltage stability indices(VSIs), voltage stability boundary(VSB) & modal analysis. In addition to suggested methods recent advertence has been issued to place FACTS devices at optimal location obtained by analysis for improving the voltage stability and reactive power compensation. Impacts of FACTS on VSBs have been studied to determine the most suitable FACTS at particular location. The critical values of voltage, active & reactive power have been evaluated and deviation in such parameters after compensation has been scrutinized to imply enhancement in voltage stability margin and verify optimal location of suggested FACTS.

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Abbreviations

IEEE .... Institute of Electrical and Electronics Engineers
FACTS .... Flexible AC Transmission System
VAR .... Volt-Ampere Reactive
LTC .... Load Tap Changing, Load Tap Changer
OEL .... Over Excitation Limiter
SCL .... Stator Current Limiter
SVC .... Static Var Compensator
AVR .... Automatic Voltage Regulator
VSA .... Voltage Sensitivity Assessment
HVDC .... High Voltage Direct Current
PMU .... Phasor Measurement Unit
DG .... Distributed Generation
VCPI .... Voltage Collpase Prediction Index
FVSI .... Fast Voltage stability Index
LCPI .... Line Collapse Poximity Index
VSI .... Voltage Stability Index
VSM .... Voltage Stability Margin
VSB .... Voltage Stability boundary
STATCOM .... Static Synchronous Compensator
TCSC .... Thyristor Controlled Series Capacitor

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Chapter 1

Introduction

1.1 Background

In Present time, due to Increasing load power system is suffering from highly stressed condition and hence it makes the system to operate nearer to its operating limits. Performance of power system ends up troublesome because of following reasons:

- Increased competition in power sector
- Limitation for expansion of transmission network due to several environmental and social burdens
- Lack of initiatives to replace the old voltage and power flow control mechanisms
- Imbalance in load-generation growth

Above factors are cause of power system stability problem. As a result, the system operates nearer to the stability limit, so a relatively small disturbance may cause the system to become unstable. As the power system is an interconnected system it's operation and stability will also be affected and they are operated with higher power transfers between the areas while there is little coordination and exchange of on-line information between utilities. In essence, the direct cause of blackouts has been found is voltage collapse.

1.2 Definitions according to IEEE

According to IEEE, the following formal definitions of terms related to voltage stability are given:

"Voltage Stability is the ability of a system to maintain voltage so that when load admittance is increased, load power will increase, and so that both power and voltage are controllable."[1]

"Voltage Collapse is the process by which voltage instability leads to loss of voltage in a significant part of the system."[1]

"Voltage Security is the ability of a system, not only to operate stably, but also to remain stable (as far as the maintenance of system voltage is concerned) following any reasonably credible contingency or adverse system change.[1]

In a more general way, voltage stability according to Van Cutsem,

"Voltage instability stems from the attempt of load dynamics to restore power consumption beyond the capability of the combined transmission and generation system."[1]

1.3 Voltage Stability Problem

Voltage instability is the incident in which the receiving end voltage diminishes under its standard value and does not return even in the wake of setting restoring mechanism, for example, VAR compensators, or keeps on oscillating due to absence of damping against the disturbances. Voltage collapse is the process by which the voltage tumbles to a low, inadmissible value because of an avalanche of events following voltage instability.[3].

Voltage stability problem is noteworthy since it affects the power system security & reliability. Voltage instability is an aperiodic, dynamic phenomenon. As a large portion of the load is voltage dependent and throughtout disturbance, voltages diminish at a load bus will cause a lessening in the power utilization. However, loads tend to restore their initial power consumption with the help of Distribution Voltage Regulators, Load Tap Changers (LTC) and thermostats. These control devices try to adjust the load side voltage to their reference voltage. The rise in voltage will be coincide by an increment in the power demand which will additionally debilitate the power system stability. Under these conditions voltages undergo a continuous decrease, which is small at starting and leads to voltage collapse.

When a single machine is connected to a load bus then there will be pure voltage instability. When a single machine is connected to infinite bus then there will be pure angle instability. When synchronous machines, infinite bus and loads are connected then there will be both angle and voltage instability but their influence on one another can be separated.

Factors affecting[4] the voltage stability:

1. Dynamic loads
2. Reactive power generations
3. Load tap changer transformers
4. Power transfer capability of transmission systems

1.4 Causes of Voltage Instability

Following are the causes of voltage instability:

1. Load dynamics: Loads are the driving force of voltage instability. Load dynamics can be understood through below examples:

    - Load Tap Changing (LTC) transformer is to keep the load side voltage in a characterized band close to the rated voltage by changing the ratio of transformer. As the greater part of the load is voltage dependant, a disturance inducing a voltage diminish at a load bus will cause a lessening in the power utilization. This tends to support stability. In any case, the LTC will then start to reestablish the voltage by changing the ratio well ordered with a predefined timing. The rise in voltage will be coincide by an increment in the power demand which will additionally debilitate the power system stability.
    - Thermostat will control the electrical warming. The thermostat acts by routinely switching the heating resistance on and off. On account of a voltage diminish, the power absorption, consequently the heating power, will be decreased. Accordingly, the thermostat will tend to supply the load for a more extended time interim. The amassed response of a huge group of this kind of burdens is viewed as a restoration of the power, corresponding to the one of the LTC.

- Induction motors have dynamic characteristics with short time constants. Restoration process occurs following voltage reduction because the motor must keep on supplying a mechanical load with a torque pretty much consistent.

2. Transmission system: Every transmission component, line or transformer, has a constrained exchange capacity. It is subject to several factors:
   - The impedance of the transmission element.
   - The power factor of the load.
   - The presence of voltage controlled sources (generators or Static Var Compensator-SVC) at one or both extremities of the element and the voltage set point of these sources.
   - The presence of reactive compensation devices (mechanically switched capacitors or reactors).
3. Generation system: At the point power system flows increase, the transmission system consumes more reactive power. The generators must increase their reactive power output. Operating point of generator can be found from its capability curve. In any case, due to Over-Excitation Limiter (OEL) and Stator Current Limiter (SCL), voltage can't be controlled after these limiters are triggered.

As described above, the three sources are strongly linked one to another. In a real voltage collapse case, the complete instability mechanism generally involves all three aspects, and often other instability phenomena too.

1.5 Countermeasure for Voltage Collapse

Countermeasures can be applied at various stages of system design from planning to real-time operation of power system. shows classification of all the counter measures that can be used to prevent the voltage collapse. Few corrective actions are shown as following:

1. Load shedding:

   It is not an actual solution to prevent voltage collapse but it is a very effective countermeasure against voltage collapse. It gives immediate voltage improvement.

Several successive load shedding can be effective for getting back to an acceptable voltage. This countermeasure is also very cost effective. Its implementation is simple and the risk of occurrence of voltage instability is small. However, disturbance will be generated to consumers due to load shedding so this option should be given the last priority for countermeasure.

2. Load Tap Changer (LTC) control modification:

   LTCs are also main cause of voltage instability as their action follows a load restoration. Tap changers should be blocked on the current tap to prevent further deterioration of voltage magnitude. The set point used by LTC controller should be decreased. The LTC logic should be reversed for restoring the voltage in the high voltage side instead of low voltage side. This can be done by decreasing load side voltage which also decrease load power.

3. Action on generation devices:

   Generation devices includes generators and reactive compensation devices. The following actions may be taken as countermeasures.

   Switching on capacitive compensation and switching off induction compensation are most effective when loading level is very high.

   Increasing the voltage set point of generators will cause an increase in the voltage, decrease in current and thus a decrease in the loading of the transmission system. This action is effective only if the load behaves nearly as a constant power load. For the load to be a constant power load, the LTC should be active.

   For peak load generation rescheduling and/or starting up of gas turbine or hydrogeneration is to be done. If small generation plants are available in the voltage stability affected areas, their starting up will greatly increase the stability. Generation rescheduling is a more complex action that must be optimized in simulations before it can be implemented.

1.6 Literature Review

[1] P. Kundur et al., "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions," *IEEE Transactions on Power Systems*, vol. 19, no. 3, pp. 1387-1401, Aug. 2004.[1]

The Systematic classification of power system stability is described. The fundamentals and the identification of various categories of power system stability are described. The linkages between power system stability, security and reliability are also discussed in brief. This paper provides basic background knowledge to understand stability and its analysis.

[2] P. Prabhakar and A. Kumar, "Voltage stability boundary and margin enhancement with FACTS and HVDC," *International Journal of Electrical Power and Energy Systems*, vol. 82, pp. 429-438, 2016.[2]

Impact of FACTS devices on VSB of the weakest load buses & lines of IEEE-14 bus and IEEE-30 bus systems. Several cases with different conditions have benn studied using voltage stability indices and Voltage stability boundary(VSB) in P-Q plane to find out the weakest bus and improving them using FACTS devices compairing their effect on enhancement of VSB. It shows that voltage stability margin can be enhanced in all cases with FACTS devices. Methods used for determination of the weakest buses & lines are eigenvectors, FVSI, L_{mn}, LCPI.

[3] M. Haque, "A fast method for determining the voltage stability limit of a power system," *Electric Power Systems Research*, vol. 32, no. 1, pp. 35-43, 1995.[3]

This paper proposes a fast method for finding the maximum load, especially the reactive power demand, at a particular load bus before reaching the voltage stability limit. Two bus equivalents of the system as a thevenin equivalent system is formed for analysis of the voltage stability. The method was tested on IEEE-14,-30 & -118 bus systems. Simulation results show that the voltage stability limit obtained by this method due to the change in reactive power demand is very close to the corresponding actual value. Unlike the other methods, the proposed method can provide much better and reliable results using the base-case system information with significantly less computation.

[4] J. Modarresi, E. Gholipour, and A. Khodabakhshian, "A comprehensive review of the voltage stability indices," ***Renewable and Sustainable Energy Reviews*****, vol. 63, pp. 1-12, 2016.**[4]

Comprehensive review of all-most all the voltage stability indices (VSIs) proposed till the publication of paper have been described for the assessment of voltage stability. Detailed review of voltage stability indices showing classification by different aspects and views, equations of several VSIs with particular assumpations, critical values and steps to find optimal location of FACTS have been briefed in this paper.

[5] I. Musirin and T. K. A. Rahman, "Novel fast voltage stability index (fvsi) for voltage stability analysis in power transmission system," ***Student Conference on Research and Development*****,2002, pp. 265-268.**[5]

This paper presents the development of a fast voltage stability index (FVSI) used to predict the volatge collapse point of the line, maximum permissible load & the most critical line of the interconnected power system. The result obtained are verified by other method also. Test are performed on the IEEE-30 bus system.

[6] G. B. Jasmon and S. Yusof, "A STATIC VOLTAGE COLLAPSE INDICATOR," ***J. Ind. Technol.*****, vol. 7, no. 1, pp. 73–85, 1998.**[6]

Various indicators of proximity to voltage collapse have been proposed and this paper presents a static indicator that can give a fast voltage stability assessment. Basic power flow equations are used to determine certain voltage stability conditions which are extended for the prediction of proximity to voltage collapse. The performance and effectiveness of the index has been compared with the impedance ratio indicator and the stability index.

[7] V. Balamourougan, T. Sidhu, and M. Sachdev, "Technique for online prediction of voltage collapse," ***IEE Proc Gener Transm Distrib*****, vol. 151, no. 4, pp. 453-60, 2004.**[7]

Technique depicted in this paper is to foresee voltage collapse in interconnected power systems which is called voltage collapse proximity index(VCPI). This technique uses the voltage magnitude and voltage angle information at buses and the network admittance matrix to anticipate the voltage collapse. The execution of the method was considered for a variety of working conditions. The technique was tested using different IEEE test systems. TThe simulations were carried out for steady-state voltage collapses and for dynamic voltage collapses. The outcomes demonstrate that, for every bus in the system, the proposed strategy can foresee its proximity to voltage collapse by means of an index. This technique is computationally proficient and reasonable for real time prediction of voltage collapse.

[8] B. Gao, G. K. Morison and P. Kundur, "Voltage stability evaluation using modal analysis," *IEEE Transactions on Power Systems*, vol. 7, no. 4, pp. 1529-1542, Nov. 1992.[8]

Modal analysis technique for analysis of voltage stability is discussed. It is computed on the steady state system model. The parameters computed in this method are the V-Q sensitivity, smallest eigenvalues of a reduced Jacobian matrix, and the associated bus, branch and generator participation factors. Comparison with L-index and V-Q sensitivity method shows that this method has certain advantages over these methods. The method is very helpful in voltage stability assessment of large complex systems.

Chapter 2

Voltage Stability Analysis

2.1 Methods of Voltage Stability Analysis

The analysis of voltage stability can be done using different kind of methods as following:

1. PV curve & QV curve:
2. Modal analysis
3. Voltage stability indices
4. Continuation power flow method

At the voltage collapse point, solution of power flow equations experiences convergence problem. So to avoid this convergence problem, 'Voltage Stability Indices'(VSI) are proposed based on power flow equations. These indices give information such as critical buses and critical branches.

All of VSIs have been derived from the characteristics of the voltage collapse point. For better comprehension of the VSIs the characteristics of voltage collapse point is to be investigated. In this manner, the characteristics of voltage collapse point are analyzed in the following segment.

2.2 Characteristics of the Voltage Collpase Point

The two bus representation of a power system is shown in below Figure 3.1 [4]

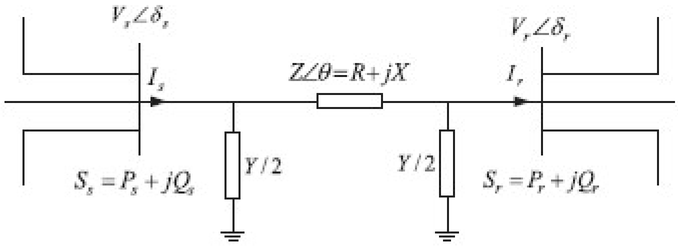

Figure 2.1: The two bus representation of a power system

The symbols in Fig. 2.1 are as below:

V_s, V_r : Voltage magnitude at the sending and receiving buses respectively.

P_s, Q_s : Active and Reactive power at the sending bus.

P_r, Q_r : Active and Reactive power at the receiving bus.

S_s, S_r : Apparent power at the sending and receiving buses respectively.

δ_s, δ_r : Voltage angle at the sending and receiving buses respectively.

I_s, I_r : Current at the sending and receiving end of the line.

Y : line shunt admittance.

R, X, : line resistance, line reactance and line impedance angle.

Z : Line impedance amplitude.

Shunt admittances are neglected for simplicity.

Active and Reactive power can be derived as follows:

V$_s$ is taken as reference so $\delta_s = 0$

$$I = \frac{V_s\angle 0 - V_r\angle\delta}{R + jX} \tag{2.1}$$

$$I = \left(\frac{S_r}{V_r}\right)^* = \frac{P_r - jQ_r}{V_r\angle - \delta} \tag{2.2}$$

Equating eq. (2.1) & (2.2)

$$\frac{V_s\angle 0 - V_r\angle\delta}{R + jX} = \frac{P_r - jQ_r}{V_r\angle - \delta}$$

$$V_sV_r\angle-\delta-V_r^2=(P_r-jQ_r)(R+jX) \tag{2.3}$$

Separating real & imaginary terms

$$V_sV_r\cos\delta-V_r^2=RP_r+XQ_r \tag{2.4}$$

$$-V_sV_r\sin\delta=XP_r-RQ_r \tag{2.5}$$

By rearranging the eq. (2.4) & (2.5) we get active and reactive power

$$P_r=\frac{V_sV_r\cos(\delta)-V_r^2-Q_rX}{R} \tag{2.6}$$

$$Q_r=\frac{P_rX-V_sV_r\sin(\delta)}{R} \tag{2.7}$$

Where, $\delta=\delta_s-\delta_r$

From eqs. (2.6) and (2.7), The fourth degree equation can be derived.

$$V_r^4-(2P_rR+2Q_rX-V_s^2)V_r^2+(P_r^2+Q_r^2)Z^2=0 \tag{2.8}$$

or

$$V_r^4+(2P_rR+2Q_rX-V_s^2)V_r^2+S_r^2Z^2=0 \tag{2.9}$$

At Voltage collapse point,

We have 2 pairs of real identical roots

1. If load is increased further, roots get complex with real and imaginary parts.
2. If voltage is stable, discriminant should be greater than or equal to zero.

If both active and reactive power are square function of voltage ($P_r=(V_r/V_n)^2P_n$ & $Q_r=(V_r/V_n)^2Q_n$ where Vn, Pn & Qn are nominal values of voltage and power at receiving end.), then there are no limits on value of the voltage at receiving end. Hence voltage collapse doesn't occur.

At the limit when Discriminant is zero, it gives maximum load ability of line as

$$S_{r\max} = \frac{V_s^2}{4Z\cos^2((\theta - \phi)/2)}$$

Where $\phi = \tan^{-1}(Q_r/P_r)$

According to the maximum power transfer theorem, following condition has to be satisfied:

1. Load absorbs maximum power.
2. Thevenin and load impedance are equal in magnitude.
3. The amplitude of the voltage drop across the thevenin impedance is equal to the amplitude of load voltage.

In the vicinity of the voltage collapse, increasing the apparent power at the sending end of the line doesn't increase the receiving end apparent power. The stressed lines turn out to big reactive power consumers and they confine the reactive power supply to the loads. As a result, the reactive power loading of other lines is increased and the lines achieve the most extreme transferable point. In the final step, the greater part of the associated lines can't supply the reactive power of the loads, which is the beginning stage of its voltage instability.

2.3 Voltage Stability Boundary (VSB)

Voltage stability boundary(VSB) is used to figure out the maximum loading capability of a particular load bus within the voltage stability limit[2, 3]. A two bus equivalent model of the power system is considered as shown in Fig. 2.1

Now re-write the eq.(2.8) considering $V_r = V$, $Z = Z_{Th}$, $R = R_{Th}$, $X = X_{Th}$, $Vs = V_{Th}$. Here load $P_r + jQ_r$ is the load at the bus k.

$$V_k^4 - (2P_r R_{Th} + 2Q_r X_{Th})V_k^2 - V_{Th}^2 V_k^2 + (P_r^2 + Q_r^2)(R_{Th}^2 + X_{Th}^2) = 0 \qquad (2.10)$$

Eq.(2.10) has only two feasible solutions which are real and positive. The higher voltage (V^H) is the stable solution and the lower volatge(V^L) is the unstable solution.

When the voltage collpase is occured this two solutions become equal.So condition for volatge collapse can given by,

$$V_k^H = V_k^L \tag{2.11}$$

At above condition the load power (active and reactive) is called critical power (P_{cr} and Q_{cr}) & corresponding voltage is called critical voltage (V_{cr}).

- Thevenin equivalent circuit behind a load bus

  The thevenin equivalent voltage V_{Th} of the load bus k can be calculated from the load flow of system. In calculating the Z bus matrix loads of all buses except bus k has to be replaced by constant impedances and the generators has to be replaced by negligible reactance. From the Fig. 2.2 calculation of load impedance can be easily understood.

$$Z_k{}^L = \frac{|V_k|^2}{P_r - jQ_r}$$

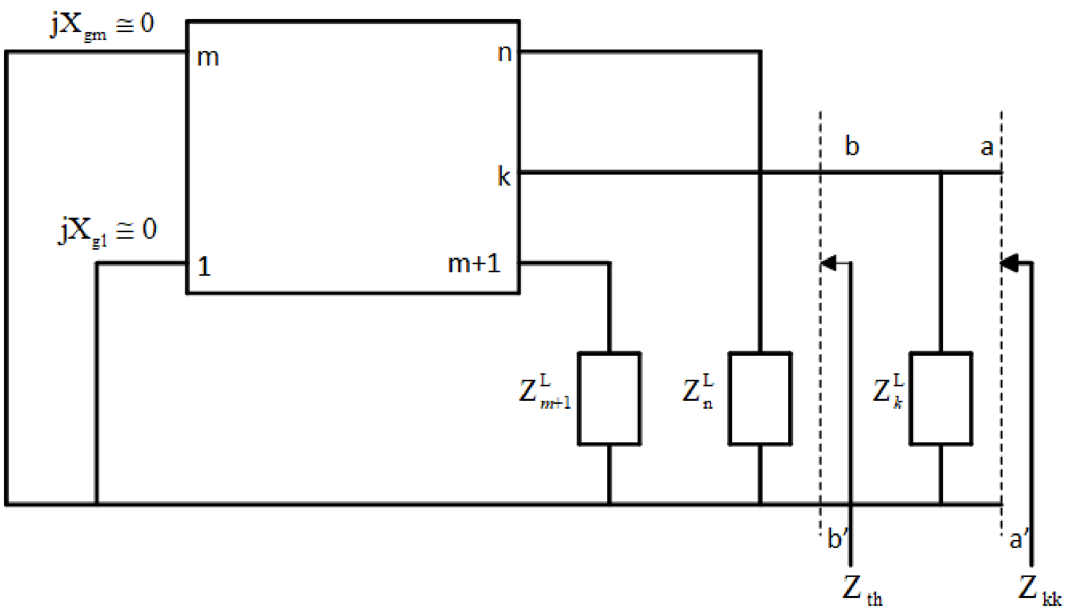

Figure 2.2: Thevenin impedance of load at bus k

- Determination of thevenin's parameters

  The parameters of thevenin's equivalent can be obtained from load flow solution considering all the load & bus impedance matrix(Z_{bus}). Z_{kk} is the k^{Th} diagonal element of Z_{bus} shows thevenin impedance of bus k.

$$Z_{Th} = \frac{Z_{kk} {Z_k}^L}{{Z_k}^L - Z_{kk}}$$

$$V_{Th} = \left(1 + \frac{Z_{Th}}{{Z_k}^L}\right) V_K$$

In the Fig. 2.3 the typical curve of voltage stability boundary is shown in the P-Q plane. The region under the critical values of active and reactive power is the feasible region while out side region is in-feasible region. We can find the stable set of active and reactive power loading from this curve at a particular bus.

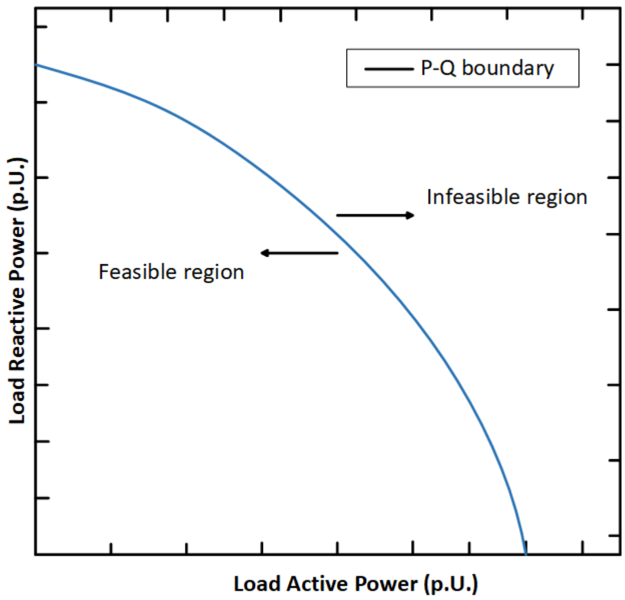

Figure 2.3: Typical voltage stability boundary in P-Q plane

2.4 Voltage Stability Indices

For estimating the voltage collapse point various methods used such as Jacobian method, P-V & Q-V curves, Modal analysis, Singular value method, Impedance index. But above mentioned methods required large number of load flow data and computational time gets increased while in the case of dynamic analysis of power system, time is very crucial and only a short interval is allowed so that the operators know what had happened before the system collapses. As a solution various VSIs had been proposed in order to get fast computation of voltage stability condition of system. They can be used for both static and dynamic analysis of voltage stability.

The condition of voltage stability is determined by using Voltage stability index (VSI).

They can either referred to a line or bus. They are derived from basic power flow equations. They give proximity of a given operating point to voltage collapse point. These indices are simple, easy to implement and computationally inexpensive. They can be used for both on-line and off-line studies.

If value of VSI is nearly 1 then it is weakest bus and if nearly 0 then it is a strongest bus.

Applications of VSI:

1. Identifying the weak buses/lines.

   In this case VSIs are used online/offline. Required data are obtained from Phasor measurement units (PMU) or static analysis. Line/bus closest to critical value is selected as the weakest line/bus.

2. Placement and sizing of DG units.

   It is done in two steps. At first weak bus/lines selected to determine the location for DG units. Then optimal location of DG units is determined to maximize the value of VSM. VSM is calculated by the VSIs.

3. Optimal location of FACTS devices

4. Capacitor allocation and Planning of the power system.

5. Triggering the countermeasures against voltage instability.

2.5 Classification and Characteristic of VSIs

Indices are classified[4] based on following ways:

1. Jacobian matrix and variables based VSIs

2. Bus, line and overall VSIs

Here Jacobin matrix based VSIs can calculate the voltage collapse point and determine the VSM. They are not suitable for real time as any changes in system lead to change in the Jacobian matrix and it has to be recalculated and also it's computation time is high. Also increase the running time of DG placement and sizing problems.

The VSIs based on system variables require less computation and suitable for real time applications. Disadvantage is that they cannot accurately estimate the VSM so only present critical lines and buses.

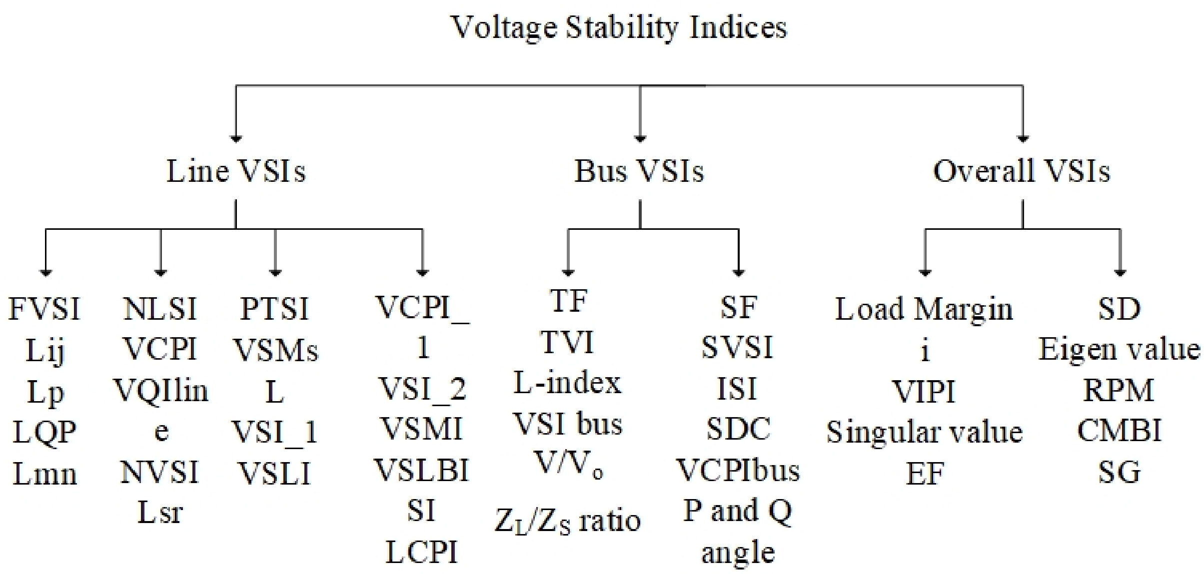

Figure 2.4: Classification of VSIs by types

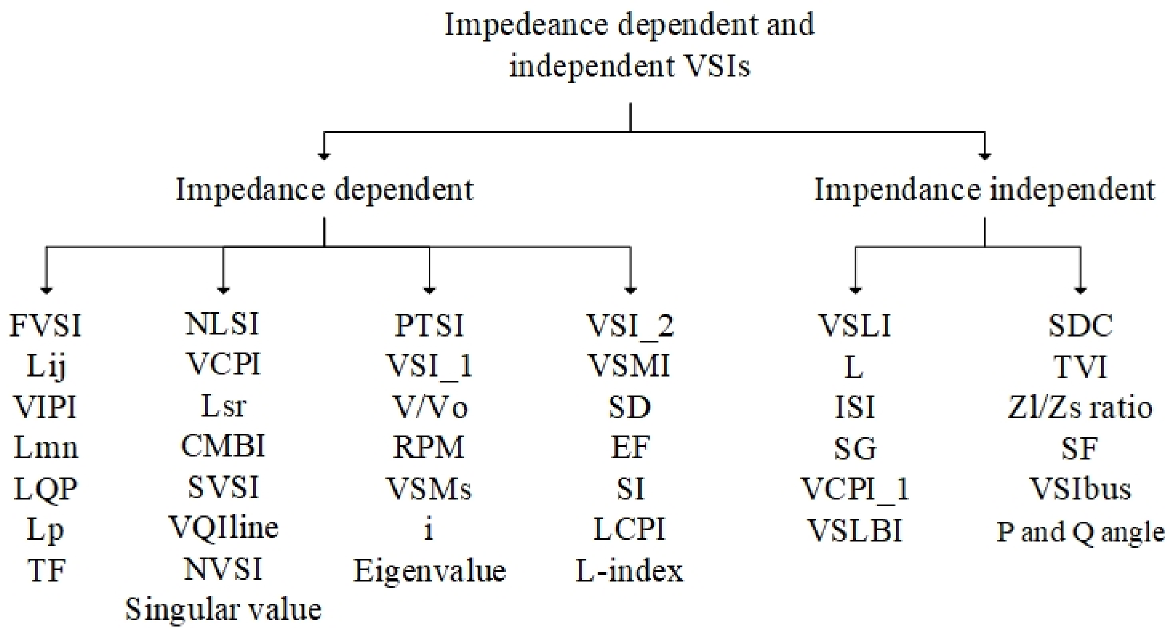

Figure 2.5: Classification of VSIs based on impedance dependency

The classification of the VSIs is shown in Fig. 2.4[4] as line VSIs, bus VSIs and overall VSIs. Generally, the accuracy of the overall VSIs is better than the line and bus VSIs but they are more complex and require more computations. The line VSIs and some bus

VSIs are simple and can determine the weak buses and lines but their accuracy is not that of overall VSIs.

VSIs are the function of power system impedance but some indices are dependent only on voltage and current at sending and receiving end instead of system impedance. Practically voltage and current dependant indices are more preferred because determining system impedance is not possible due to atmospheric effect and insufficient info about power system. So it gives errors in the indices. Classification according to this is as shown in Fig. 2.5[4]. In Fig. The comparison of accuracy and simplicity of different types of VSIs is shown Fig. 2.6[4].

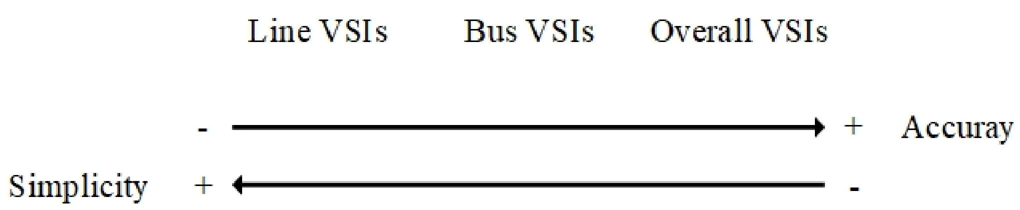

Figure 2.6: Comparison between simplicity accuracy of different types of VSIs

In the Fig. 2.7[4] steps to use VSIs for suitable location of FACTS placement are shown. In the first step weak lines and buses need to be identified. So, VSIs that can determine the weak buses and lines are used. And for second step except few VSIs, all other type of VSIs with higher precision and accuracy can be used.

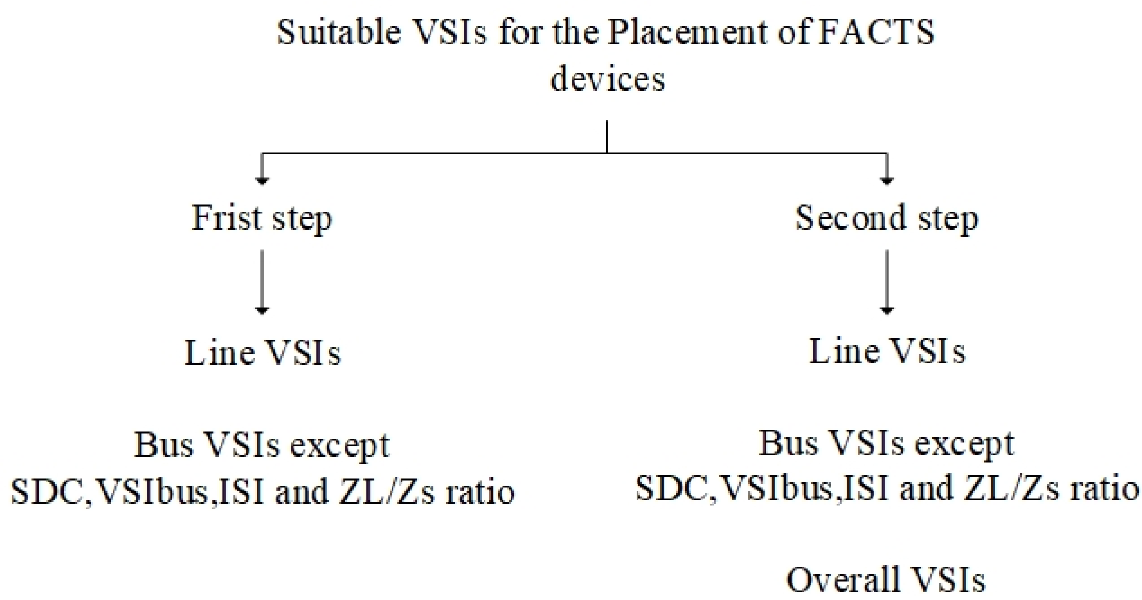

Figure 2.7: Suitable VSIs for FACTs placement

2.5.1 Line VSIs

- FVSI (Fast Voltage Stability Index)[5]

  Musirin proposed the FVSI based on the concept in which the discriminant of the voltage quadratic equation is set to be greater than or equal to zero. FVSI is calculated as following.

  Consider the Fig. 2.1 put eq. (2.6) into (2.4), we get

$$V_sV_r\cos\delta - V_r^2 = \frac{-V_sV_r\sin\delta R + R^2Q_r}{X} + XQ_r$$

$$V_r^2 - \left(\frac{R}{X}\sin\delta + \cos\delta\right)V_sV_r + \left(X + \frac{R^2}{X}\right)Q_r = 0 \tag{2.12}$$

  Roots of Vr

$$V_r = \frac{\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_s \pm \sqrt{\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_s\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_r}}{2}$$

  To obtain real roots of Vr, discriminant should be greater than or equal to zero

$$\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_s\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_r \geq 0$$

$$\frac{4Z^2Q_rX}{V_s^2\left(R\sin\delta + X\cos\delta\right)^2} \geq 1$$

  δ is normally very small so, $\delta = 0$, $R\sin\delta = 0$ & $X\cos\delta = X$

$$FVSI = \frac{4Z^2Q_r}{V_s^2X} = \frac{4Z^2Q_j}{V_i^2X_{ij}} \tag{2.13}$$

  Here, 'i' as the sending bus and 'j' as the receiving bus

- Line Stability Factors[6]

  Consider the Fig. 2.1

  By taking sending end as the reference node & P_r is the real power transferring from sending end to receiving end, we obtain

$$P_r = P_s - R\frac{(P_s^2 + Q_S^2)}{V_s^2} \tag{2.14}$$

Rearranging the above eq. (2.14)

$$\frac{RP_s^2}{V_s^2} - P_s + \left(P_r + \frac{RQ_s^2}{V_s^2}\right) = 0 \tag{2.15}$$

For roots of P_s,

$$1 - 4\left(\frac{R}{V_s^2}\right)\left(P_r + \frac{RQ_s^2}{V_s^2}\right) \geq 0 \tag{2.16}$$

Voltage collapse occured if above condtition is violated.

In the same manner, reactive power flow(Q_s) can be derived as:

$$1 - 4\left(\frac{X}{V_s^2}\right)\left(Q_r + \frac{XP_s^2}{V_s^2}\right) \geq 0 \tag{2.17}$$

Considering power flow from sending end to receiving end, real power(P_r) & reactive power(Q_r) flow condtion at receiving end can be obtained as:

$$1 - 4\left(\frac{R}{V_r^2}\right)\left(-P_s + \frac{RQ_r^2}{V_r^2}\right) \geq 0 \tag{2.18}$$

$$1 - 4\left(\frac{X}{V_r^2}\right)\left(-Q_s + \frac{XP_r^2}{V_r^2}\right) \geq 0 \tag{2.19}$$

From above eqs. (2.16),(2.17),(2.18),(2.19),

$$LPP = 4\left(R/V_s^2\right)\left(P_r + RQ_s^2/V_s^2\right) \tag{2.20}$$

$$LQP = 4\left(X/V_s^2\right)\left(Q_r + XP_s^2/V_s^2\right) \tag{2.21}$$

$$LPN = 4\left(R/V_r^2\right)\left(-P_s + RQ_r^2/V_r^2\right) \tag{2.22}$$

$$LQN = 4\left(X/V_r^2\right)\left(-Q_s + XP_r^2/V_r^2\right) \tag{2.23}$$

Above equations are the line stability factors and can be calculated for all the system lines. The line having the highest stability factor indicates the weakest line of system & the proximity towards voltage collapse.

Here the highest value is the closest to 1.

2.5.2 Bus VSIs

- VCPI(Voltage Collapse Prediction Index)[7]

The VCPI is derived from the basic power flow equation and its value varies between 0 & 1. The formulation of this index is as follows:

For an N bus system current injected into the k^{th} bus is given by,

$$I_k = V_k \sum_{\substack{m=1 \\ m\neq k}}^{N} Y_{km} - \sum_{\substack{m=1 \\ m\neq k}}^{N} V_m Y_{km} \tag{2.24}$$

where,

Y_{km} = Mutual admittance between k^{th} & n^{th} bus

Y_{kk} = Self admittance of bus k

V_k = Voltage at k_{th} bus

V_m = Voltage at m_{th} bus

Complex power injected at the k_{th} bus is given by,

$$S_k = V_k I_k^* \tag{2.25}$$

substitute eq. (2.25) into (2.24)

$$S_k^* = |V_k|^2 \sum_{\substack{m=1 \\ m\neq k}}^{N} Y_{km} - V_k^* \sum_{\substack{m=1 \\ m\neq k}}^{N} V_m Y_{km} \tag{2.26}$$

$$Y_{kk} = \sum_{\substack{=1 \\ \neq k}}^{N} Y_{km} \tag{2.27}$$

sustitute eq. (2.27) into (2.26)

$$S_k^* = |V_k|^2 Y_{kk} - V_k^* \sum_{\substack{m=1 \\ m \neq k}}^{N} V_m^{'} Y_{kk} \tag{2.28}$$

$$Where, \qquad V_m^{'} = \frac{Y_{km}}{\sum\limits_{\substack{j=1 \\ j \neq k}}^{N} Y_{kj}} V_m = \left|V_k^{'}\right| \delta_m^{'} \tag{2.29}$$

Rearranging (2.29),

$$\frac{S_k^*}{Y_{kk}} = |V_k|^2 - V_k^* \sum_{\substack{m=1 \\ m \neq k}}^{N} V_m^{'} \tag{2.30}$$

Eq. (2.30) can be written as,

$$\frac{S_k^*}{Y_{kk}} = \left[|V_k|^2 - (|V_k| \cos \delta_k - j\,|V_k| \sin \delta_k) * \sum_{\substack{m=1 \\ m \neq k}}^{N} \left(\left|V_m^{'}\right| \cos \delta_m^{'} + j \left|V_m^{'}\right| \sin \delta_m^{'} \right) \right] \tag{2.31}$$

where δ_k is the voltage angle at k^{th} bus

$$\frac{S_k^*}{Y_{kk}} = \left[|V_k|^2 - \left(\sum_{\substack{m=1 \\ m \neq k}}^{N} \left|V_m^{'}\right| |V_k| \cos \left(\delta_k - \delta_m^{'} \right) \right) + j \left(\sum_{\substack{m=1 \\ m \neq k}}^{N} \left|V_m^{'}\right| |V_k| \sin \left(\delta_k - \delta_m^{'} \right) \right) \right] \tag{2.32}$$

Right hand side of eq. (2.32) is complex quantity and can be written as,

$$\frac{S_k^*}{Y_{kk}} = a - jb \tag{2.33}$$

$$a - jb = \left[|V_k|^2 - \left(\sum_{\substack{=1 \\ \neq k}}^{N} \left|V_m^{'}\right| |V_k| \cos \left(\delta_k - \delta_m^{'} \right) \right) + j \left(\sum_{\substack{=1 \\ \neq k}}^{N} \left|V_m^{'}\right| |V_k| \sin \left(\delta_k - \delta_m^{'} \right) \right) \right] \tag{2.34}$$

where a and b are real numbers, comparing the real and imaginary parts of eq.(2.34)

$$a = |V_k|^2 - \sum_{\substack{m=1 \\ m \neq k}}^{N} \left| V_m' \right| |V_k| \cos\left(\delta_k - \delta_m'\right) \tag{2.35}$$

$$b = \sum_{\substack{m=1 \\ m \neq k}}^{N} \left| V_m' \right| |V_k| \sin\left(\delta_k - \delta_m'\right) \tag{2.36}$$

Eqs. (2.35) & (2.36) represents two unknowns V_k & δ.

$$f_1\left(|V_k|, \delta\right) = |V_k|^2 - \sum_{\substack{m=1 \\ m \neq k}}^{N} \left| V_m' \right| |V_k| \cos\delta \tag{2.37}$$

$$f_2\left(|V_k|, \delta\right) = \sum_{\substack{m=1 \\ m \neq k}}^{N} \left| V_m' \right| |V_k| \sin\delta \tag{2.38}$$

The partial derivatives of these equations are evaluated with respect to V_k and δ. Evaluating each element of the partial derivative,

$$J = \begin{vmatrix} 2|V_k| - \sum\limits_{\substack{m=1 \\ m \neq k}}^{N} \left| V_m' \right| \cos\delta & V_k \sum\limits_{\substack{m=1 \\ m \neq k}}^{N} \left| V_m' \right| \sin\delta \\ \sum\limits_{\substack{m=1 \\ m \neq k}}^{N} \left| V_m' \right| \sin\delta & V_k \sum\limits_{\substack{m=1 \\ m \neq k}}^{N} \left| V_m' \right| \cos\delta \end{vmatrix} \tag{2.39}$$

If the determinant of the above matrix is zero then there is the collapse of voltage at the k_{th} bus.Hence, the matrix becomes singular at voltage collapse.

Solving the above matrix and equating to zero provides

$$\frac{|V_k| \cos\delta}{\sum\limits_{\substack{m=1 \\ m \neq k}}^{N} |V_m'|} = \frac{1}{2} \tag{2.40}$$

Eq. (2.40) can be written as,

$$\frac{V_k}{\sum\limits_{\substack{m=1 \\ m \neq k}}^{N} V_m'} = \frac{1}{2} + jk \tag{2.41}$$

where, k is real constant

Eq. 2.41 using complex number identities can be written as

$$\left| 1 - \frac{\sum\limits_{\substack{m=1 \\ m \neq k}}^{N} V'_m}{V_k} \right| = 1 \tag{2.42}$$

So, final eqaution for VCPI can be written as,

$$VCPI_k = \left| 1 - \frac{\sum\limits_{\substack{m=1 \\ m \neq k}}^{N} V'_m}{V_k} \right| \tag{2.43}$$

$$V'_m = \frac{Y_{km}}{\sum\limits_{\substack{j=1 \\ j \neq k}}^{N} Y_{kj}} V_m$$

Where,

V_k and V_m are the voltage phasors at bus k and bus m

N is the number of buses

Y_{km} is the admittamce between the buses k and m

This index is based on the concept that the voltage equation must have a solution. The determinant of a matrix must be a zero.

Table 2.1: VSIs

No	VSI	CV	Equation	Assumptions
1	FVSI	1	$FVSI = (4Z^2Q_r)/(V_s^2X)$	$\sin\delta \approx 0, \cos\delta \approx 1$
2	LQP	1	$LQP = 4\,(X/V_s^2)\,(Q_r + (P_s^2X)/V_s^2)$	R $\approx 0, Y \approx 0$
3	VCPI (bus)	1	$VCPI_k = \left\| 1 - \frac{\sum_{m=1, m \neq k}^{N} V'_m}{V_k} \right\|$	Voltage of a bus is not depend on the other bus voltages

*CV=Collapse Value

2.6 Modal Analysis

Power system can be represented by following algebric eqs. (2.44) and (2.45)[8]

$$P_i = \sum_{k=1}^{n} |V_i|\,|V_k|\,|Y_{ik}| \cos(\theta_i - \theta_k - \alpha_{ik}), \qquad i = 1, 2, ..., n \tag{2.44}$$

$$Q_i = \sum_{k=1}^{n} |V_i|\,|V_k|\,|Y_{ik}| \sin(\theta_i - \theta_k - \alpha_{ik}), \qquad i = 1, 2, ..., n \tag{2.45}$$

where,

n = Total number of buses

P_i & Q_i = active and reactive power injection at bus i

V_i & θ_i = voltage magnitude and volatge angle at bus i

$Y_{ik}\angle\alpha_{ik}$ = The admittance of line between i^{th} & k^{th} bus

by linearizing above two equation with respect to an operating point, we get

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{2.46}$$

where,

ΔP = incremental change in active power at bus

ΔQ = incremental change in active & reactive power at bus

ΔV = incremental change in volatage power at bus

$\Delta\theta$ = incremental change voltage angle at bus

For determining Q-V sensitivity at each operating point P has to be kept constant & calculate the voltage stability by considering the incremental relationship between Q&V.

Hence, consider $\Delta P = 0$ in eq. (2.46)

$$\Delta Q = J_R \Delta V \tag{2.47}$$

where, $J_R = \left[J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV}\right]$ is known as the reduced Jacobian matrix

$$\Delta V = J_R^{-1} \Delta Q \tag{2.48}$$

$$Here\ taking, \qquad J_R^{-1} = \xi \Lambda^{-1} \eta$$

where,

ξ = right eigen vector matrix of J_R

Λ = diagonal matrix of J_R

η = left eigen vector matrix of J_R

i_{th} modal reactive power variation,

$$\Delta Q_{mi} = K_i \xi_i$$

where K_i is a normalization factor so that

$$K_i^2 \sum_j \xi_{ji}^2 = 1$$

where ξ_{ji}^2 is the j^{th} element of ξ_i.

corresponding i_{th} modal voltage varition,

$$\Delta V_{mi} = \frac{1}{\lambda_i} \Delta Q_{mi} \tag{2.49}$$

Here λ_i shows the weakness of the corresponding modal voltage. If it is small, weaker the modal volatge & if equal to zero, i_{th} modal voltage collapse.

2.6.1 V-Q Sensitivity

$$\frac{\partial V_k}{\partial Q_k} = \sum_i \frac{\xi_{ki} \eta_{ik}}{\lambda_i} = \sum_i \frac{P_{ki}}{\lambda_i} \tag{2.50}$$

At bus k if the eigenvalue λ is positive, voltage is stable and hence V-Q sensitivity is also positive. When load in system is increased eigenvalues becomes smaller till the critical point of voltage stability. At collpase at least one of the λ of J_R is zero.

2.6.2 Bus Participation Factor

$$P_{ki} = \xi_{ki} \eta_{ik} \tag{2.51}$$

P_{ki} is the contribution factor of the i_{th} eigenvalue to the V-Q sensitivity of bus k. For small eigenvalues P_{ki} determines the buses neare to voltage collpase.

2.6.3 Branch Participation Factor

$$P_{lji} = \frac{\Delta Q_{jli}}{\Delta Q_{l\max i}} \tag{2.52}$$

Branches having higher value of P_{lji} are responsible to weak the mode i.

2.6.4 Generator Participation Factor

$$P_{gki} = \frac{\Delta Q_{gki}}{\Delta Q_{g\max i}} \tag{2.53}$$

Generators having higher value of P_{gki} are responsible for maintaining the stability of mode i.

2.6.5 Flow Chart

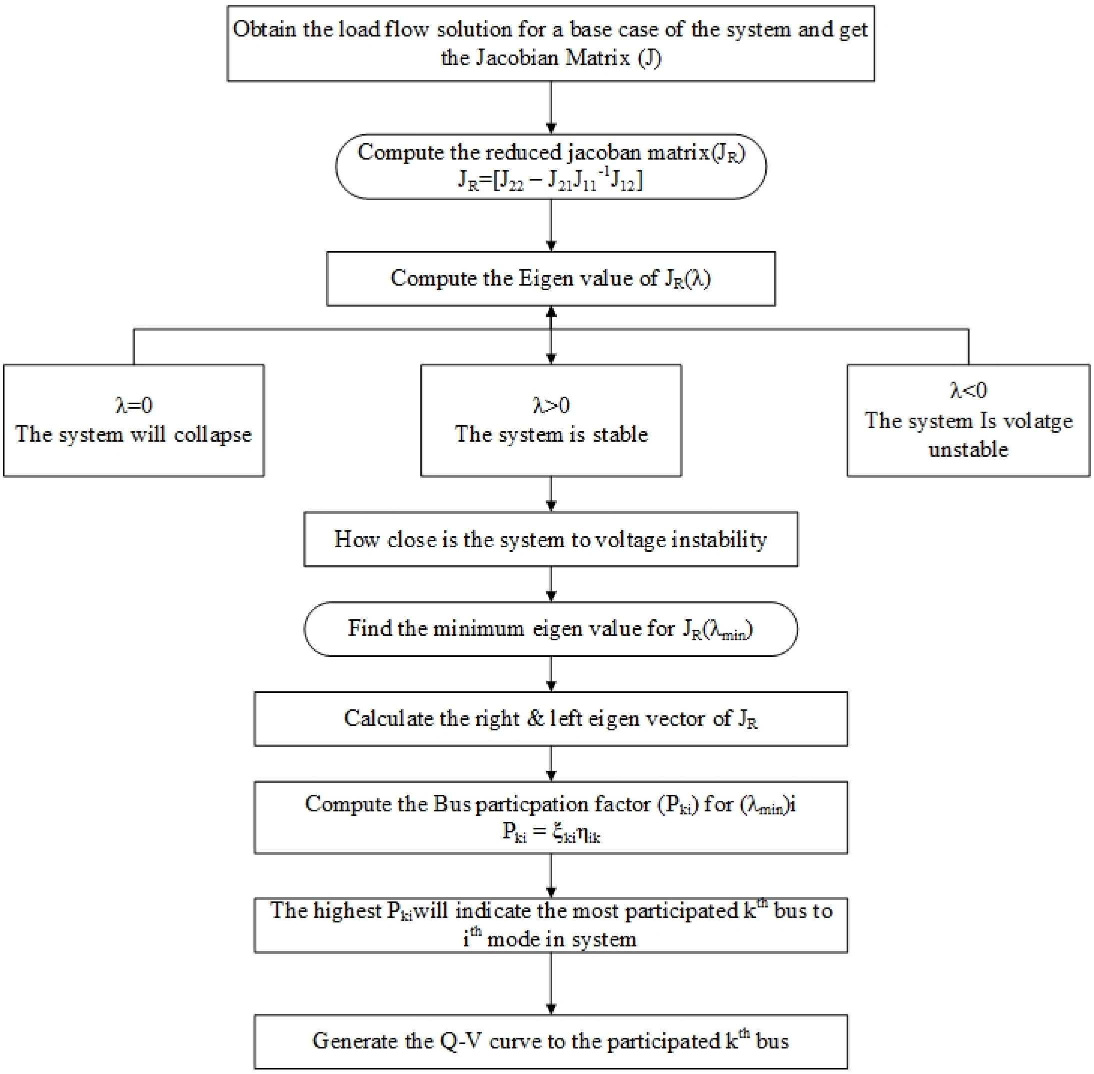

Figure 2.8: Flow chart for modal analysis

Chapter 3

FACTS Devices

FACTS devices are used for the purpose of reactive power support and voltage control. As reactive power compensation high capacity SVC & STATCOM are used in shunt at required buses.[9]

3.1 STATCOM

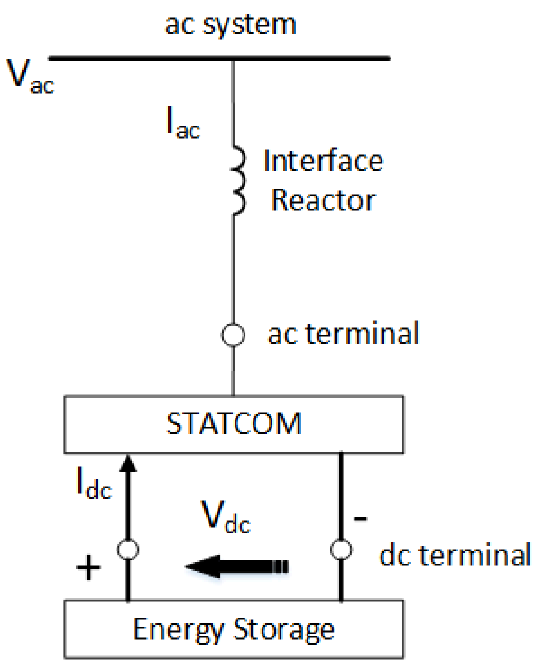

Figure 3.1: STATCOM Diagram

The STATCOM is the static compensator. It is used to supply both the capacitive and the inductive compensation.It is also capable to control its output current independently over the rated maximum capacitive or inductive range irrespective of the amount of ac-system voltage. Any combination of real power absorption or generation with var absorption or generation is achievable if the STATCOM is equipped with an energy-storage device of suitable capacity. Basic diagram of STATCOM is shown in Fig. 3.1

STATCOM consists of one VSC(Voltage source converter), energy strorage and associated with shunt-connected transformer. STATCOM provide a better option for improving short-term voltage instability problems than SVC [Dynamic VAR] as it is capable to generate or absorb reactive power at a faster rate in a more robust manner as SVC operation is flawed at low voltages. Based on the shunt connection of the converter, equivalent converter admittance (Y_{vr}) can be obtained as:

$$Y_{vr} = S_k^*/V_k^2$$

where,
S_K: Power injected at the bus k by the converter
V_K: Bus voltage magnitude

The values of bus voltage and power injected by the converter are obtained by load flow and to include the effect of STATCOM in Z_{bus}, the diagonal element is modified as:

$$Y_{net(k)} = Y_{load(k)} + Y_{vr}$$

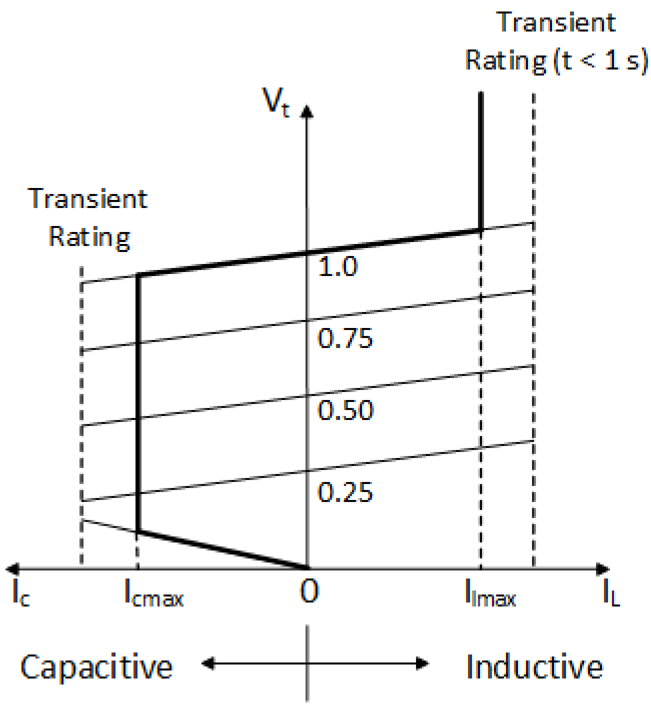

Figure 3.2: VI characteristic of STATCOM

Fig. 3.2 shows the VI characteristic of STATCOM. It can supply the full output of capacitive current almost independently of the system voltage means it can supply constant current at lower voltages. This capability can be useful when support is needed during/after faults where possibility of voltage collapse is the most.

3.2 SVC

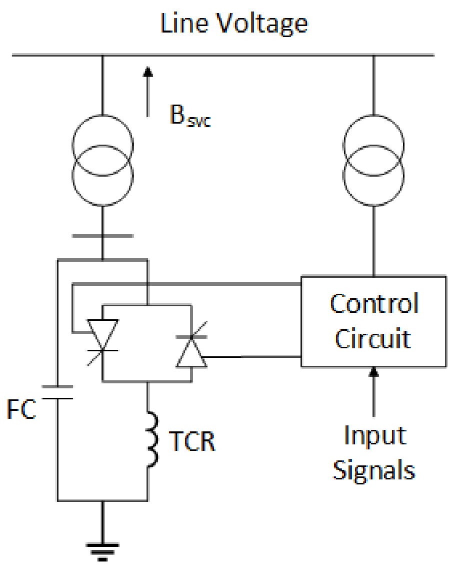

Figure 3.3: SVC Diagram

SVC is static synchronous compensator. Basic diagram of SVC is as shown in Fig. 3.3. Whose output is adjusted to exchange capacitive or inductive so as to maintain/control specific parameters of electrical power system, typically a bus voltage. The main function of SVC is to regulate the voltage at a given bus by controlling its equivalent reactance. The SVC combines a series capacitor bank shunted by thyristor controlled reactor. The SVC is modelled as a variable admittance such that its value remains within specified limits.

The diagonal element of Z_{bus} is modified by considering the susceptance of SVC connected to the corresponding bus. The net susceptance at the bus becomes:

$$Y_{net} = Y_{load} + B_{SVC} * I$$

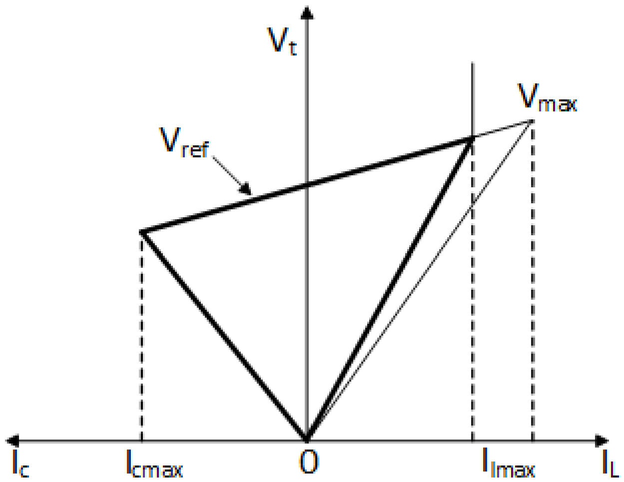

Figure 3.4: VI characteristic of SVC

The V-I characteristic shown in Fig. 3.4 of the SVC indicates that regulation with a given slope around the nominal voltage can be achieved in the normal operating range defined by the maximum capacitive and inductive currents of the SVC.

In the active control range, current/susceptance and reactive power is varied to regulate voltage according to a slope (droop) characteristic. The slope value relies upon the coveted sharing of reactive power production between various sources, and other needs of the system. The slope is typically 1-5 percent. At the capacitive limit, the SVC becomes a shunt capacitor. At the inductive limit, the SVC becomes a shunt reactor (the current or reactive power may also be limited).

Chapter 4

Simulation & Results

4.1 Simulation in IEEE-14 Bus System

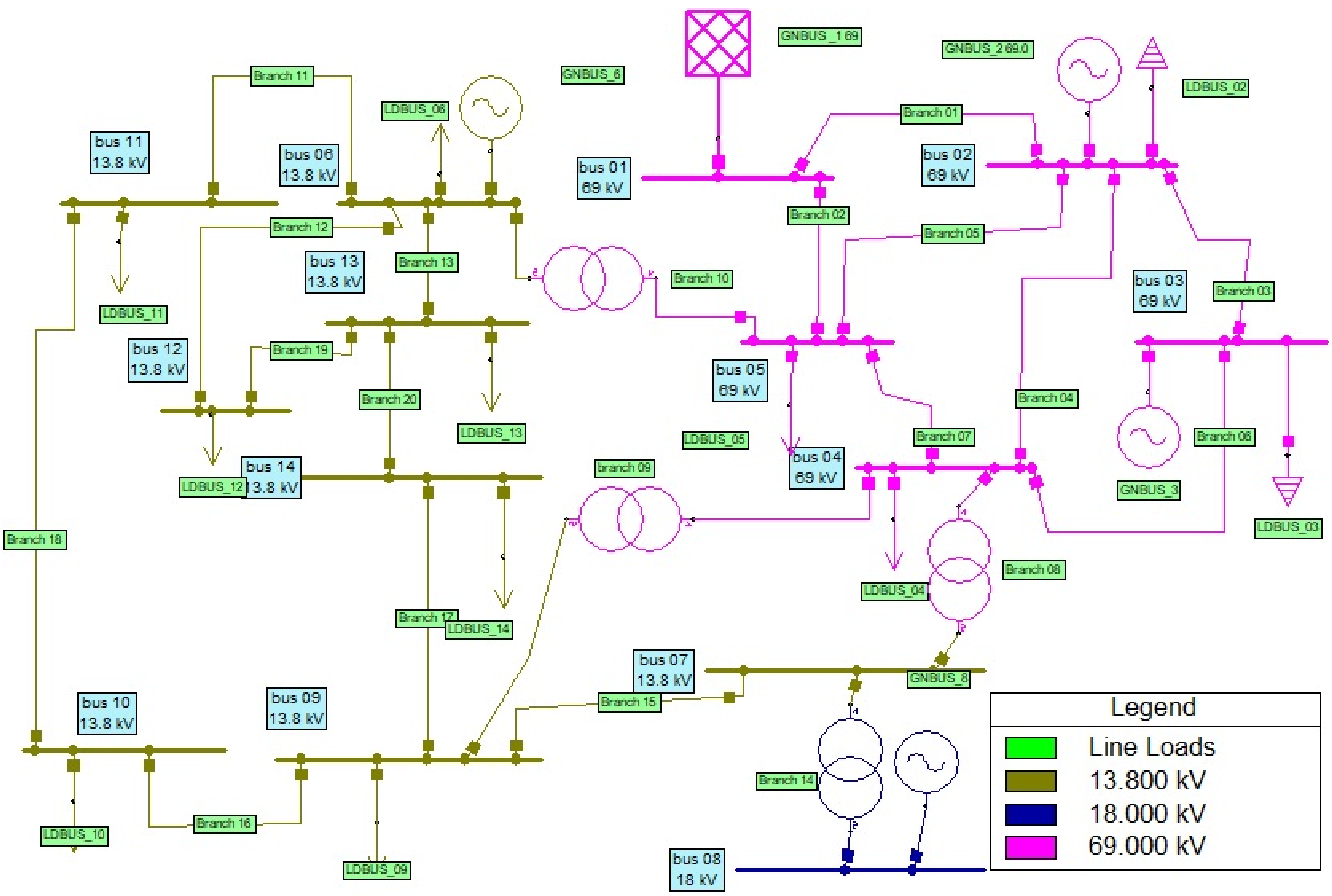

Figure 4.1: IEEE 14 Bus Simulation

Simulation of IEEE 14-bus system is developed in NEPLAN V5.53 as shown in Fig. 4.1. Here bus-1 is defined as slack bus. There are 2 synchronous generators, 3 synchronous compensator, 11 constant impedance loads. Data for IEEE 14 bus are given in the Appendix A.

Load Flow Results:

Table 4.1: Load Flow Results

Bus No.	Voltage	Phase angle	P Load	Q Load	P Gen	Q Gen
	p.u.		MW	MVar	MW	MVar
01	1.06	0	0	14.978	232.582	0
02	1.045	-5	21.7	12.7	40	48.824
03	1.01	-12.8	94.2	19	0	27.372
04	1.012	-10.2	47.8	4	0	0
05	1.016	-8.8	7.6	1.6	0	0
06	1.07	-14.4	11.2	7.5	0	22.51
07	1.0493	-13.2	0	0	0	0
08	1.09	-13.2	0	0	0	25.163
09	1.0328	-14.8	29.5	16.6	0	0
10	1.0318	-15	9	5.8	0	0
11	1.0471	-14.8	3.5	1.8	0	0
12	1.0534	-15.3	6.1	1.6	0	0
13	1.047	-15.3	13.5	5.8	0	0
14	1.0207	-16.1	14.9	5	0	0

Above Table 4.1 shows the load flow results of IEEE 14-bus system at base load condition. Load flow is done using the Newton-Raphsan method.

4.2 Voltage Stability Boundary(VSB) at Base load

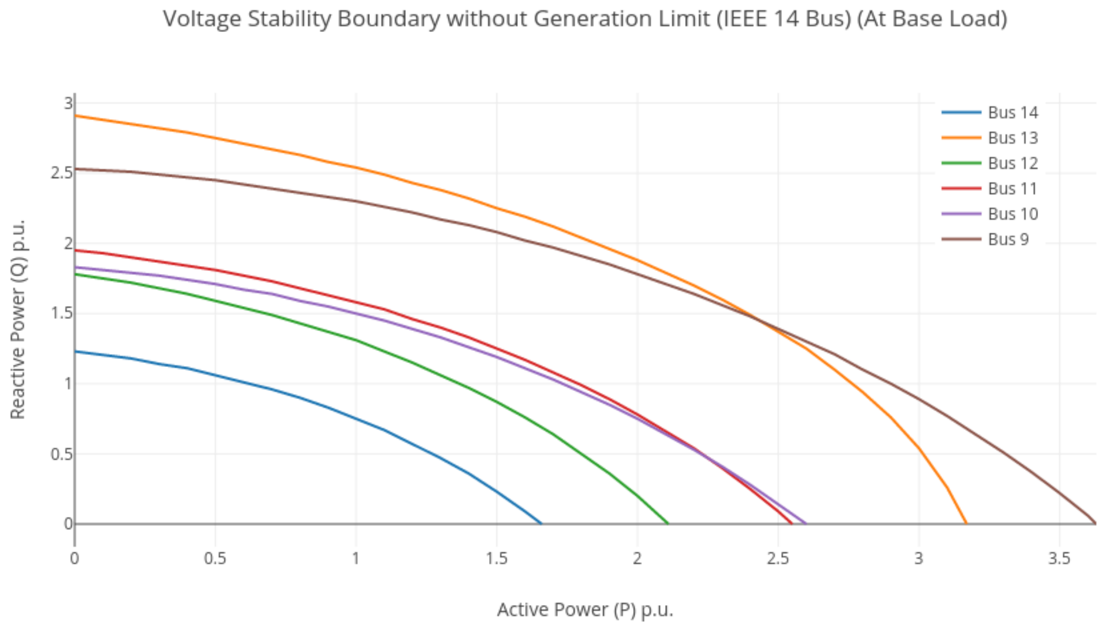

Figure 4.2: Voltage Stability Boundary without generation limit(At Base Load)

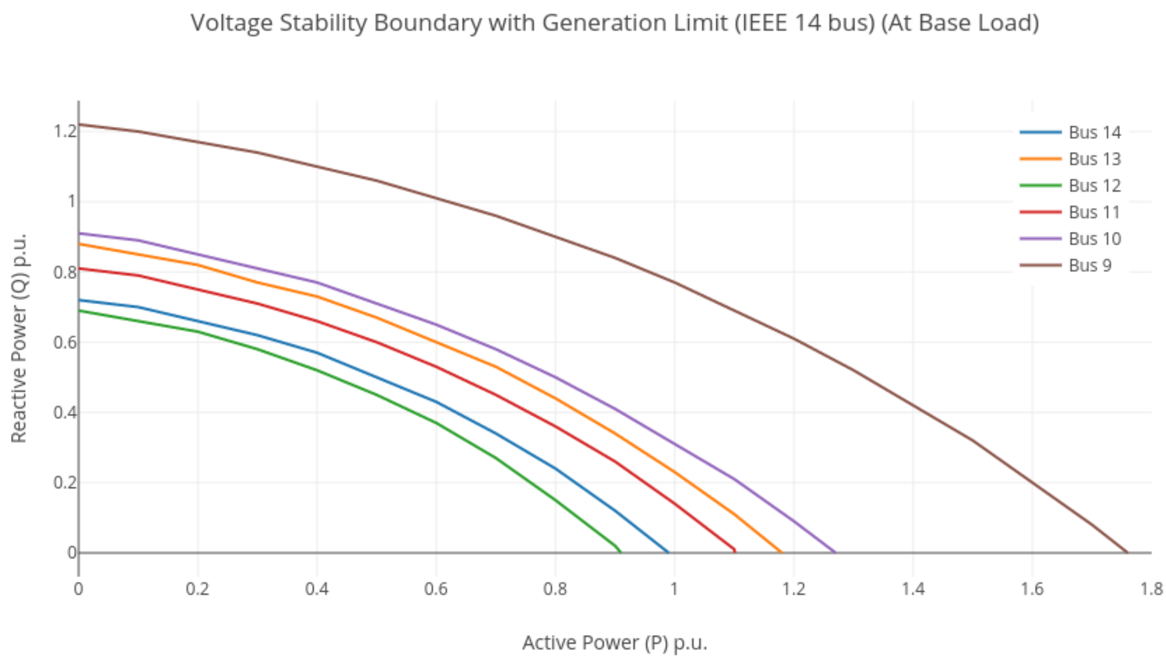

Figure 4.3: Voltage Stability Boundary with generation limit(At Base Load)

In above two Figs. 4.2 & 4.3 voltage stability boundaries of bus 9 to 14 are shown. In Fig. 4.2 the VSB without generator power limits is shown while in Fig. 4.3 VSB with generator power limits is shown. VSB is the margin within which the bus loading can be increased within the line load-ability constraints.

At any given bus by plotting VSB of that bus and current loading on that bus, minimum distance towards voltage collapse can be found which shows how much loading on that bus can be increased maintaining voltage stability. The bus 12 has the minimum voltage stability boundary of 0.65 MVA(p.u.).

Table 4.2: Critical values for voltage, active power & reactive power of IEEE 14 bus system

Bus No.	V_{cr} **(p.u.)**	P_{cr} **(p.u.)**	Q_{cr} **(p.u.)**
14	0.6996	0.97	0.71
13	0.727	1.16	0.86
12	0.7175	0.89	0.68
11	0.7253	1.08	0.8
10	0.7293	1.24	0.9
9	0.7615	1.73	1.2

The critical voltage, maximum active power & reactive power loading of IEEE 14 bus system considering the generator reactve power limits are calculated and shown in Table 4.2. Here, critical values are calculated using following assumptions:
For V_{cr} : Q=0; For P_{cr} : Q=0; For Q_{cr} : P=0

Table 4.3: Min_Dist_VC for IEEE 14 bus system

Bus No	14	13	12	11	10	9
Min_Dist_VC (MVA, p.u.)	0.5734	0.7135	0.612	0.7422	0.7731	0.894

The mininmum distance towards voltage collapse of several load buses according to their voltage stability boundaries are calculated (at base load) and shown in Table 4.3. Which shows the max amount of apparent power (MVA, p.u.) that can be increased at respective buses maintaining the voltage stability at that bus. The bus 14 has minimum voltage stability margin of 0.573 MVA(p.u.)

Here case 1 & 2 is considered to assure the performance and accuracy of methods which are used for analysis & to compare the effect of FACTS on voltage stability margin.

4.3 Case 1: At bus 11 heavy loading (Q=0.75 p.u.)

Voltage Stability Indices

- Line stability indices (FVSI & LQP)

Table 4.4: LSIs (Q=0.75 p.u. at bus 11)

Line No	FVSI	LQP
1	0.122	0.100
2	0.398	0.324
3	0.139	0.049
4	0.243	0.221
5	0.235	0.234
6	0.230	0.256
7	0.005	0.001
8	0.276	0.252
9	0.538	0.483
10	0.666	0.587
11	0.541	0.659
12	0.040	0.045
13	0.059	0.068
14	0.214	0.214
15	0.260	0.252
16	0.201	0.229
17	0.058	0.062
18	0.545	0.643
19	0.011	0.023
20	0.045	0.053

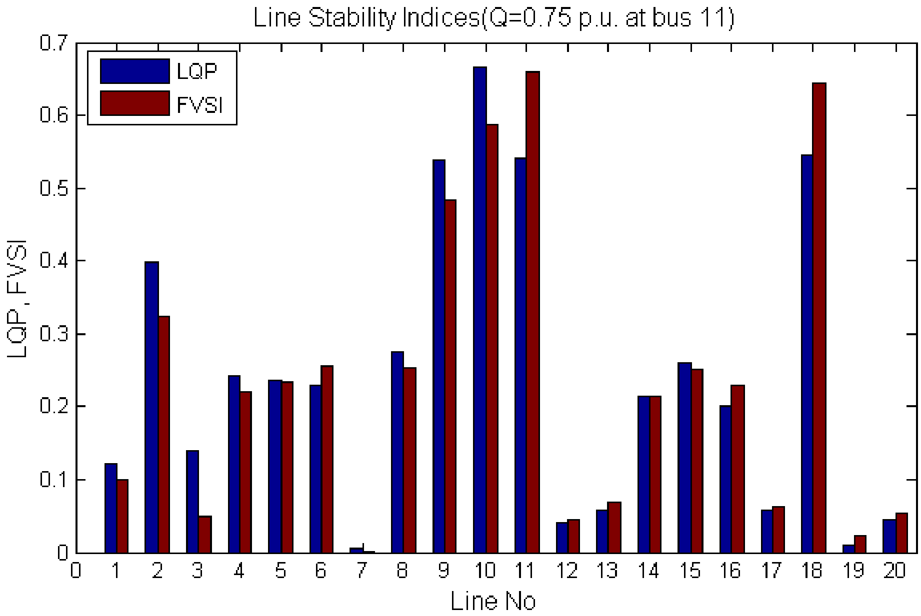

Figure 4.4: LSIs (Q=0.75 p.u. at bus 11)

In above Table 4.4 the LSIs of 20 lines are shown & in Fig. 4.4 comparison of those indices are shown.Here results of two line stability indices, FVSI LQP are shown. These both indices give same result which shows that the lines 10 & 11 between buses (5-6) & (6-11) respectively are highly loaded for given case. Here, line 10 shows the transformer which is between buses 5 & 6, hence line 11 required compensation. Series compensation has to be provided or shunt compensation on highly loaded bus which can be found from VCPI as described below has to be provided. It shows that if compensation is provided in this line, transfer capacity and VSB of respective buses can be further increased to provide more loading.

- Bus stability index (VCPI)

Table 4.5: VCPI (Q=0.75 p.u. at bus 11)

Bus No	VCPI
1	0.072435
2	0.009014
3	0.009463
4	0.014855
5	0.014741
6	0.036704
7	0.004089
8	0.050872
9	0.013837
10	0.010664
11	0.163756
12	0.009280
13	0.014546
14	0.030354

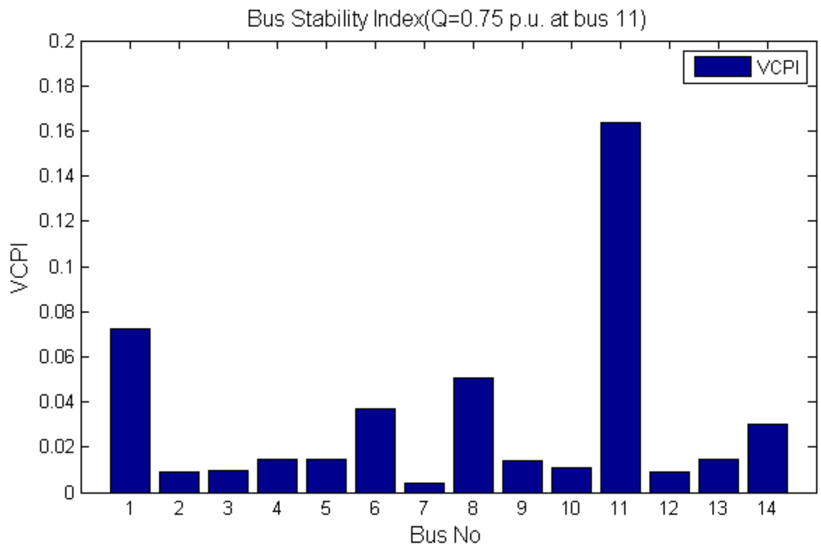

Figure 4.5: VCPI (Q=0.75 p.u. at bus 11)

In Table 4.5 VCPI of 14 buses are shown and their comparison is shown in Fig. 4.5. From the result it is clear that VCPI of bus no 11 is higher means it is the most critical bus and required shunt compensation.

Modal Analysis

- V-Q sensitivity

Table 4.6: V-Q Sensitivity (Q=0.75 p.u. at bus 11)

Bus No	V-Q Sensitivity
11	1.3460
14	0.8491
12	0.8401
10	0.8358
13	0.7654
9	0.6145
7	0.4555
4	0.1740
5	0.1555

For given load condition the V-Q sensitivity of buses are shown in the Table 4.6. According to which the highest sensitivity is of bus 11 which means for any change in reactive power the change in voltage at that bus will be maximum and it is nearer to voltage collapse. It shows that supply of reactive power at that bus will improve voltage stability at that bus as well as other buses which have higher mutual V-Q sensitivity with bus 11 which is shown as below.

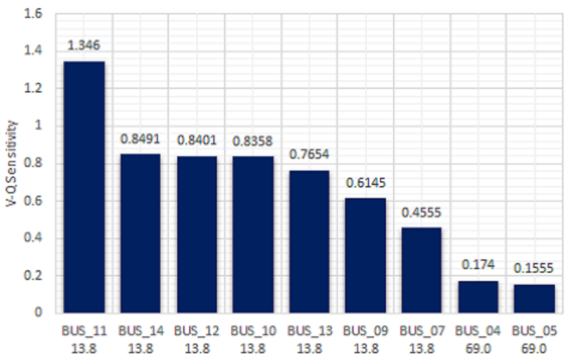

Figure 4.6: V-Q Sensitivity (Q=0.75 p.u. at bus 11)

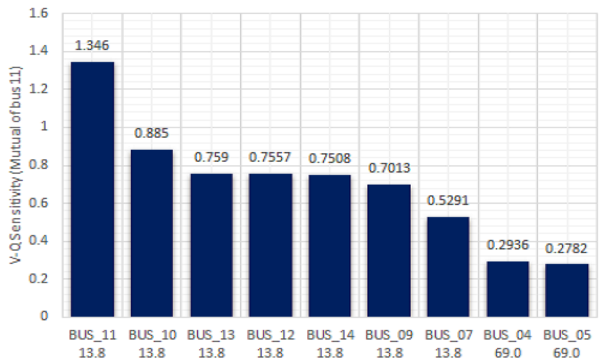

Figure 4.7: V-Q Sensitivity (Mutual of bus 14) (Q=0.75 p.u. at bus 11)

In above Figs. 4.6 & 4.7 V-Q sensitivity of buses and mutual v-q sensitivity of bus 11 is shown. Here mutual sensitivities show that buses 10,13,12,14 have higher value. Hence providing compensation at bus 11 will affect those bus more which has higher value of mutual sensitivity with bus 11.

- Eigen Value Analysis

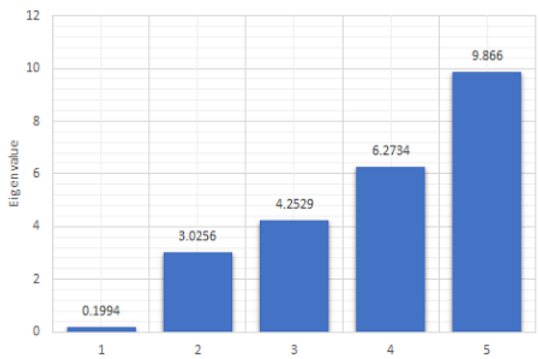

Figure 4.8: Eigenvalues (Q=0.75 p.u. at bus 11)

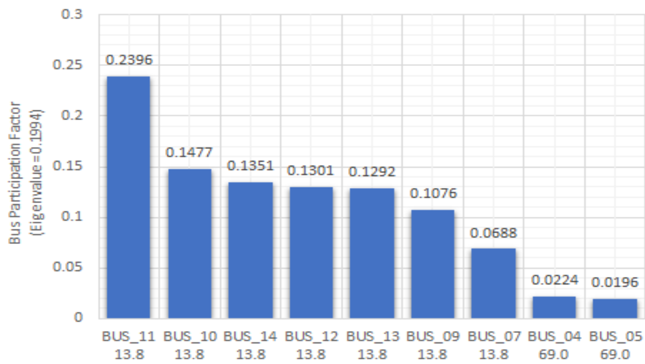

Figure 4.9: Bus participation factor for min. eigenvalue(0.279) (Q=0.75 p.u. at bus 11)

From results of eigenvalue analysis as shown in Fig. 4.8 the minimum eigenvalue(0.279) is obtained. And also bus participation factors for that minimum eigenvalue (Fig. 4.9) are also calculated which shows the bus 11 having the highest participation factor for that minimum eigenvalue. It shows that bus 11 is nearer to voltage collpase.

VSB

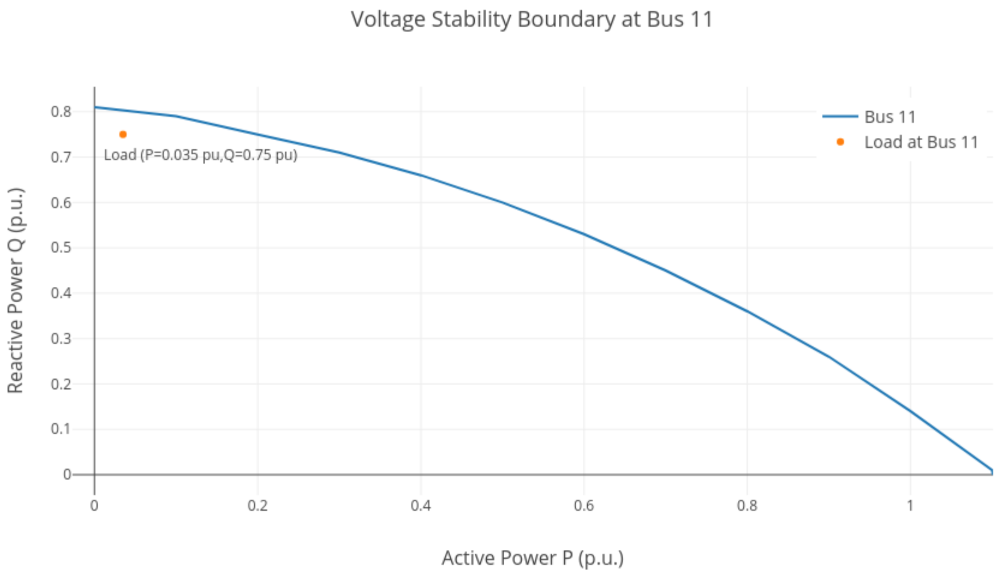

Figure 4.10: VSB of bus 11 (Q=0.75 p.u. at bus 11)

VSB of bus 11 is shown in Fig. 4.10 from this the minimum distance between the point of current loading and curve of VSB can be calculated which shows the maximum loading which can be increased before voltage collapse. From figure the minimum distance towards voltage collapse is calculated which is 0.0488 MVA(p.u.) which shows stability margin of bus 11 and hence it is found out that shunt compensation at that bus will improve VSB of that bus and improve voltage stability of the system.

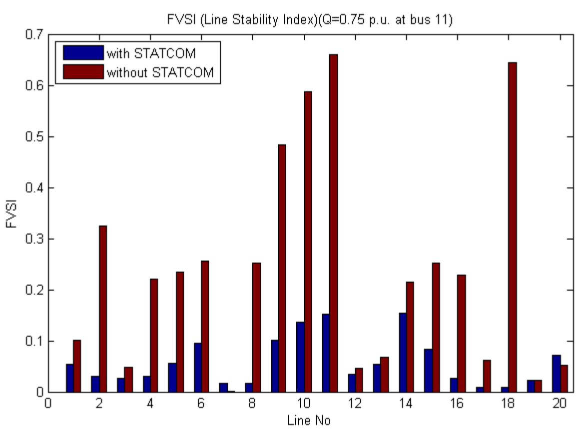

Figure 4.11: FVSI with & without STATCOM (Q=0.75 p.u. at bus 11)

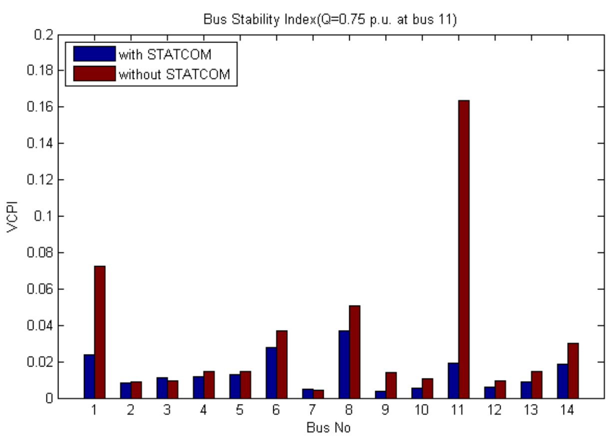

Figure 4.12: VCPI with & without STATCOM (Q=0.75 p.u. at bus 11)

The STATCOM is connected at bus 11 and it supplies 57.07 Mvar of reactive power maintaining voltage stability at 1.00(p.u.). From Figs. 4.11 & 4.12 the effect of compensation can be observed in terms of decrease of index value.

4.4 Case 2: Loading Factor=1.5

A second case is considered with loading factor 1.5 then finding and placing the SVC/STATCOM at optimal location comparing the effect of both the devices on VSB.

Determination of the weakest bus and installation of SVC/STATCOM

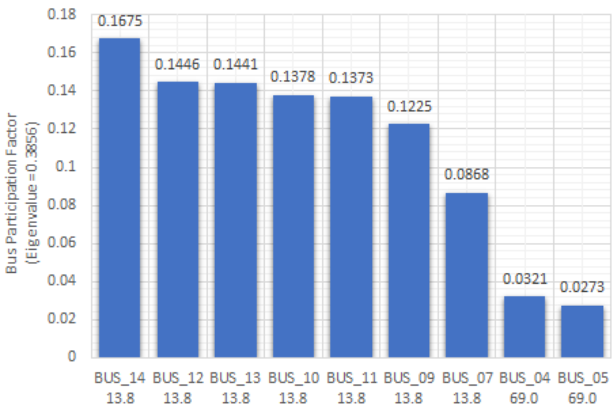

Figure 4.13: Bus participation factor for min. eigenvalue(0.3856) (Loading Factor = 1.5)

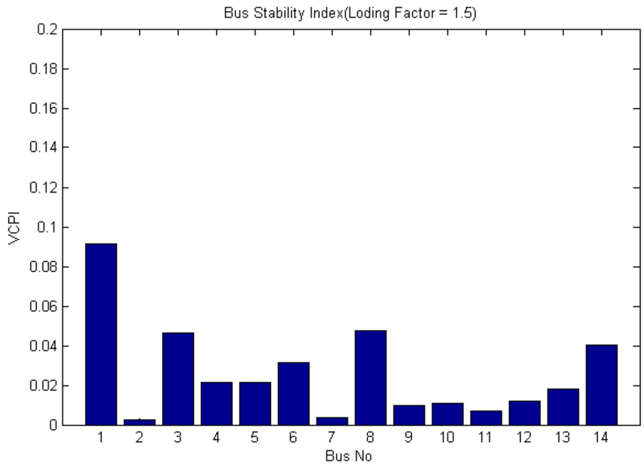

Figure 4.14: VCPI (Loading Factor = 1.5)

Table 4.7: V-Q Sensitivity (Loding Factor = 1.5)

Bus No	V-Q Sensitivity
14	0.5808
12	0.5422
13	0.4773
11	0.4677
10	0.4461
9	0.385
7	0.3275
4	0.1473
5	0.1301

Fig. 4.13 shows that bus 14 having maximum participation in minimum eigen value(0.3865).

From Fig. 4.14 the load bus with high index is bus 14. Table 4.7 show bus 14 having highest sensitivity factor. Above three results show that bus 14 is the weakest bus and so it is the optimal location for the placement of shunt devices (SVC/STATCOM).

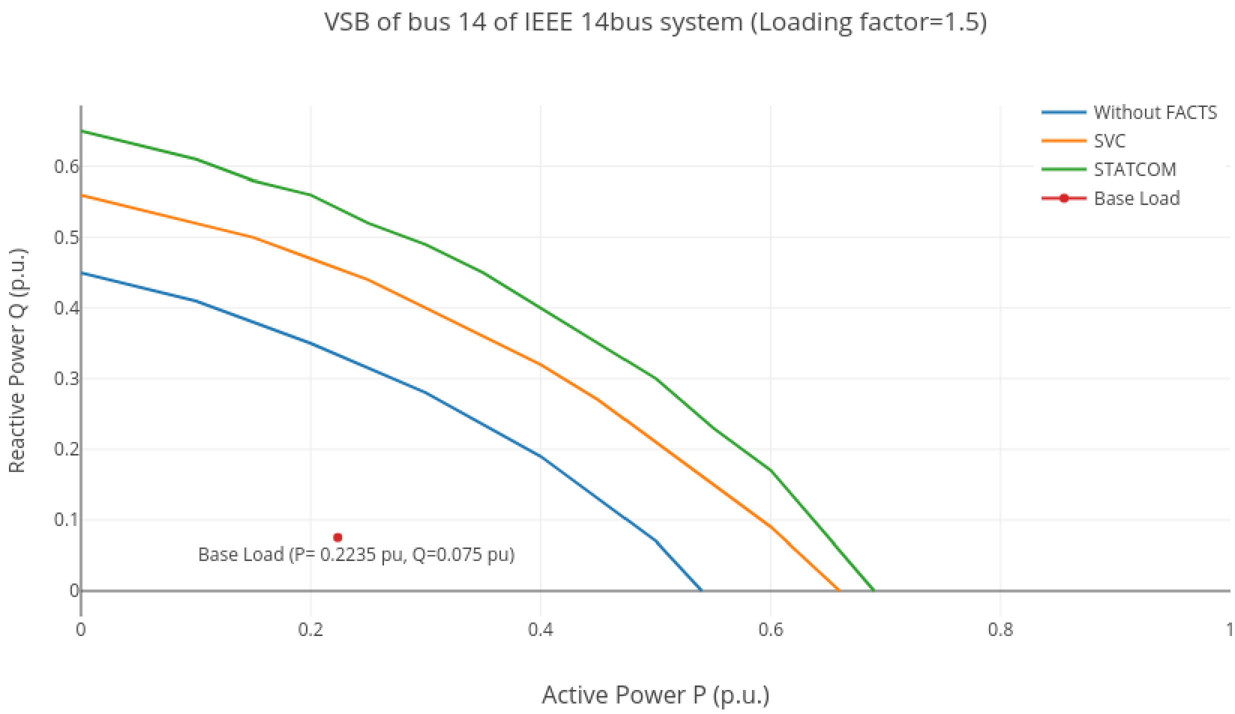

Figure 4.15: VSB of bus 14 with SVC & STATCOM (Loading Factor = 1.5)

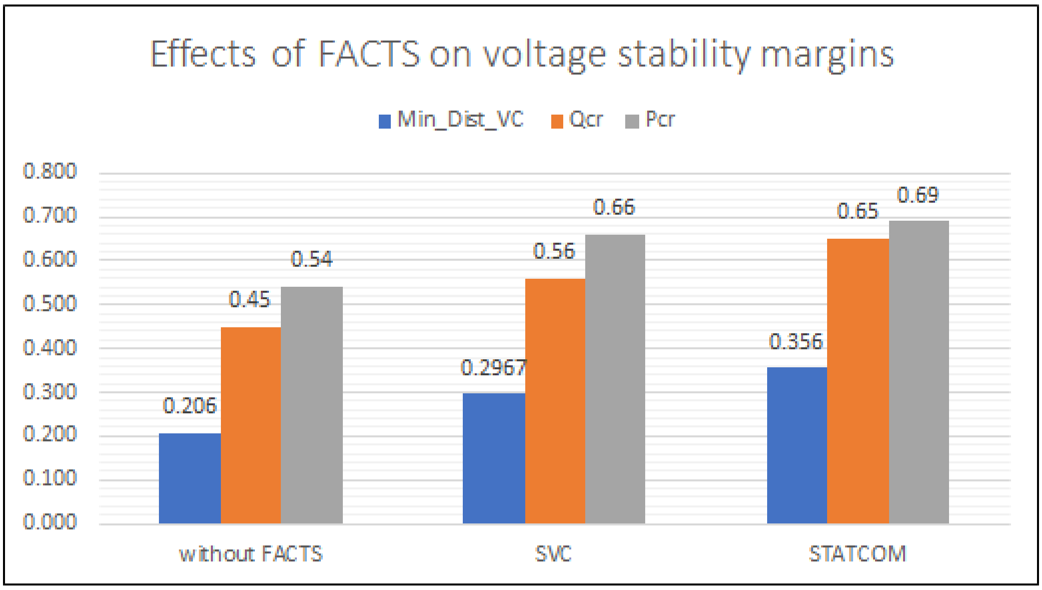

Figure 4.16: Comparison of FACTS (Loading Factor = 1.5)

Voltage stability boundary at bus 14 with SVC & STATCOM at loading factor 1.5 is shown in Fig. 4.15. Here to maintain voltage at 1.0 p.u. at bus 14, SVC generates 35.936

Mvar, while for STATCOM to maintain 1.01 p.u., it generates 38.01 Mvar.Voltage stability boundaries are shifted upwards for both the cases showing enhancement in voltage stability margin. Here all VSBs are almost parallel to each other.As static model of SVC and STATCOM behave almost in the same manner they become overlapping for same voltage level.

From Fig. 4.16 it is observed that results VSB has enhanced with FACTS devices. The minimum distance towards voltage collapse, critical reactive & active power in p.u. are shown. Slight difference in the target voltage are made intentionally to observe their impacts on voltage stability margins.

Chapter 5

Conclusion & Future Work

Conclusion

Voltage stability assessment is carried out using voltage stability boundary(VSB), voltage stability indices and modal analysis on IEEE-14 bus system. VSB is used to calculate the margin of voltage stability, critical values of active & reactive power. FVSI,LQP VCPI indices are calculated to find the proximity of bus/line towards the voltage collapse and optimal location of FACTS devices. Results obtained are compared and validated by the modal analysis method. Impacts of FACTS are observed and compared. Conclusions obtained are as following:

- VSIs can be used in real time system to find optimal location for FACTS devices.
- VSB gives margin of voltage stability and can be enhanced in all the cases to improve voltage stability of the system
- FACTS device can improve the margin and critical values of active & reactive power
- STATCOM has better impact on VSB than SVC

Future Work

- Continuation power flow (CPF) method can be implemented
- Study of the impact of TCSC, UPFC & HVDC on the VSB enhancement
- Dynamic simulation to analyze the FACTS impacts on real time system

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Appendix A

IEEE 14-Bus Data

Table A.1: Line data

From Bus	To Bus	Resistance (pu)	Reactance (pu)	Line charging (pu)
1	2	0.01938	0.05917	0.0528
1	5	0.05403	0.22304	0.0492
2	3	0.04699	0.19797	0.0438
2	4	0.05811	0.17632	0.0374
2	5	0.05695	0.17388	0.034
3	4	0.06701	0.17103	0.0346
4	5	0.01335	0.04211	0.0128
4	7	0	0.20912	0
4	9	0	0.55618	0
5	6	0	0.25202	0
6	11	0.09498	0.1989	0
6	12	0.12291	0.25581	0
6	13	0.0615	0.13027	0
7	8	0	0.17765	0
7	9	0	0.11001	0
9	10	0.03181	0.0845	0
9	14	0.12781	0.27038	0
10	11	0.08205	0.19207	0
12	13	0.22092	0.19988	0
13	14	0.17093	0.34802	0

Table A.2: Bus Data

Bus No.	Bus Voltage		Generation		Load	
	Magnitude Per Unit	Phase Angle Degrees	Real MW	Reactive MVAR	Real MW	Reactive MVAR
1	1.06	0	232.4	-16.9	0	0
2	1.045	-4.98	40	42.4	21.7	12.7
3	1.01	-12.72	0	23.4	94.2	19
4	1.019	-10.33	0	0	47.8	3.9
5	1.02	-8.78	0	0	7.6	1.6
6	1.07	-14.22	0	12.2	11.2	7.5
7	1.062	-13.37	0	0	0	0
8	1.09	-13.36	0	17.4	0	0
9	1.056	-14.94	0	0	29.5	16.6
10	1.051	-15.1	0	0	9	5.8
11	1.057	-14.79	0	0	3.5	1.8
12	1.055	-18.07	0	0	6.1	1.6
13	1.05	-15.16	0	0	13.5	5.8
14	1.036	-16.04	0	0	14.9	5

Table A.3: Transformer Data

Transformer	Between Buses	Tap Setting
1	4-7	0.978
2	4-9	0.969
3	5-6	0.932

Table A.4: Shunt Capacitor Data

BusNumber	Susceptance Per Unit
9	0.190

Table A.5: Regulated Bus Data (P-V Buses)

Bus No	Voltage Magnitude (p.u.)	Reactive Power Limits	
		Minimun	Maximum
2	1.045	-40	50
3	1.01	0	40
6	1.07	-6	24
8	1.09	-6	24

Table A.6: MW Limits for Branches

Line	MW
1 – 2	0.6
2 – 3	0.7
2 – 4	0.8
1 – 5	0.5
2 – 5	0.4
3 – 4	0.3
4 – 5	0.2
5 – 6	0.5
4 – 7	0.4
7 – 8	0.2
4 – 9	0.2
7 – 9	0.2
9 – 10	0.2
6 – 11	0.3
6 – 12	0.2
6 – 13	0.2
9 – 14	0.2
10 – 11	0.2
12 – 13	0.2
13 – 14	0.2