OPTIMAL PLACEMENT OF FACTS DEVICE BASED ON N-1 SECURITY AND STABILITY FOR BUS SYSTEMS USING PSAT

Tanvir Choudhury (160021078)

Shahran Eyakin Anim (160021052)

Tahmid Mahmud (160021152)

Submitted in partial satisfaction of the requirements for the undergraduate thesis

Islamic University of Technology (IUT)

CERTIFICATE OF APPROVAL

The thesis titled '*Optimal Placement of FACTS Device Based on N−1 Security and Stability for Bus Systems Using PSAT*' submitted by Tanvir Choudhury (St. Id. 160021078), Shahran Eyakin Anim (St. Id. 160021052) and Tahmid Mahmud (St. Id. 160021152) of Academic Year 2016−17 has been found as satisfactory and accepted as partial fulfillment of the requirement for the Degree BACHELOR OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING.

Approved By:

____

Dr. Ashik Ahmed

Supervisor and Professor,

Department of Electrical and Electronic Engineering

Islamic University of Technology (IUT)

Boardbazar, Gazipur-1704

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Abstract

With increasing deregulation in the electricity markets and also overall increases in consumer demand, the components of the power system are operated increasingly nearer to their rated limits. All of this also has to be done while considering the security and reliability of the system in an economic manner. There are many promising avenues of research which investigates modifications to existing infrastructure in order to meet the changing scenario and one promising path is the addition of FACTS devices.

In this work, continuation power flow is used to evaluate the risk of large voltage deviations due to outages and the optimal placement of the shunt device SVC is determined in order to alleviate this issue. Similarly, the performance index based contingency ranking method is used in order to rank the severity on line flows due to possible outages and this is used to determine the optimal allocation of the series device TCSC. This is done for IEEE 5, 14 and 30 bus system and on the WSCC 9 bus system.

In addition, the effectiveness of placement and stability is evaluated for testing in time domain under perturbations such as sudden changes in load demand and three-phase symmetrical faults. Simulations are done in the PSAT software.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation

The industry of power generation has been shifting from centrally-run monopolies to a more free competitive environment. The deregulation results in more private companies actively participating to provide our power supply. This has several benefits such as paving the way for renewables and lower price, however this comes at a price. For such companies to appeal to consumers they must be highly cost effective in their generation leading to the main issue of power suppliers operating equipment close to their rated limits increasing the chances of equipment failures and cascading outages. These are power system security concerns.

To tackle this issue utilities could continue to expand to include more transmission lines and generating plants but there are very strict regulations such as ones regarding environmental and land-use limiting such actions. Utilities must use their infrastructure in the most effective manner. One tool to aid utilities are FACTS devices. However, such devices have high installation costs so a balanced approach must be taken to find the most optimal way of including such devices.

1.2 Power System Security

The capability of a power system to successfully manage outage events and maintain system operation with all constraints within limits is power system security. These possible outage events that may occur are referred to as contingencies. These events are typically: loss of generation, load, or transmission components or swings in net load. These outages may be planned for maintenance or unplanned. The ability to 'handle' these events can be measured in how much the load is affected by these events and how effective the system is at recovering from these events and reach a stable operating point in terms of power system dynamics.

The failure of security does not just lead to isolated equipment failures. Most equipment have automatic switching devices for protection. Any outage can lead to exceeding the parameters of another equipment such as the power flow of a line and this can lead to a cascade of failures causing a widespread blackout.

Power system operators of the past did not need to be as concerned with the idea of power system security as we are today. Most credible outages could be considered in the planning stages of building the infrastructure. They mainly needed to ensure adequate spinning reserve for excess loads or to make up for any generator failures. However, the need to evaluate contingencies in real-time as the conditions of the system changes beyond those considered at the planning stages gave rise to the importance of security.

This modern interpretation of security can said to have started from the 1965 North East blackout [1] involving parts of USA and Canada. A faulty protective relay led to a series of cascading failures due to heavily loaded transmission lines in the winter season. While measures have been taken since then, with the increasing power consumption and deregulation since then, the study of security has becoming a necessity.

1.3 Security and Economy

The security and economy go side by side. The security attained for the power system must be economic for long term operation. Unrealistic spending on maintaining the security is never desirable. So while building a system, initial cost and maintenance

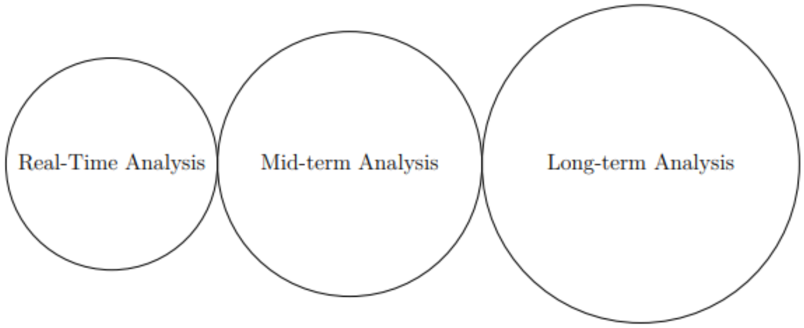


Figure 1.1: Time Scale of Security Analysis

cost must be analyzed. It is not practical to build a system which is completely secure against all possible contingencies. Rather, the probability of such occurrences are minimized. Overall, a trade-off exists between security and economy.

For economic reasons and of more widespread availability of electricity, supply interconnections exist throughout the power grid, Without interconnections, isolated individual systems would be at risk with no disruptions in other areas. The larger the network the larger the security issue.

1.4 Security Analysis

As shown in the figure there are three fundamental time frames for security assessment for a power system. They are:

i) *Real-time Analysis*: The on-line security assesmetn is performed by energy management systems (EMS).This consists of system monitoring and contingency analysis. The figure shows the steps involved.

The overall system is constantly monitored through the use of the supervisory control and data acquisition (SCADA) system at the control centers. Measurement data such as line power or bus voltages are telemetered from various remote terminal units (RTUs) scattered throughout the power system at an interval of every few seconds to the control center [2]. These data are stored in the real-time database for the EMS. The direct readings are unreliable so filtering must be done to remove noise. Next,

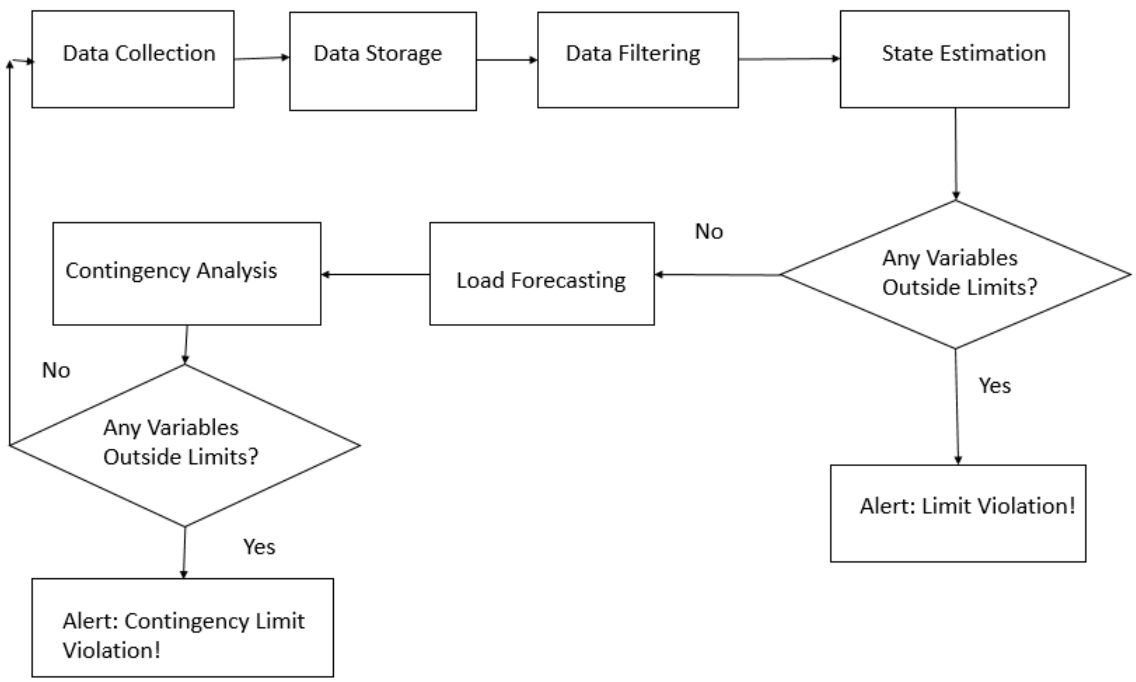


Figure 1.2: Security Operation

state estimation is done for computing the closest estimate of the state variables for the power system based on the current data. Limit violations are now checked and if violations are found corrective actions are taken. If not contingency analysis is done to simulate possible outages using load forecasts and the state estimation. Since the process is in real-time the calculation process must be fast.

ii) *Mid-term Analysis*: Consists of security constrained optimal power flow, security constrained unit commitment and optimal maintenance of equipment along with the optimal allocation of resources such as fuel [3].

iii) *Long-term Analysis*: Deals with the construction and modification of the generating plants and transmission systems.

1.5 Contingency Analysis

Contingency analysis is not only for real-time analysis as we have seen but can also be used for long-term planning. In this thesis, contingency analysis has been used to find the optimal placement of FACTS devices. To be specific contingency ranking was used. This allows us to contingencies in order of their severity. The performance index formulas used for contingency ranking are given below. They are often combined into one single performance index objective function but are used separately here.

$$PI_p = \sum_{i=1}^{Nl} (\frac{S_i}{S^i_{max}})^{2n} \tag{1.1}$$

$$PI_v = \sum_{i=1}^{Nb} |V_i - V_{ref}|^2 \tag{1.2}$$

Where Nl and Nb are the number of transmission lines and buses. S_i, S^i_{max}, V_i and V_{ref} are the line apparent powers, line power limits, bus voltages and the reference voltage of $1p.u.$ and Equation 1.1 was used to rank the contingencies in terms of the severity of line power flow. Equation 1.2 was not used for contingency ranking but to display the change in voltage profile. Continuation power flow was used for the purpose of ranking contingencies in order of their effect on bus voltages. The higher the value of these indices the greater the risk so the value of n can be adjusted to differentiate severe contingencies from less severe contingencies.

For real-time security analysis fast methods of power flow are used to rank contingencies such as DC power flow [4]. The construction period for a FACTS device is around 12 to 18 months so the optimal placement of FACTS devices can be evaluated under long-term security analysis but speed and less complexity is still desired due to the size of practical bus systems. As a result, the power based performance index was calculated using fast-decoupled power flow.

Chapter 2

FACTS

2.1 FACTS Devices

Flexible alternating-current transmission systems (FACTS) are a family of power electronics devices developed to solve some long-standing problems in power system. Power systems used to have high reserve capacities and low line power flows. However, economical and environmental constraints gradually increased loading of existing components closer to their designed limit. Longer transmission distances, rapidly varying high power loads and more interconnected local area networks result in more challenges from all fronts such as voltage and power fluctuations, reduced stability margins, reduced reliability and security. Further compounding these requirements, there has been a rapidly growing interest in renewable technology.

Initially, mechanically switched shunt and series capacitors, reactors, tap-changing transformers, phase-shifting transformers and synchronous generator control were used to address much of these issues and still are to this day. However, mechanical wear and tear, the extra control variables introduced for operators, the slow response time of these devices and the discrete ranges of control limited their use and practicality. This is why FACTS devices were established.

2.2 Classification of FACTS devices

The classification of some common FACTS devices are shown in Figure 2.1 in terms of how they are connected to the system. We are mainly concerned with SVC and TCSC in our work. These two are thyristor-based and not based on voltage source converters as the rest in the figure are.

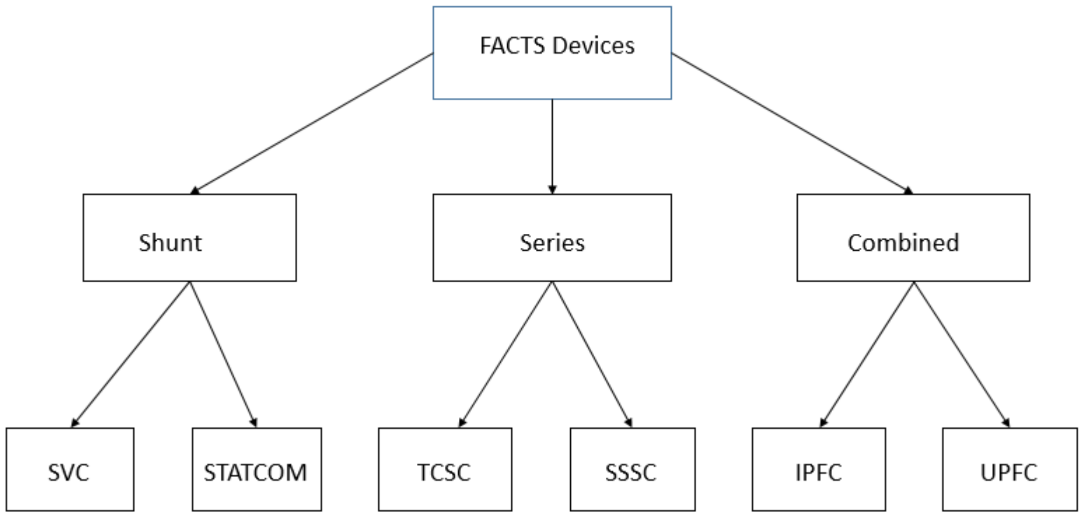


Figure 2.1: Classification of some common FACTS devices

Relevent FACTS devices are:

i) *Static Var Compensator*: Static Var Compensator (SVC) was the first generation of FACTS devices first installed in 1974 [4]. The SVC may be considered to be a shunt-connected variable susceptance which adjusts to keep bus voltage at a fixed value. In practice, it consists of thyristor controlled reactors (TCR) and thyristor controlled capacitors (TSC) and also filters to filter out harmonics which are generated due to the use of thyristors. Additionally, capacitor and inductor banks may also be added to improve range of susceptance.

The advantages of SVC include:

a) Voltage Control

b) Voltage Stability Improvement

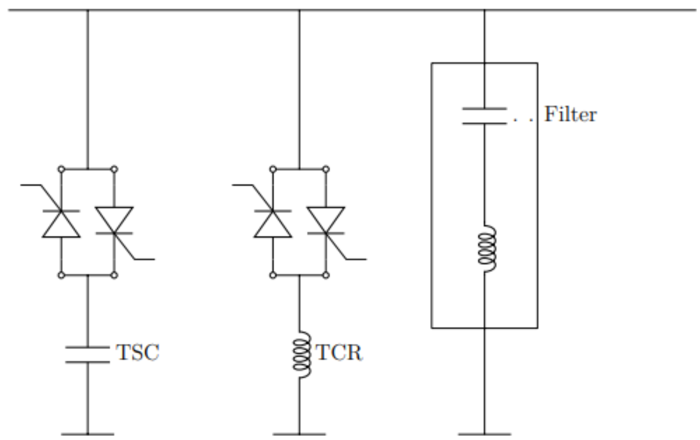


Figure 2.2: Basic Structure of SVC

b) Damping Oscillations

c) Transient Stability Improvement

d) Steady-State Power Transfer Capability

The structure of the SVC can be simplified to give the firing-angle model which is shown in figure 2.3. The firing angle of the thyristors vary to control the overall reactance based on the reference voltage.

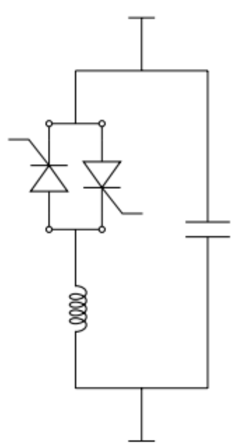


Figure 2.3: Firing-Angle Model of SVC

ii) *Thristor-controlled Series Compensator*: The Thyristor-controlled Series Comoensator

(TCSC) was first installed in 1992 [5]. The firing angle model of the TCSC is similar to the SVC firing-angle model but it is connected in series to the line as shown in figure 2.4.

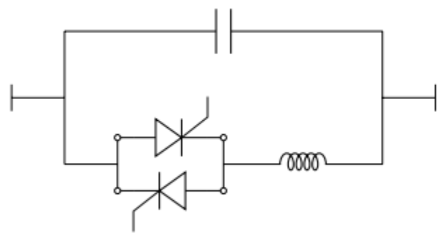


Figure 2.4: Firing-Angle Model of TCSC

The reactance of the TCSC is controlled by the thyristor firing angle which affects the overall line reactance.

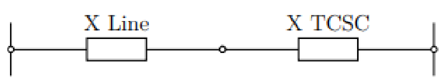


Figure 2.5: Transmission Line with TCSC

$$X_{eq} = X_{Line} + X_{TCSC} \tag{2.1}$$

where [6],

$$X_{TCSC} = \frac{X_C X_L \pi}{X_L \pi - X_C(\pi - 2\alpha - \sin 2\alpha)} \tag{2.2}$$

The simplest TCSC model can be considered to be a series-connected reactance viriable within a specified range.

The advantages of TCSC include:

a) Dynamic Control of Line Power Flow

b) Supply Reactive Power

c) Reduction of Fault Current

d) Reduction of Sub-Synchronous Resonance

Chapter 3

Literature Review

With an increase in demand of power, the size of power plants has been constantly increasing. However, the key goal from the power system operator end is to ensure continuous supply regardless of the increasing complexity of the network while operating in a cost effective manner. This is why security is important.

N-1 security is the most common security assessment used and this criteria is used to develop security constrained optimal power flow solutions (SCOPF). Aside from the general use of FACTS devices for voltage stability and improvement in line flows there are other uses such as in the renewable sector [8-9]. Sources such as wind and solar power give variable generation throughout the day and so bus voltage control is crucial which can be maintained with the aid of FACTS devices.

FACTS devices can also improve stability along with other specialized control devices such as power system stabilizers (PSS) [10-11].

There are numerous papers concerned with the optimal placement and sizing of FACTS device using soft computing methods especially evolutionary algorithms [12], mainly particle swarm optimization and genetic algorithm. Genetic algorithm follows a model based on the theory of natural selection where there are processes corresponding to mutation, selection and crossover. Therefore, it uses probabilistic and not deterministic rules. In 1995, particle swarm optimization was suggested by Kennedy and Eberhart [13]. It is modelled after the ability of flocks of birds to make sudden synchronized actions due to the sharing of information. The specific objective function to be minimized varies depending on the author but whether the genetic algorithm [14-17] is used or particle swarm optimization [18-20] the main parameters are usually cost, real power loss and security indexes.

Chapter 4

Methodology

4.1 Software Used

4.1.1 PSAT

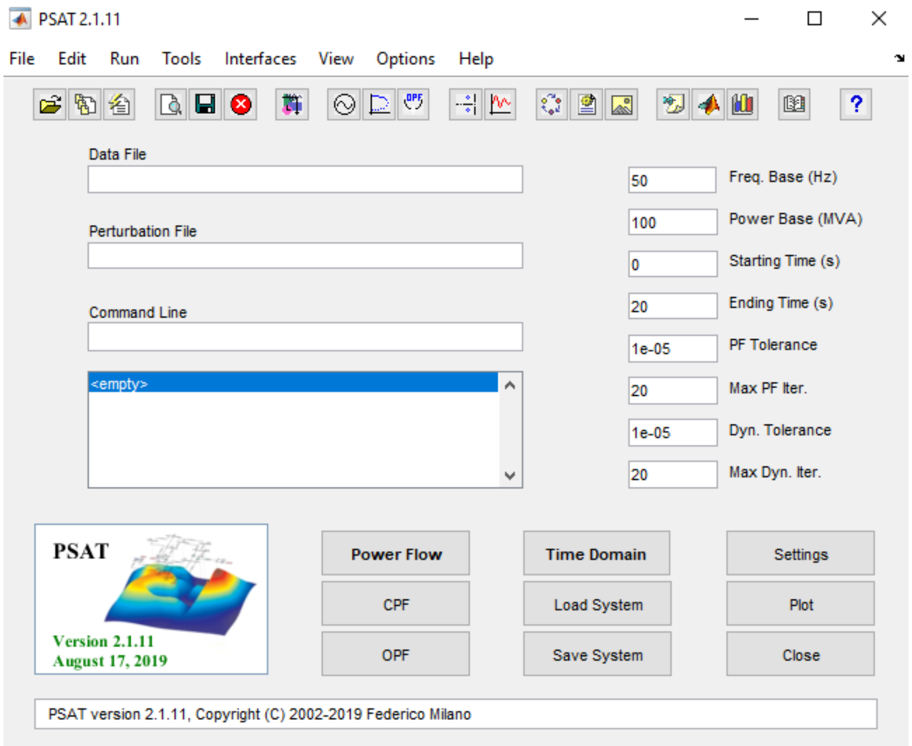


Figure 4.1: PSAT GUI

PSAT (Power System Analysis Toolbox) is a free Matlab toolbox used for analysis of electric power systems. There is an interactive GUI and command line functions to perform all relevant tasks. A Simulink-based library is included in order to build models or data can be directly manipulated. The operations which can be performed on the designed models are [23]:

1. Power flow
2. Continuation power flow
3. Optimal power flow
4. Small signal stability analysis
5. Time domain simulations

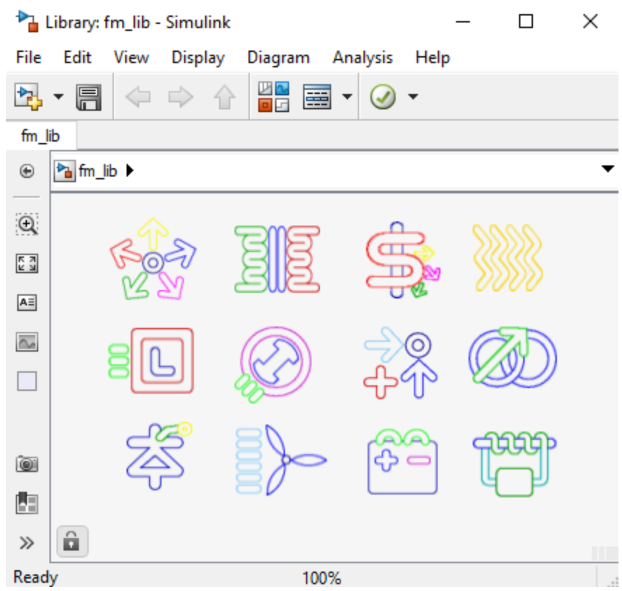


Figure 4.2: PSAT Library

4.2 Mathematical Methods

4.2.1 Power Flow

Newton-Raphson is a well-established method for finding the power flow solutions. First, we define the input variables and the type of each bus [21]. The types of bus are:

a) *Slack Bus/Swing Bus* - The reference bus for which voltage and phase angle are specified. It compensates for any deviation between scheduled load and generated power.

b) *Regulated/PV Bus* - The bus at which a generator is added. So, real power generated and voltage is specified.

c) *Load/PQ Bus* - This represents the load bus where the real and reactive power consumption is specified.

For systems composed of such buses, the Newton-Raphson method is used to solve the set of non-linear equations that emerge by taking first order approximations. As we can see from the known variables at each type of bus, the crucial variables we must initially deal with are the power and voltage.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{4.1}$$

Equation 4.1 shows the main equation for finding the unknown where the square matrix is the Jacobian matrix or the set of the first derivatives used to relate P and Q to V and θ. Certain Jacobian elements are not included, for example, PV and slack bus voltage will not change so these variables are not considered in Equation 4.1.

Assuming a high enough X/R ratio we can see that the ΔP and ΔQ lose much of their sensitivity to changes in ΔV and $\Delta\theta$ respectively. So, according to Fast Decoupled Load Flow method we can take the approximation,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & 0 \\ 0 & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{4.2}$$

To be specific, the XB method was used where the line resistances are neglected when calculating $J_{P\theta}$. The Fast Decoupled Load Flow method has faster convergence but does it over a greater number of iterations.

Including SVC and TCSC to power flow:

1) To include SVC: According to the variable susceptance model we know by placing SVC in the kth bus

$$Q_{SVC} = -(V_k)^2 B_{SVC} \tag{4.3}$$

so for the ith iteration,

$$(\frac{\Delta B_{SVC}}{B_{SVC}})^{(i+1)} = (\frac{\Delta Q_k}{Q_k})^{(i+1)} \tag{4.4}$$

$$(B_{SVC})^{(i+1)} = (B_{SVC})^{(i)} + (\frac{\Delta B_{SVC}}{B_{SVC}})^{(i+1)}(B_{SVC})^{(i)} \tag{4.5}$$

2) To include TCSC: The Jacobian matrix is modifed according to [22] for the variable reactance model and for the ith iteration where TCSC is placed in line mn,

$$(\frac{\Delta X_{TCSC}}{X_{TCSC}})^{(i+1)} = (\frac{\Delta P_{mn}}{\frac{\partial P_{mn}}{\partial X_{TCSC}}} X_{TCSC})^{(i)} \tag{4.6}$$

and,

$$(X_{TCSC})^{(i+1)} = (X_{TCSC})^{(i)} + (\frac{\Delta X_{TCSC}}{X_{TCSC}})^{(i+1)}(X_{TCSC})^{(i)} \tag{4.7}$$

4.2.2 Continuation Power Flow

The loading of a power system can be increased only upto a certain limit before the voltage stability margins are exceeded. This point is called the saddle-node bifurcation point. Originally, the power flow was calculated repeatedly for different loading to find this point. However, the Jacobian matrix becomes singular at the bifurcation point causing the solution to diverge and also repeated calculation of power flow is time-consuming, so the method was modified. Here, the P-V curve for continuation power flow was found using the predictor-corrector [24] method avoiding any singularity. This is done by the PSAT software.

First, the intial power flow solution is found at base load when $\lambda = 0$. The power flow equations are generalized to include the loading parameter, λ.

$$P_G = (\lambda + \gamma k_g) P_{Go} \tag{4.8}$$

$$P_L = \lambda P_{Lo} \tag{4.9}$$

$$Q_L = \lambda Q_{Lo} \tag{4.10}$$

where, k_g is distributed slack bus variable and γ is the generator participation coefficient.From these, the tangent vector, τ, with respect to the loading parameter is approximated and drawn for $\Delta\lambda$, where

$$\Delta\lambda = \frac{\pm 0.5}{|\tau|} \tag{4.11}$$

0.5 is the default step size control for PSAT. The advantage of this method is that for low λ values the tangent vector magnitude is low so the value of $\Delta\lambda$ is high, but closer to the bifurcation point the value of $\Delta\lambda$ will be high. For the return path, the step size control will be -0.5 due to the reduction in λ value. Using the tangent vector we have the predicted value for $\lambda + \Delta\lambda$.

The next part involves the corrector step. An orthogonal vector is taken from the tangent vector and this along with the generalized power flow equations are used to find the corrected point. The P-V figure which results for one bus is given in the figure.

4.2.3 Optimal Power Flow

The optimal power flow is normally used to optimize an objective function such as cost or real power loss. Here, cost is minimized but optimal power flow was mainly

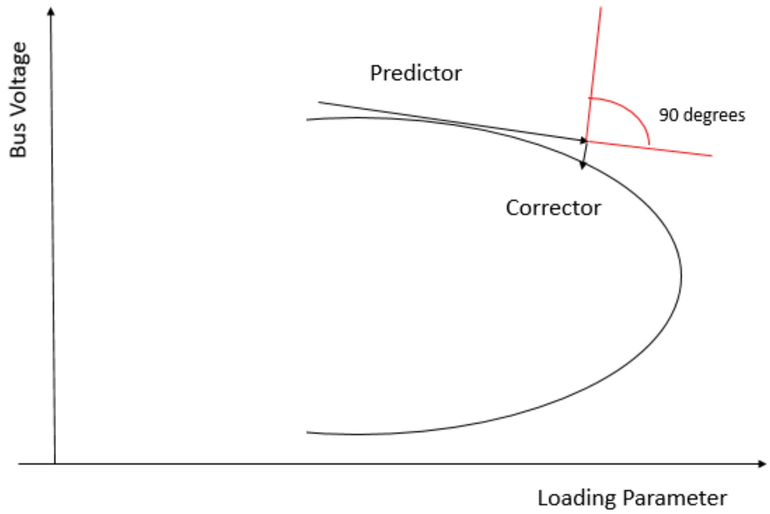


Figure 4.3: Predictor-Corrector Method for CPF

used to determine the necessity and placement of the FACTS device and the benefits that emerge from this inclusion, while keeping all voltage and line power constraints within limits.

$$Minimize \sum C \tag{4.12}$$

where, $V_{min} < V < V_{max}$

$P_{Gmin} < P_G < P_{Gmax}$

$Q_{Gmin} < V < Q_{Gmax}$

$S^{ij} < S^{ij}_{max}$

The interior points method [25] is used to solve this optimization problem. First, the inequality constraints are converted to equality constraints by using a logarithmic barrier. Next, we can eliminate the equality constraints using Lagrange multipliers. Finally, Merhotra predictor-corrector method is used to solve the unconstrained optimization problem. These steps are performed by the PSAT software.

4.2.4 Small Signal Stability

This determines if the system is able to withstand small perturbations, which is also a requirement for withstanding larger perturbations. If a power sysytem is not small signal stable it is not practical to implement. This is done by eigenvalue analysis. The state matrix is determined by PSAT and used to find the eigenvalues. Since the disturbance is small, we can linearize the system to make first-order approximations. The state matrix is then defined in terms of the Jacobian matrix

$$A_{state} = J_{P\theta} - J_{PV} J_{QV}^{-1} J_{Q\theta} \tag{4.13}$$

The eigenvalues are then found by solving for s,

$$det(sI - A_{state}) = 0 \tag{4.14}$$

The eigenvalues for a state matrix are equivalent to the poles of a transfer function [26] so they will operate in the same manner in the s-plane.Therefore, if any non-negative real part of any eigenvalue exists then the system is small signal unstable.

Chapter 5

Results

5.0.1 IEEE BUS 5

Static Model

(a)Without FACTS

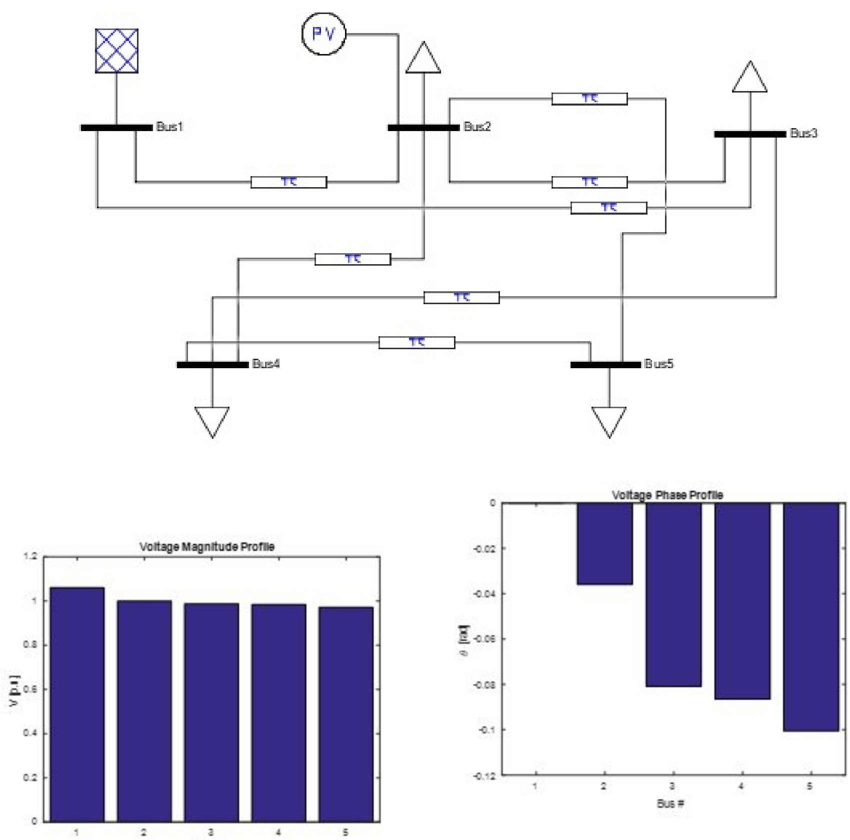


Figure 5.1: Power Flow of IEEE 5 Bus: Model, Voltage and Phase Angle

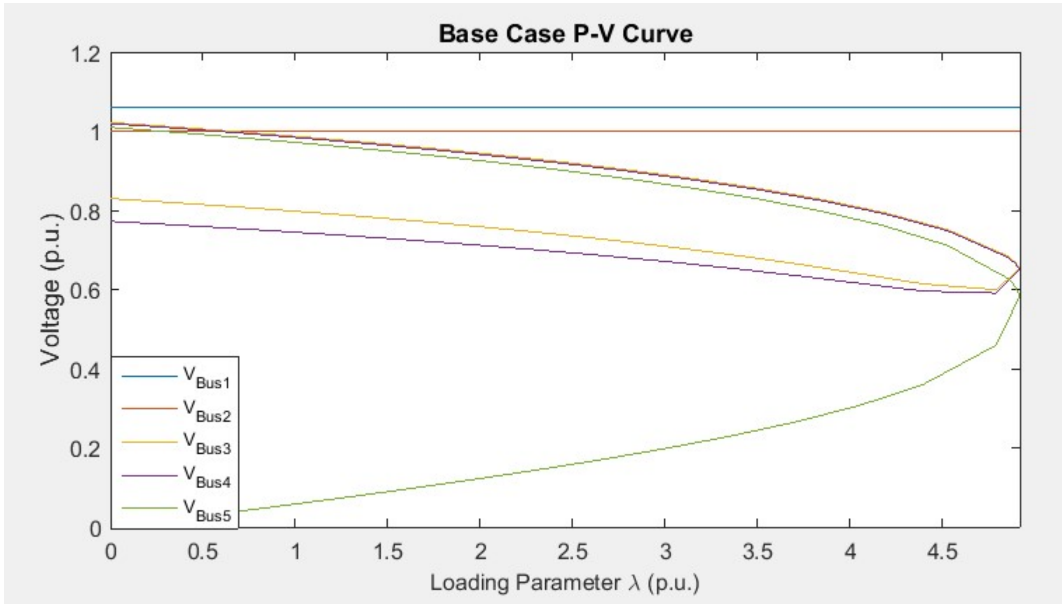


Figure 5.2: Base Case P-V Curve,IEEE 5 Bus

Using continuation power flow we can see that bus 5 is the weak bus. The P-V curve shows the bifurcation point has the lowest voltage for bus 5.

1. *Generator Outage*

Voltage Profile for generator outage in Bus 2.

At Base Load		At 20% Load Increase	
V [p.u.]	Phase [rad]	V [p.u.]	Phase [rad]
1.060	0	1.060	0
1.0245	-0.06382	1.013	-0.07671
1.0061	-0.09971	0.98922	-0.1207
1.0043	-0.10652	0.98686	-0.12908
0.99562	-0.12367	0.97597	-0.15045

Table 5.1: Voltages for Outage of Generator: IEEE 5 Bus

None of the voltages are below the minimum limit. All voltages are above 0.95 p.u. so generator outage does not result in a severe contingency.

2. *Line Outages*

Line Outage Case	Lambda Maximum Values		Outage Line
	At Base Load	At 20% Load Increase	
1	4.9199	4.1	Pre-Contingency
2	4.1238	3.4254	1-3
3	3.8027	3.153	2-3
4	3.7406	3.0767	4-2
5	1.3714	1.2766	2-5
6	4.496	3.7523	4-3
7	4.4329	3.6937	4-5
8	1.776	1.4081	1-2

Table 5.2: Loading Parameter for Line Outages: IEEE 5 Bus

The most severe outage case has minimum lambda value. Bus 5 voltage for Case 5 (outage of line 2-5) is below voltage limit. Bus 3, 4 and 5 voltages are below limits at 20% load increase as shown below.

At Base Load		At 20% Load Increase	
V [p.u.]	Phase [rad]	V [p.u.]	Phase [rad]
1.060	0	1.06	0
1	-0.03108	1	-0.04728
0.96017	-0.11038	0.93969	-0.14113
0.95029	-0.12592	0.92678	-0.161
0.8579	-0.29536	0.80061	-0.38453

Table 5.3: Case 5: Outage of Line 2-5

Next, to determine whether a line flow limit is exceeded, the PI_P index values are calculated for each outage at base load and a 20% load increase. Line power limits are not violated. Highest risk is for outage of line 1-2. By observation, the higher the severity of the outage the more the severity increases at higher loads. This is shown in the figure below.

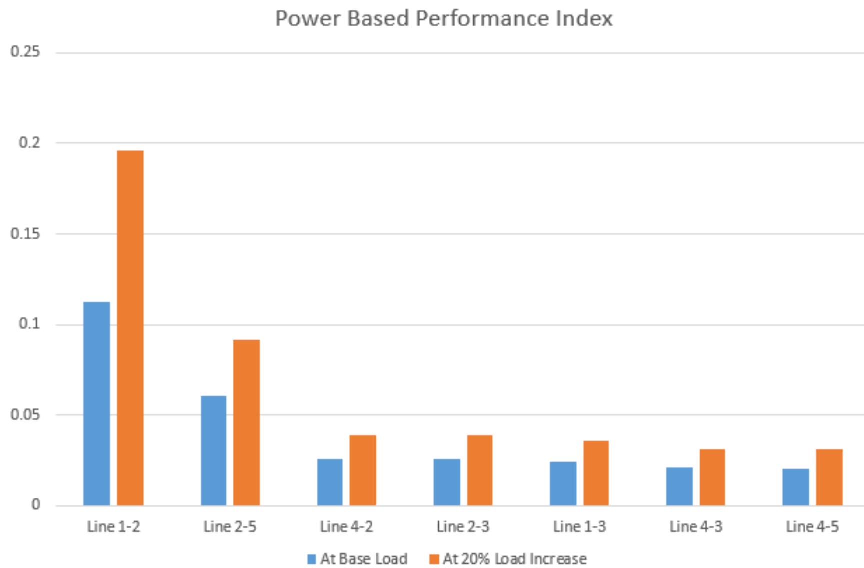


Figure 5.3: PI_P Ranking for Line Outages: IEEE 5 Bus

	Percentage (%)
Maximum Load Increase	49.5
Maximum Load Increase with outage of line 2-5	-44.8

Table 5.4: Secure Loading Range: IEEE 5 Bus

Maximum Load Increase with Voltage within Limits

Loading can be increased by 49.5% before V5=0.95 p.u. As the voltage of bus 5 is below limits for outage of line 2-5 as seen before, the loading must be decreased by 44.8% for the voltages to be greater than 0.95 p.u. for all outages. This means all loading must be decreased by 44.8% if the system is to maintain voltage limits for all possible outages.

(b) Modified form where a SVC is added to Bus 5

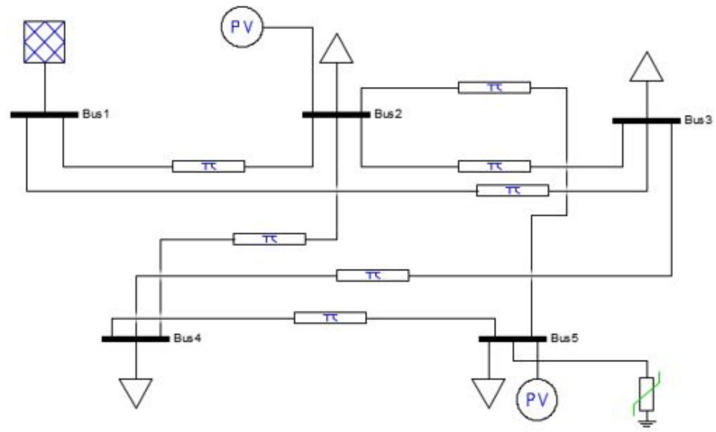


Figure 5.4: IEEE 5 Bus with SVC added to Bus 5

1. *Generator Outage*

V [p.u.]	Phase [rad]
1.06	0
1.0261	-0.04728
1.0079	-0.14113
1.0064	-0.161
1	-0.38453

Table 5.5: Voltages for Outage of Generator: IEEE 5 Bus with SVC

Voltage Profile for outage of generator in Bus 2. All voltages are within limits.

2. *Line Outages*

Line Outage Case	Lambda Maximum Values	Outage Line
1	2.9597	Pre-Contingency
2	2.5992	1-3
3	2.6463	2-3
4	2.5794	4-2
5	2.0068	2-5
6	2.8886	4-3
7	3.3634	4-5
8	1.8027	1-2

Table 5.6: Loading Parameter for Line Outages: IEEE 5 Bus with SVC

Worst case outage is now Case 8 (outage of line 1-2). All voltages are within limit for this outage as shown below

Case 8:

V [p.u.]	Phase [rad]
1.06	0
1	-0.36277
0.97891	-0.32446
0.98014	-0.34799
1	-0.41439

Table 5.7: Case 8 - Outage of Line 1-2: IEEE 5 Bus with SVC

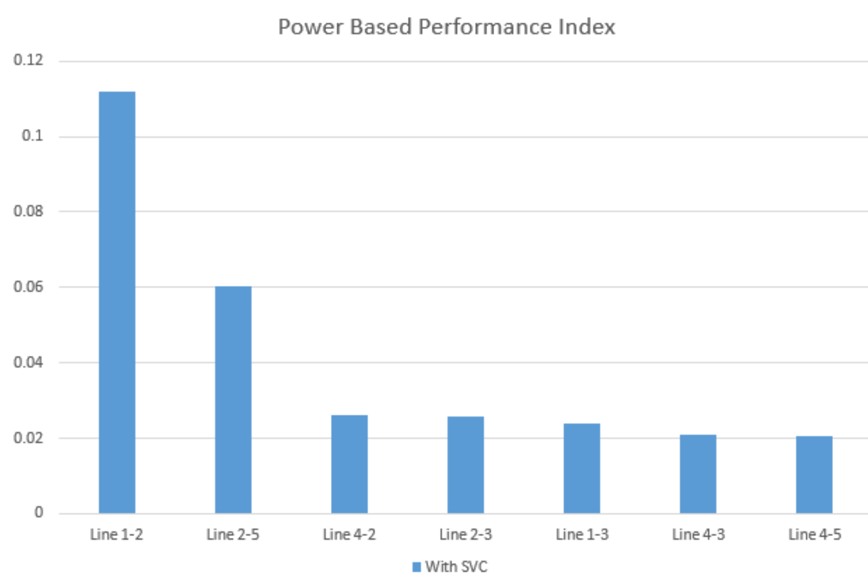


Figure 5.5: PI_P Ranking for Line Outages: IEEE 5 Bus with SVC in Bus 5

Line powers are within limits. Highest risk is for outage of line 1-2.

Maximum Load Increase with Voltage within Limits

	Percentage (%)
Maximum Load Increase	121.5
Maximum Load Increase with outage of line 1-2	28.9

Table 5.8: Secure Loading Range: IEEE 5 Bus with SVC

Loading can be increased by 121.5% before V3=0.95 p.u. The voltages can be within limits for all outages up to an increase in load of 28.9%.

(c) TCSC is added to the Modified Form with SVC

Critical Outage Case is the outage of line 1-2 as it had the highest PI_P for all previous cases. For this outage, TCSC has been added to each line to find the optimum TCSC placement that minimizes the PI_P value for the outage of line 1-2.

TCSC Placement Line	PIp
1-3	0.0278
4-5	0.1093
2-5	0.1099
3-4	0.1109
2-3	0.1114
2-4	0.1119

Table 5.9: Adding TCSC Alternately to Each Line: IEEE 5 Bus with SVC

Lowest PI_P value occurs when TCSC is placed in line 1-3.

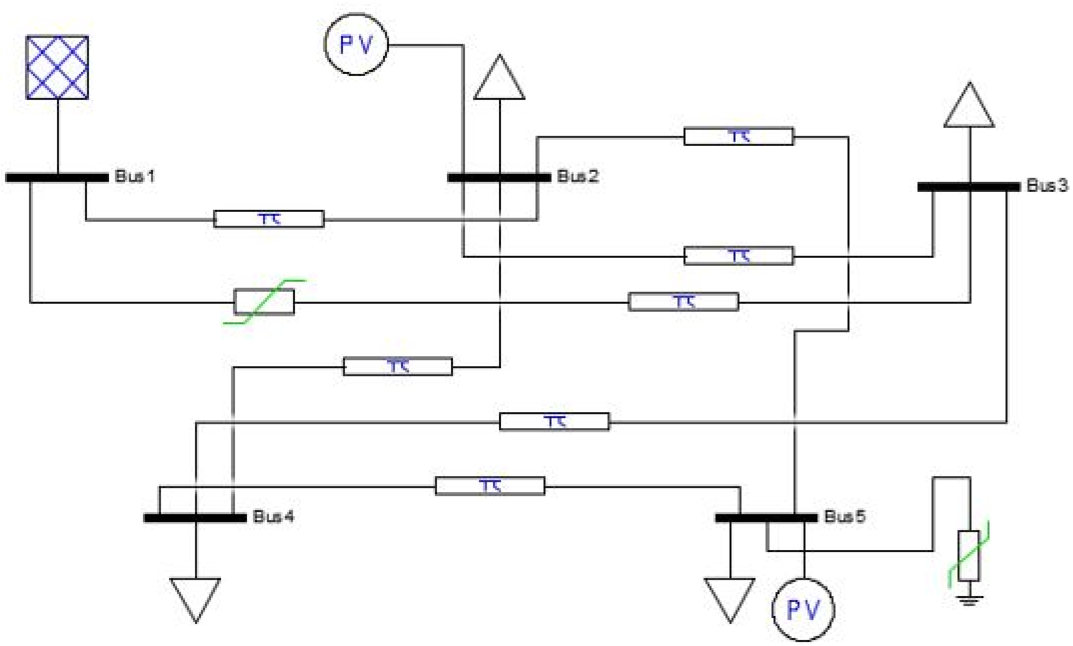


Figure 5.6: IEEE 5 Bus with SVC in Bus 5 and TCSC in Line 1-3

Outage of line 1-2 will cause current from slack bus to flow through line 1-3 instead so it makes sense that TCSC should be placed in line 1-3. Series compensation of TCSC was taken randomly as -50%, at capacitive compensation range. The values of performance index has improved for every outage case. Line power is still within limits. Highest risk is now for the outage of line 2-5. Performance Index values have improved for each line.

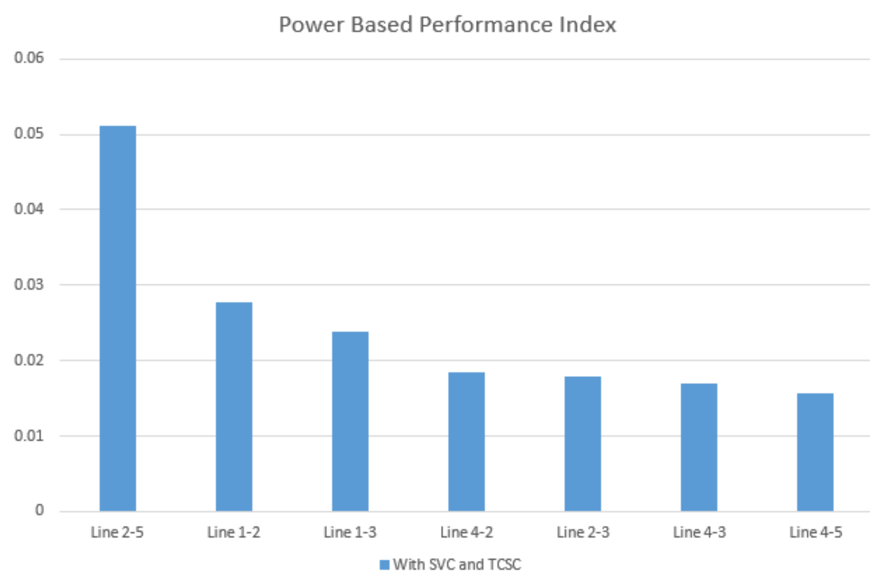


Figure 5.7: PI_P Ranking for Line Outages: IEEE 5 Bus with SVC and TCSC

Maximum Load Increase with Voltage within Limits

	Percentage (%)
Maximum Load Increase	136
Maximum Load Increase with outage of line 1-2	46.5

Table 5.10: Secure Loading Range: IEEE 5 Bus with SVC and TCSC

Loading can be increased by 136% before V3=0.95 p.u. The voltages are within limits for all outages up to an increase in load of 46.5%.

Optimal Power Flow

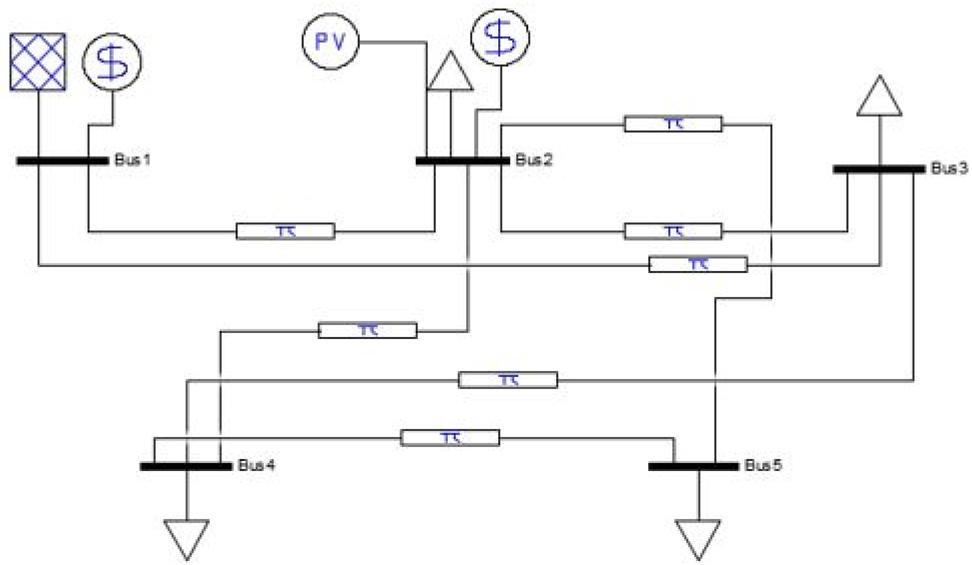


Figure 5.8: IEEE 5 Bus OPF Model

	Cost Function [$/h]	PIv	Total Losses [MW]
Base Case:	749.2875	0.0079	3.367
With Outage of Line 2-5	-	-	-
With Outage of Line 1-2	757.1998	0.0068	4.468
SVC added to Bus 5:	664.534	0.0063	3.648
With Outage of Line 2-5	825.1642	0.0191	9.39
With Outage of Line 1-2	672.4316	0.0066	4.73
With SVC and TCSC in Line 1-3:	665.4055	0.0063	3.853
With Outage of Line 2-5	829.6833	0.0222	11.387
With Outage of Line 1-2	672.724	0.0065	4.703

Table 5.11: Optimal Power Flow Solution: IEEE 5 Bus

Outage of line 2-5 will cause voltage of bus 5 to go below limit even with dispatch. This is why the solution does not converge. So, SVC is added to bus 5. It can be seen that cost with FACTs device is less as the burden on the generators is reduced. The value of PI_V is reduced with the addition of FACTS due to the improved voltage profile. However, the real power losses are increased.

5.0.2 Dynamic Model

Without FACTS

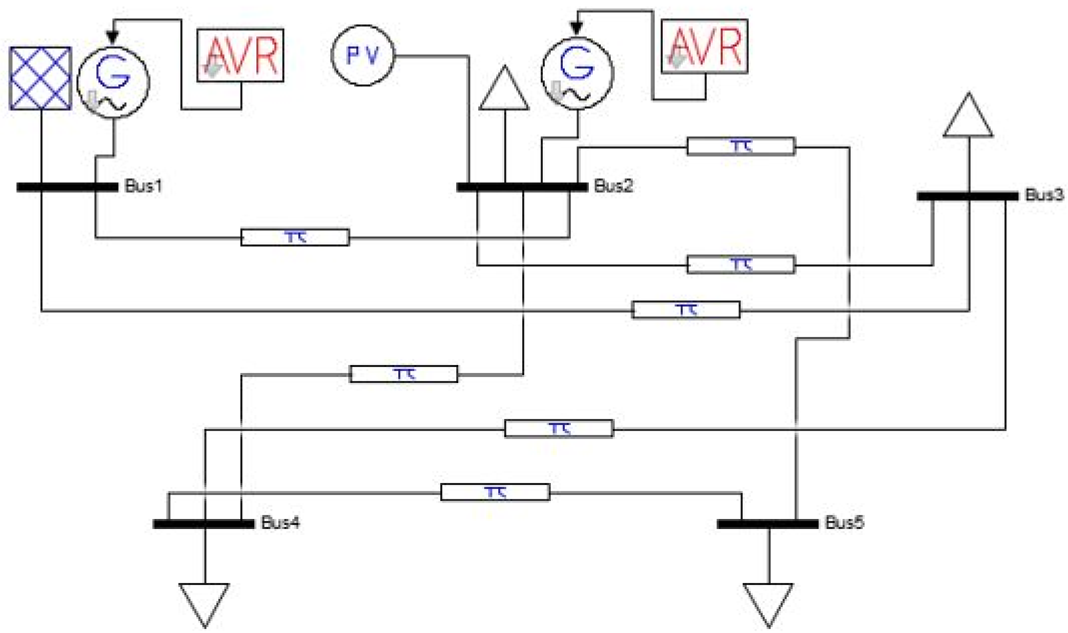


Figure 5.9: IEEE 5 Bus Dynamic Model

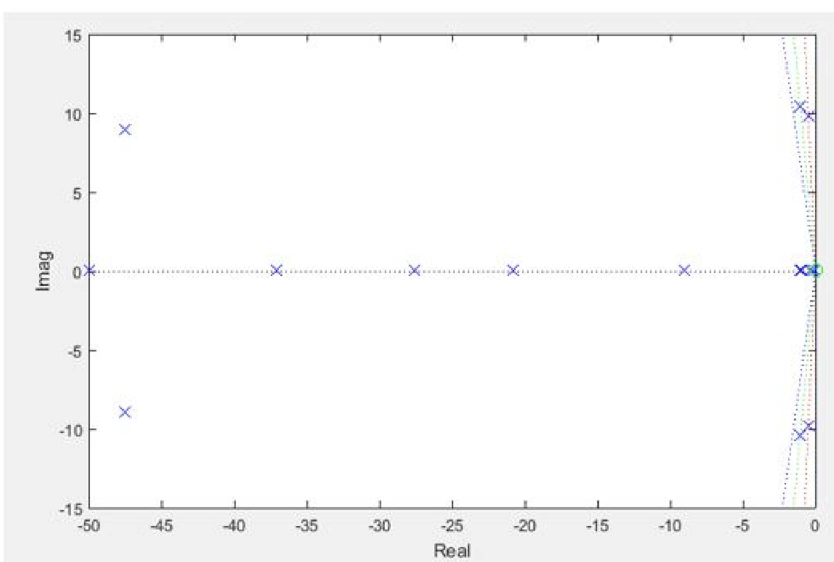


Figure 5.10: Eigenvalues in s-plane: IEEE 5 Bus

Dynamic order:	19
Buses	5
Posistive eigs:	0
Negative eigs:	18
Complex pairs:	3
Zero eigs:	1

Figure 5.11: Signs of Eigenvalue: IEEE 5 Bus

The results show that all eigenvalues of the system have a negative real part. Zero eigenvalue will not effect on the stability of the system. Therefore, system is small signal stable.

When SVC is added

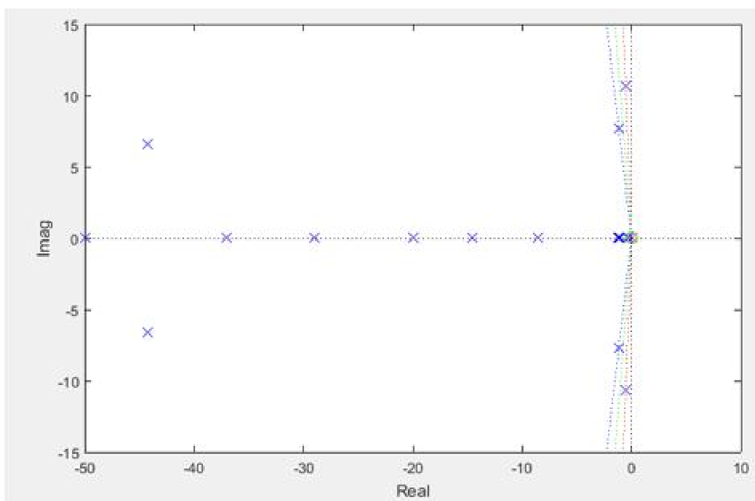


Figure 5.12: Eigenvalues in s-plane: IEEE 5 Bus with SVC

Dynamic order:	21
Buses	5
Posistive eigs:	1
Negative eigs:	19
Complex pairs:	3
Zero eigs:	1

Figure 5.13: Signs of Eigenvalue: IEEE 5 Bus with SVC

This is unstable, so both TCSC and SVC are used

(a) Load Increase

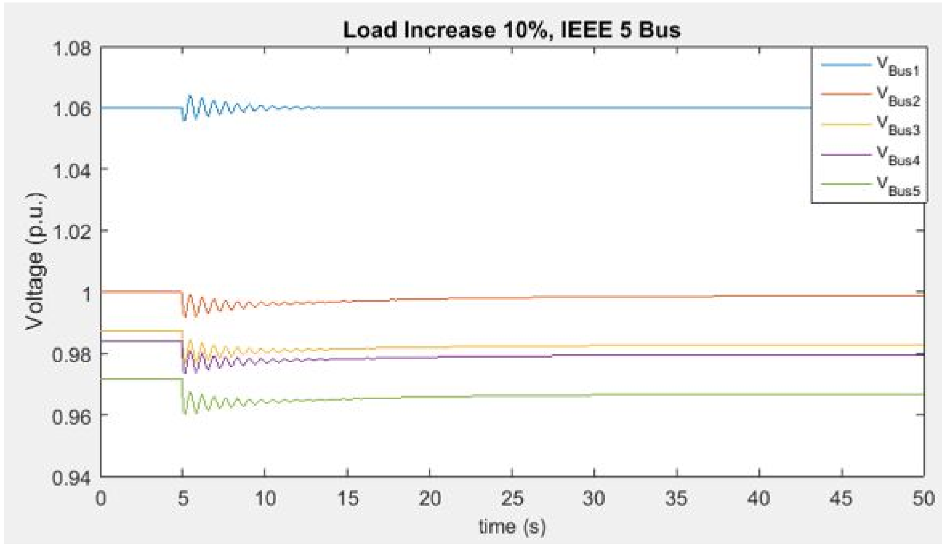


Figure 5.14: Load Increase 10% at t=5 s: IEEE 5 Bus

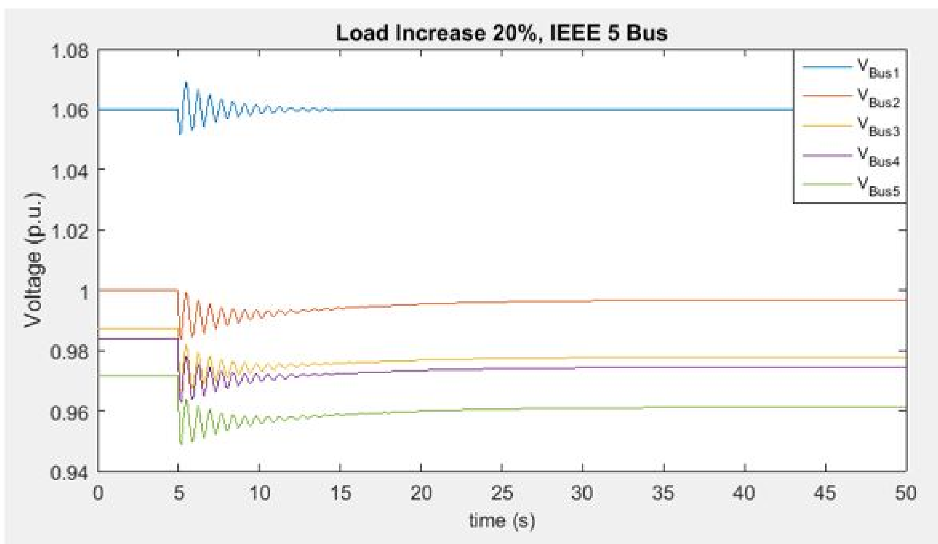


Figure 5.15: Load Increase 20% at t=5 s: IEEE 5 Bus

Load increases at t=5s. It can be seen that the oscillation amplitude increases as load increases.

With SVC and TCSC the oscillation frequency and amplitude seems to have increaed for each of these disturbances.

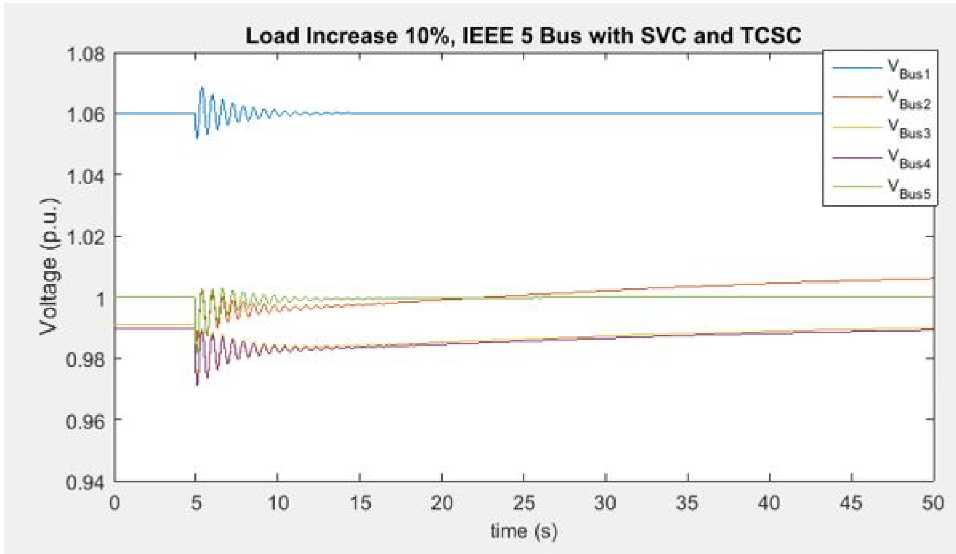


Figure 5.16: Load Increase 10% at t=5 s: IEEE 5 Bus with SVC and TCSC

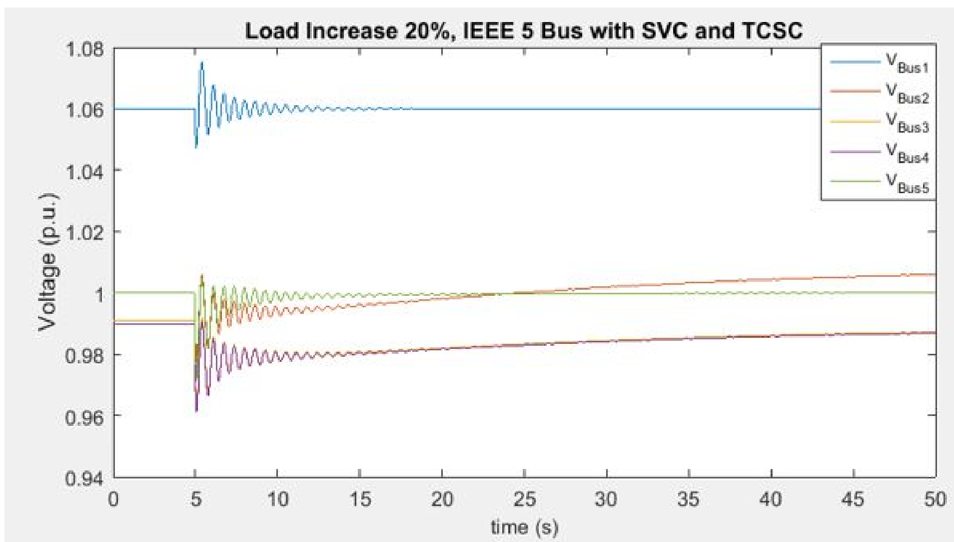


Figure 5.17: Load Increase 20% at t=5 s: IEEE 5 Bus with SVC and TCSC

(b) With Line Fault in Line 1-2

Fault is introduced at t= 5 s. Fault is cleared at t = 5.1 s. We can see that the inclusion of FACTS devices reduces the overshoot of voltage. This fault can be considered as a large disturbance.

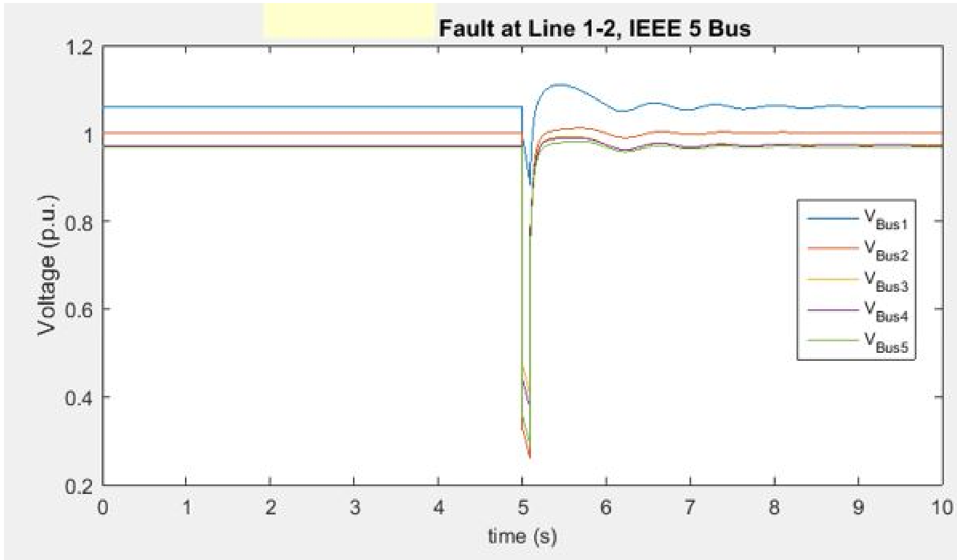


Figure 5.18: Three-Phase Line Fault: IEEE 5 Bus

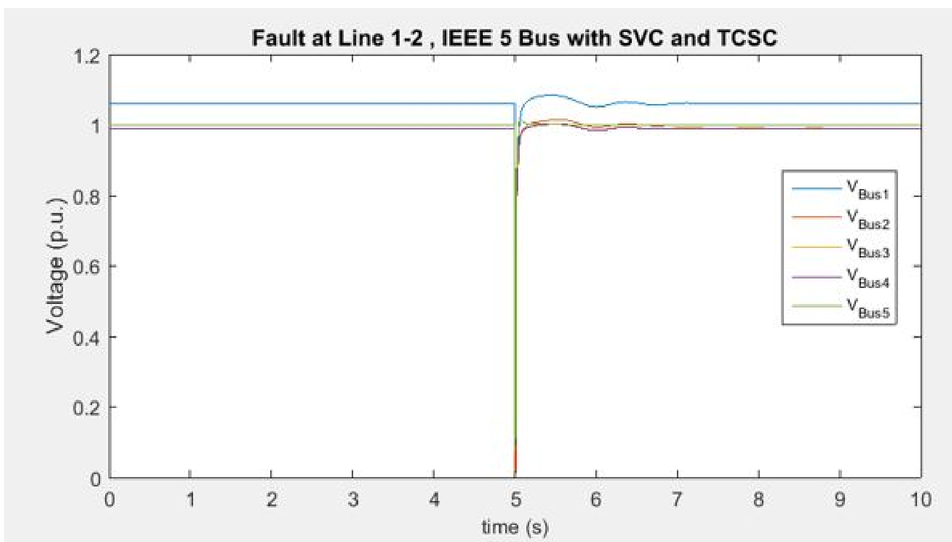


Figure 5.19: Three-Phase Line Fault: IEEE 5 Bus with SVC and TCSC

5.1 WSCC 9 BUS

Static Model

(a)Without FACTS [27]

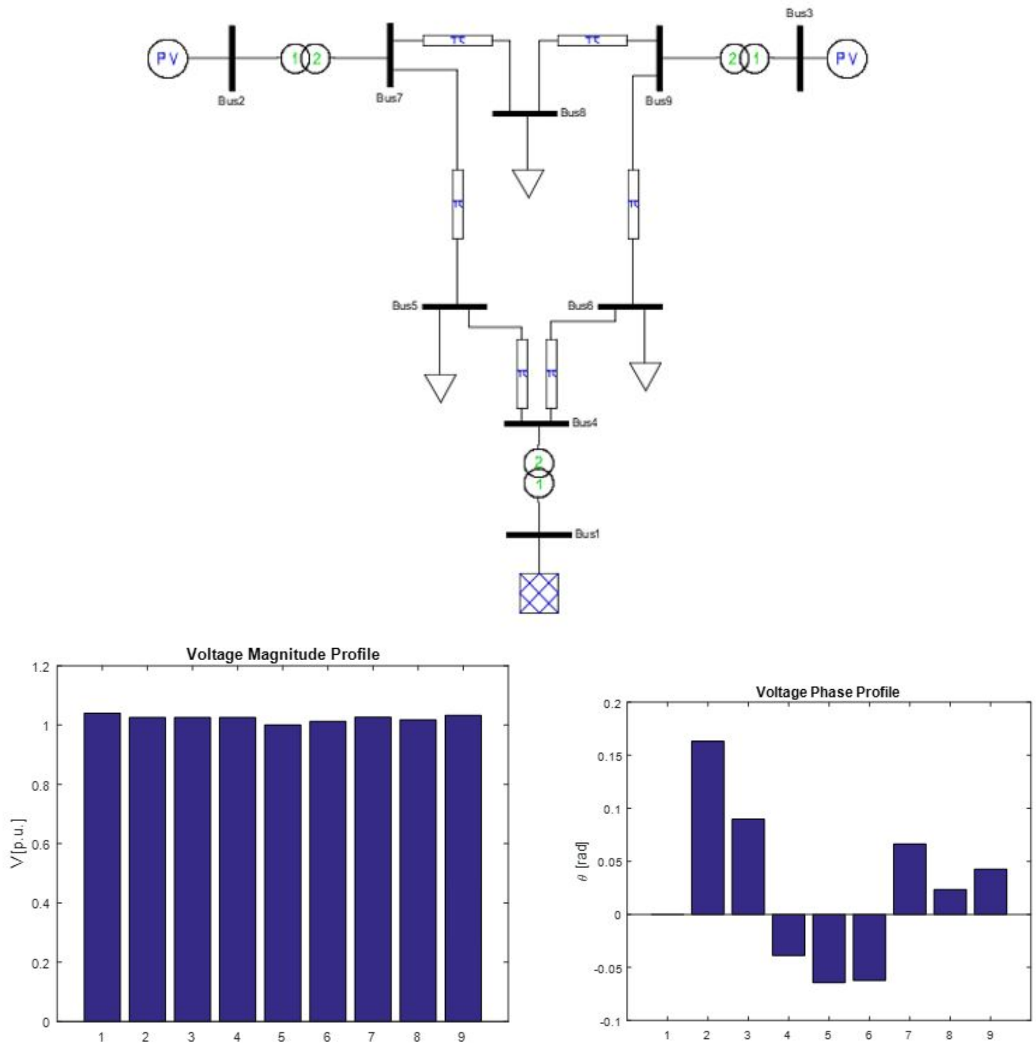


Figure 5.20: Power Flow of WSCC 9 Bus: Model, Voltage and Phase Angle

Using continuation power flow we can see that bus 5 is the weak bus. The P-V curve shows the bifurcation point has the lowest voltage for bus 5.

1. *Generator Outage*

Worst Case generator outage is Case 2 (outage of generator in Bus 3). Voltages are within limits.

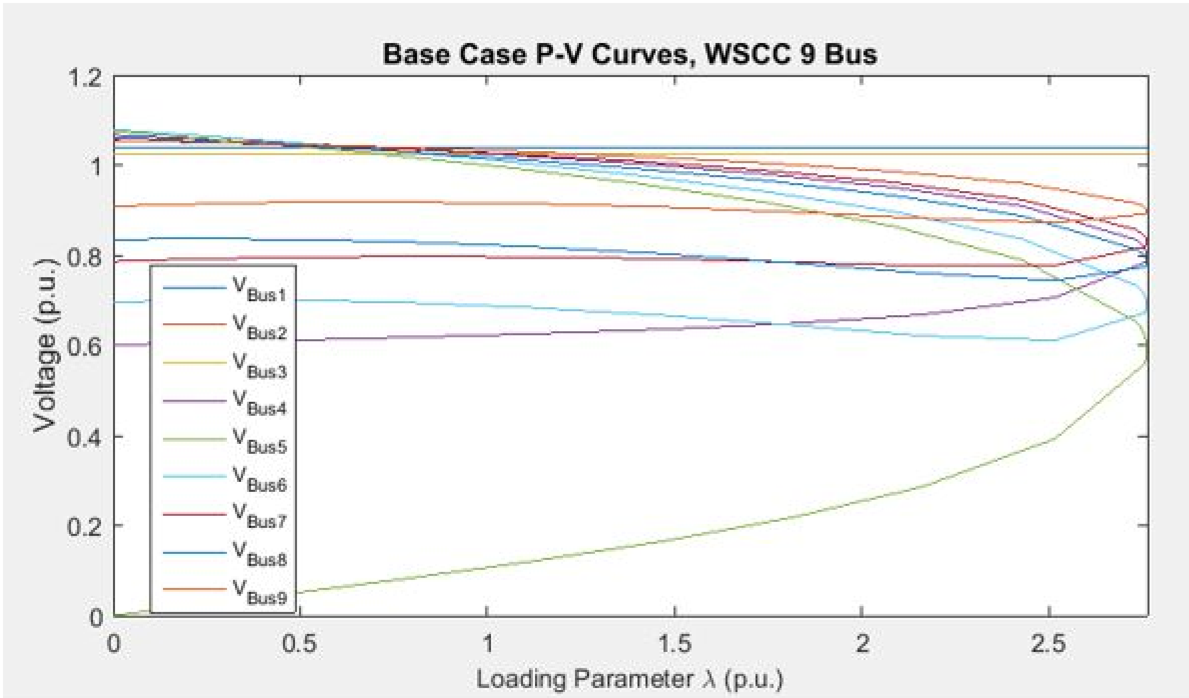


Figure 5.21: Base Case P-V Curve, WSCC 9 Bus

Generator Outage Case	Lambda Max Values		Generator Bus
	Base Load	20% Load Increase	
1	2.7634	2.4378	Pre-Contingency
2	1.9782	1.6026	3
3	2.3333	1.9309	2

Table 5.12: Loading Parameter for Generator Outages: WSCC 9 Bus

Case 2:

At Base Load		At 20% Load Increase	
V [p.u.]	Phase [rad]	V [p.u.]	Phase [rad]
1.04	0	1.04	0
1.0135	-0.26163	0.98047	-0.3537
1.025	-0.14963	1.025	-0.23747
1.0252	-0.12697	1.005	-0.16639
0.99739	-0.22325	0.96274	-0.29276
1.012	-0.20284	0.98535	-0.27174
1.0135	-0.26163	0.98047	-0.3537
1.0069	-0.27286	0.97574	-0.37269
1.0278	-0.19693	1.013	-0.28546

Table 5.13: Case 2 - Outage of Generator in Bus 3: WSCC 9 Bus

2. *Line Outage*

Line Outage Case	Lambda Max Values		Outage Line
	Base Load	20% Load Increase	
1	2.7634	2.4378	Pre-Contingency
2	1.6745	1.3217	6-4
3	1.9132	1.6884	7-5
4	1.9692	1.7381	9-6
5	1.9054	1.7065	7-8
6	2.4518	2.2059	8-9
7			1-4
8			2-7
9			3-9
10	1.2426	0.96566	5-4

Table 5.14: Loading Parameter for Line Outages: WSCC 9 Bus

Lambda values not computable for cases where the buses are islanded. Worst cases are 10 and 2 (outage of lines 5-4 and 6-4). Bus 5 voltage for Case 10 and Bus 6 voltage for Case 2 are below limits. For 20% load increase worst case outages are Case 10 (outage of line 5-4), Case 2 (outage of line 6-4), Case 3 (outage of line 7-5), Case 4 (outage of line 9-6) and Case 5 (outage of line 7-8) where the voltages are below the limit. For all these cases, the voltages below limits are for Bus 5 and 6.

Case 10:

At Base Load		At 20% Load Increase	
V [p.u.]	Phase [rad]	V [p.u.]	Phase [rad]
1.04	0	1.04	0
1.025	-0.02924	1.025	-0.23592
1.025	-0.03411	1.025	-0.18973
1.0387	-0.04083	1.0328	-0.07295
0.83915	-0.35962	0.7713	-0.62426
1.0202	-0.10587	1.0029	-0.19127
0.988	-0.13001	0.96558	-0.33904
0.98907	-0.14833	0.9649	-0.34647
1.0243	-0.08158	1.0114	-0.2378

Table 5.15: Case 10 - Outage of Line 5-4: WSCC 9 Bus

Case 2:

At Base Load		At 20% Load Increase	
V [p.u.]	Phase [rad]	V [p.u.]	Phase [rad]
1.04	0	1.04	0
1.025	0.09471	1.025	-0.05371
1.025	-0.02457	1.025	-0.21987
1.028	-0.03941	1.0212	-0.07606
1.0025	-0.08483	0.98687	-0.16704
0.9413	-0.23058	0.89308	-0.46984
1.0234	-0.00256	1.0122	-0.15206
1.0085	-0.06268	0.99037	-0.23703
1.0174	-0.07235	1.0028	-0.26835

Table 5.16: Case 2 - Outage of Line 6-4: WSCC 9 Bus

Therefore, SVC must be added to both bus 5 and 6 if we want N-1 security based only on the power flow solution.

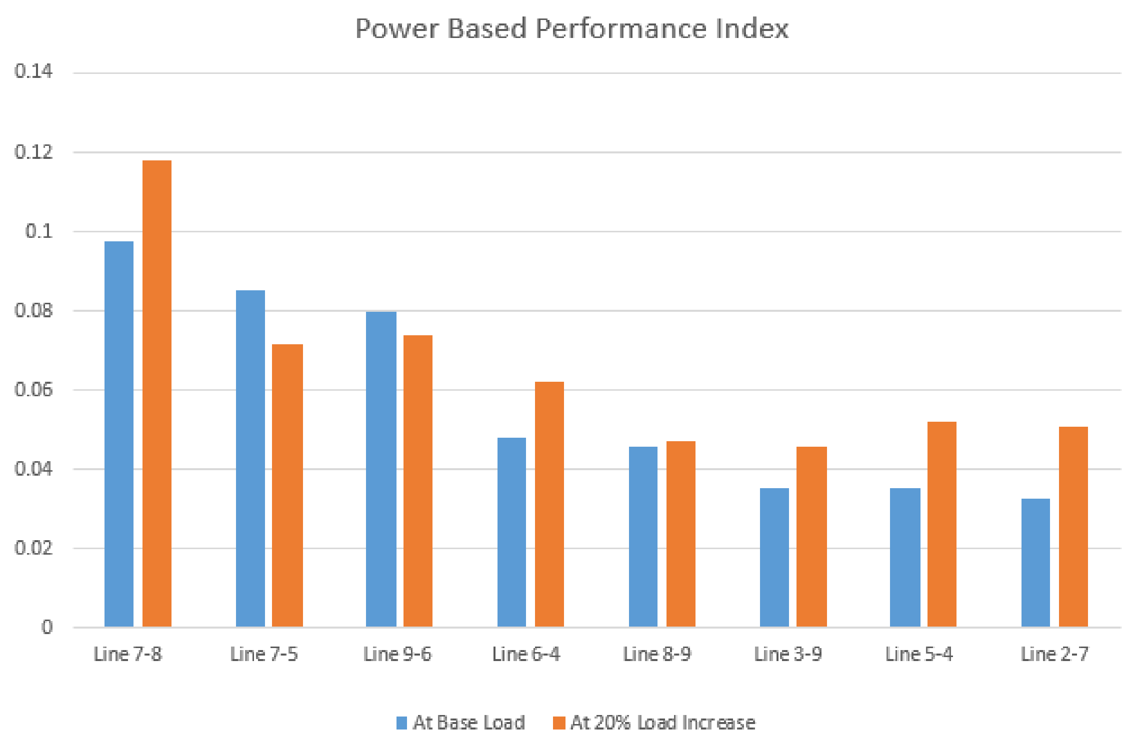


Figure 5.22: PI_P Ranking for Line Outages: WSCC 9 Bus

Line Power within limits. Highest risk is for outage of line 7-8.

Maximum Load Increase within Limits

	Percentage (%)
Maximum Load Increase	58.1
Maximum Load Increase with outage of line 5-4	-33.5

Table 5.17: Secure Loading Range: WSCC 9 Bus

Load can be increased by 58.1% with voltages within limits. Load must be decreased by at least 33.5% so that no line outages cause the voltage to drop below the limits.

(b) Modified form where SVC is added to Bus 5 and 6

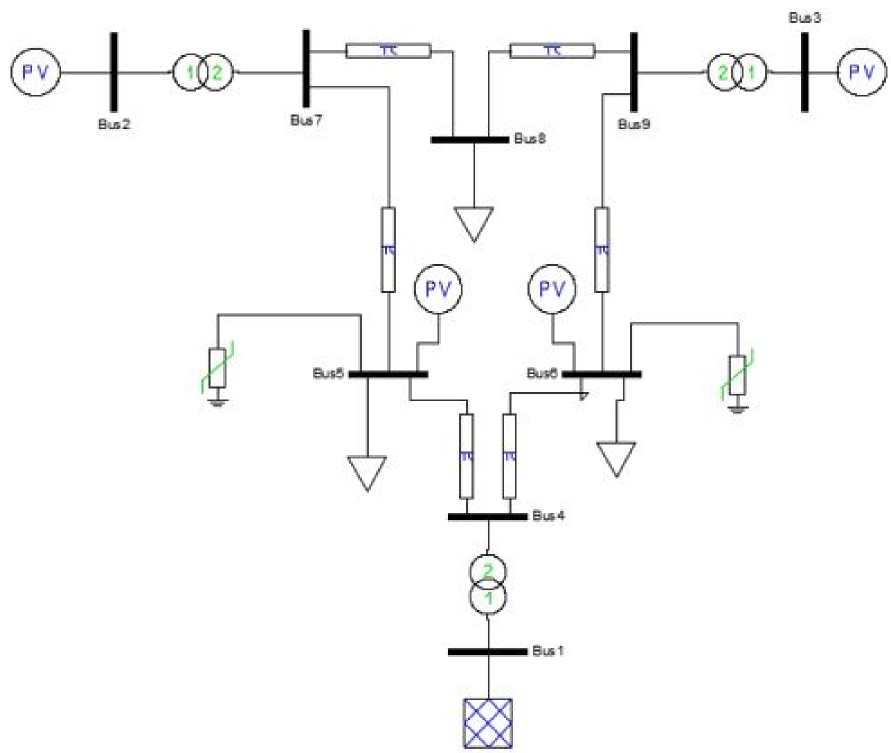


Figure 5.23: WSCC 9 Bus with SVC in Bus 5 and 6

1. *Generator Outage*

Worst outage is for Case 2 (outage of generator 3). But, voltages are within limits for all cases.

Generator Outage Case	Lambda Max Values	Generator Bus
1	2.251	Pre-Contingency
2	1.9402	3
3	2.2708	2

Table 5.18: Secure Loading Range: WSCC 9 Bus

Case 2:

V [p.u.]	Phase [rad]
1.04	0
1.0136	-0.26263
1.025	-0.15043
1.023	-0.12726
1	-0.22438
1	-0.20221
1.0136	-0.26263
1.0061	-0.2739
1.0254	-0.19784

Table 5.19: Case 2 - Outage of Generator in Bus 3: WSCC 9 Bus with SVC

2. *Line Outage*

Line Outage Case	Lambda Max Values	Outage Line
1	2.251	Pre-Contingency
2	2.136	6-4
3	1.9503	7-5
4	1.7966	9-6
5	1.7372	7-8
6	2.1499	8-9
7		1-4
8		2-7
9		3-9
10	1.5096	5-4

Table 5.20: Loading Parameter for Line Outages: WSCC 9 Bus with SVC

Worst outage case outage is Case 10 (outage of line 5-4). Voltages for this case are within limits.

Case 10:

V [p.u.]	Phase [rad]
1.04	0
1.025	-0.02818
1.025	-0.0306
1.0309	-0.03973
1	-0.33028
1	-0.10192
1.0247	-0.12532
1.0146	-0.14243
1.0286	-0.07786

Table 5.21: Case 10 - Outage of Line 5-4: WSCC 9 Bus with SV

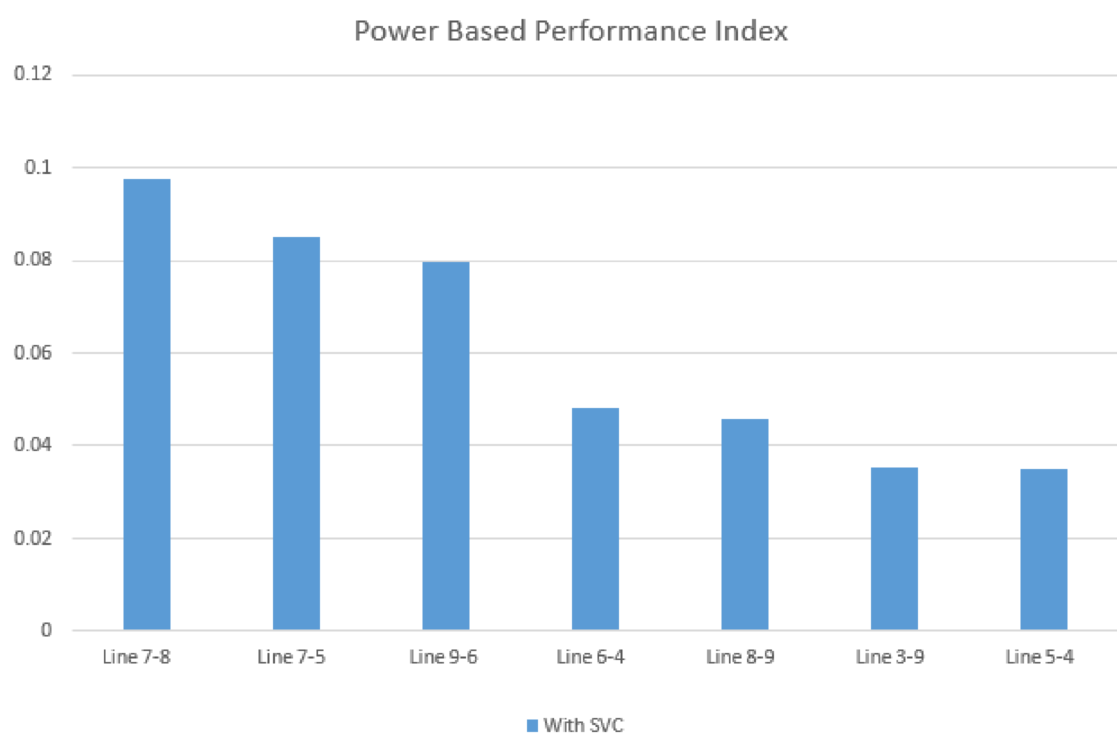


Figure 5.24: PI_P Ranking for Line Outages: WSCC 9 Bus with SVC

Line Power within limits. Highest risk is for outage of line 7-8.

Maximum Load Increase within Limits

	Percentage (%)
Maximum Load Increase	170.5
Maximum Load Increase with outage of line 5-4	71

Table 5.22: Secure Loading Range: WSCC 9 Bus with SVC

Load can be increased by 170.5% with voltages within limits. Load can be increased by 71% with no line outage causing the voltages to drop below the limits.

TCSC Placement Line	PIp
5-4	0.0930
9-6	0.0928
8-9	0.0905
2-7	0.0891
3-9	0.0864
6-4	0.0864
7-5	0.0435

Table 5.23: Adding TCSC Alternately to Each Line: WSCC 9 Bus with SVC

(c) TCSC added to the Modified form with SVC

Critical Outage Case is the outage of line 7-8 as it had the highest PI_P for all previous cases. For this outage, TCSC has been added to each line to find the optimum TCSC placement that minimizes the PI_P value for the outage of line 7-8.

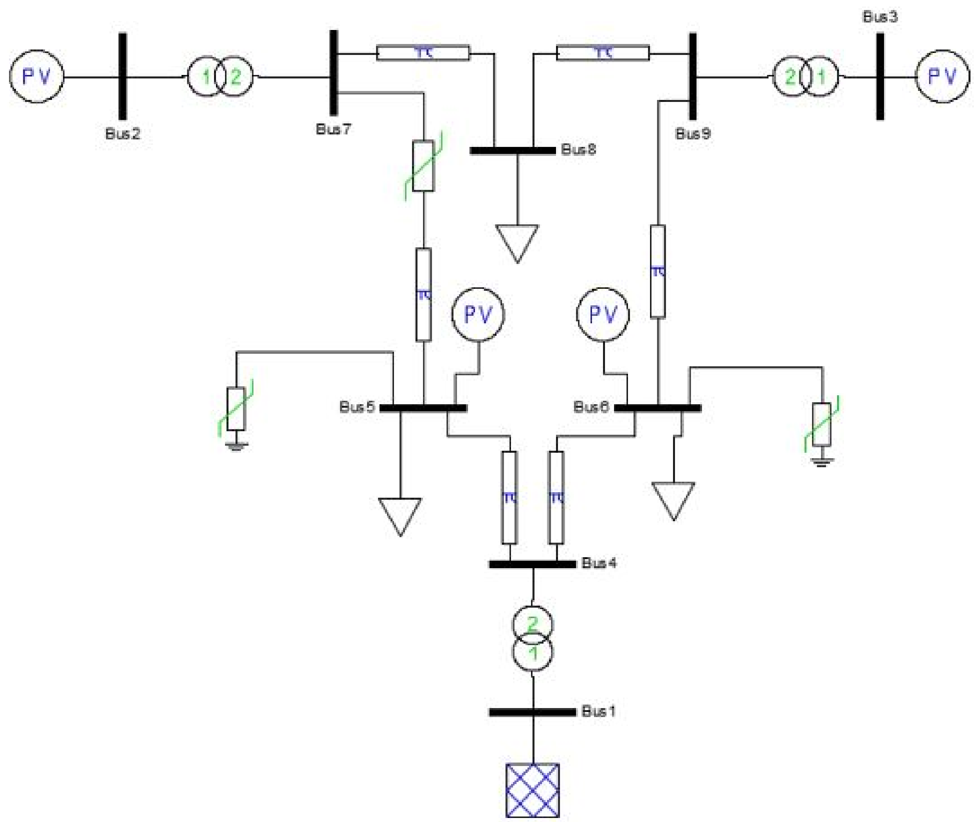


Figure 5.25: WSCC 9 Bus with SVC in Bus 5 and 6 and TCSC in Line 5-7

TCSC is placed in line 5-7 as it has the smallest value of PI.

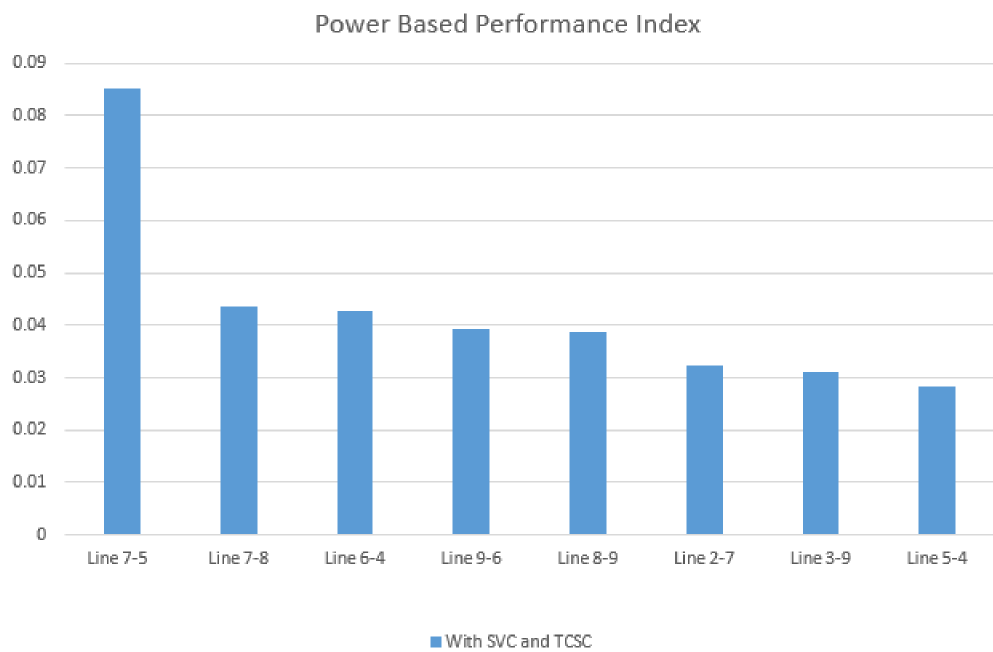


Figure 5.26: PI_P Ranking for Line Outages: WSCC 9 Bus with SVC and TCSC

Worst case outage was initially for outage of line 7-8 in. Outage of line 7-8 will cause excess current flow through line 5-7 instead so it makes sense that TCSC is placed in line 5-7. Series compensation of TCSC was taken randomly as -50%. The values of performance index has improved for every outage case. Line Power is still within limits. Highest risk is now for outage of line 5-7.

Maximum Load Increase within Limits

	Percentage (%)
Maximum Load Increase	160.5
Maximum Load Increase with outage of line 5-4	58.3

Table 5.24: Secure Loading Range: WSCC 9 Bus with SVC and TCSC

Load can be increased by 160.5% with voltages within limits. Load can be increased by 58.3%, with no line outage causing the voltages to drop below the limits. The TCSC may have reduced the PI values but the maximum load that can be increased has decreased.

Optimal Power Flow

	Cost Function [$/h]	PIv	Total Losses [MW]
Base Case:	1396.6196	0.0162	3.056
With Outage of Line 5-4	-	-	-
With Outage of Line 6-4	1405.5002	0.0161	5.194
With Outage of Line 7-8	1405.4717	0.0142	4.724
SVC added to Bus 5:	1311.5641	0.0121	3.258
With Outage of Line 5-4	1612.5718	0.0160	7.413
With Outage of Line 6-4	1320.5336	0.0124	5.41
With Outage of Line 7-8	1320.4905	0.0124	4.938
SVC added to Bus 6:	1311.613	0.0076	3.265
With SVC in Bus 5 and TCSC:	1481.2333	0.0174	4.069

Table 5.25: Optimal Power Flow Solution: WSCC 9 Bus

We can see that we only need to place SVC in only one bus either bus 5 or 6 to make the system N-1 secure based on the optimal power flow solution. SVC is placed in bus 5 only. Placing it in bus 5 is cheaper and there is less line loss than if it were placed in bus 6.

5.1.1 Dynamic Model

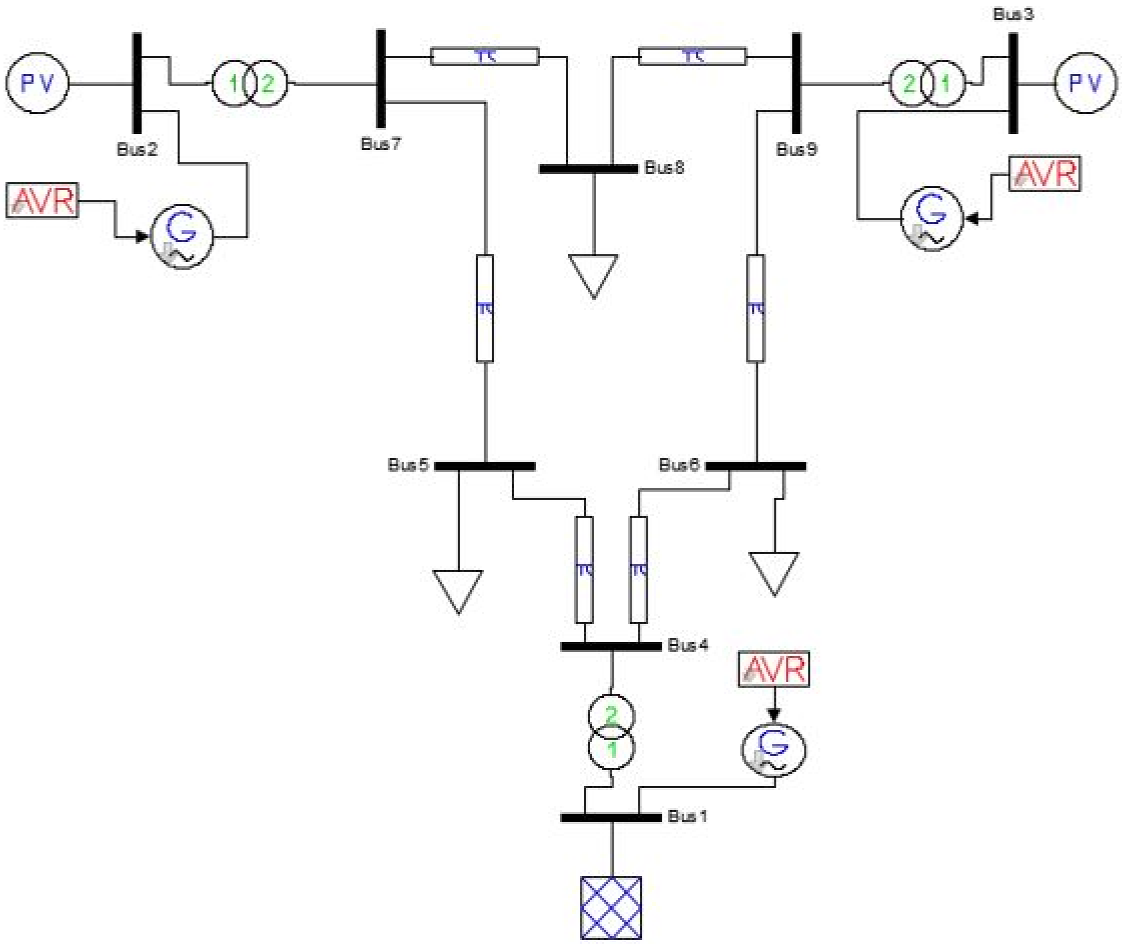


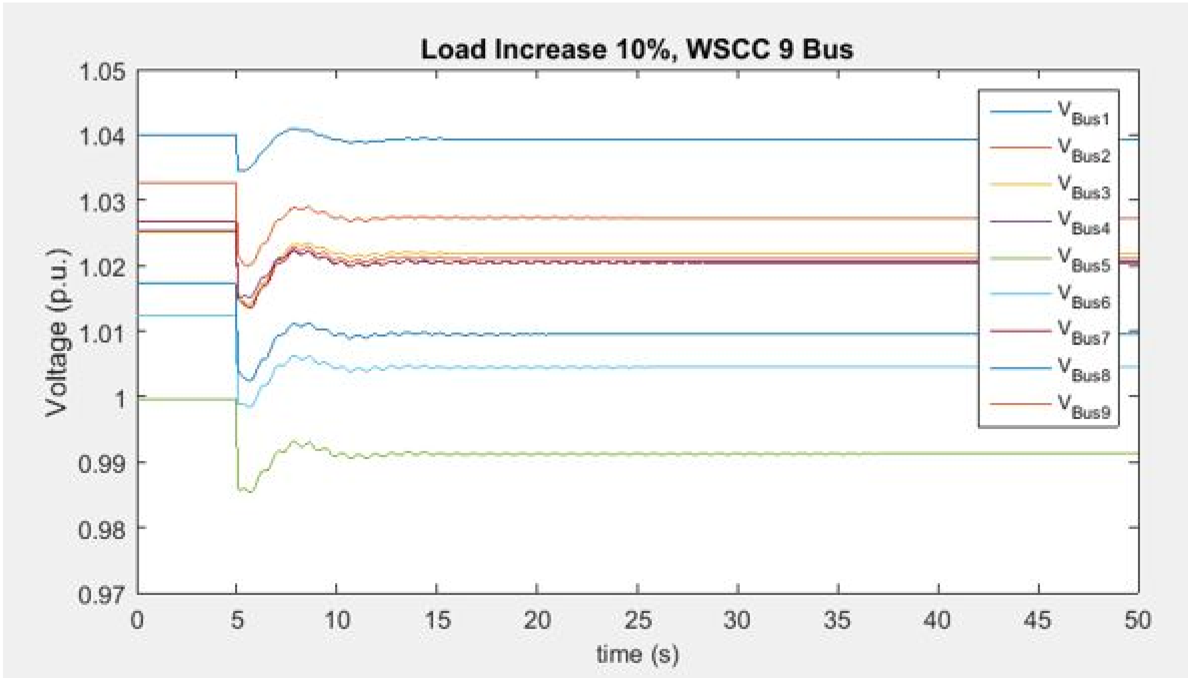
Figure 5.27: WSCC 9 Bus Dynamic Model

Dynamic order:	24
Buses	9
Posistive eigs:	0
Negative eigs:	22
Complex pairs:	8
Zero eigs:	2

Figure 5.28: Signs of Eigenvalues: WSCC 9 Bus

[28] There are no positive eigenvalues, so the system is small signal stable.

(a) Load Increase



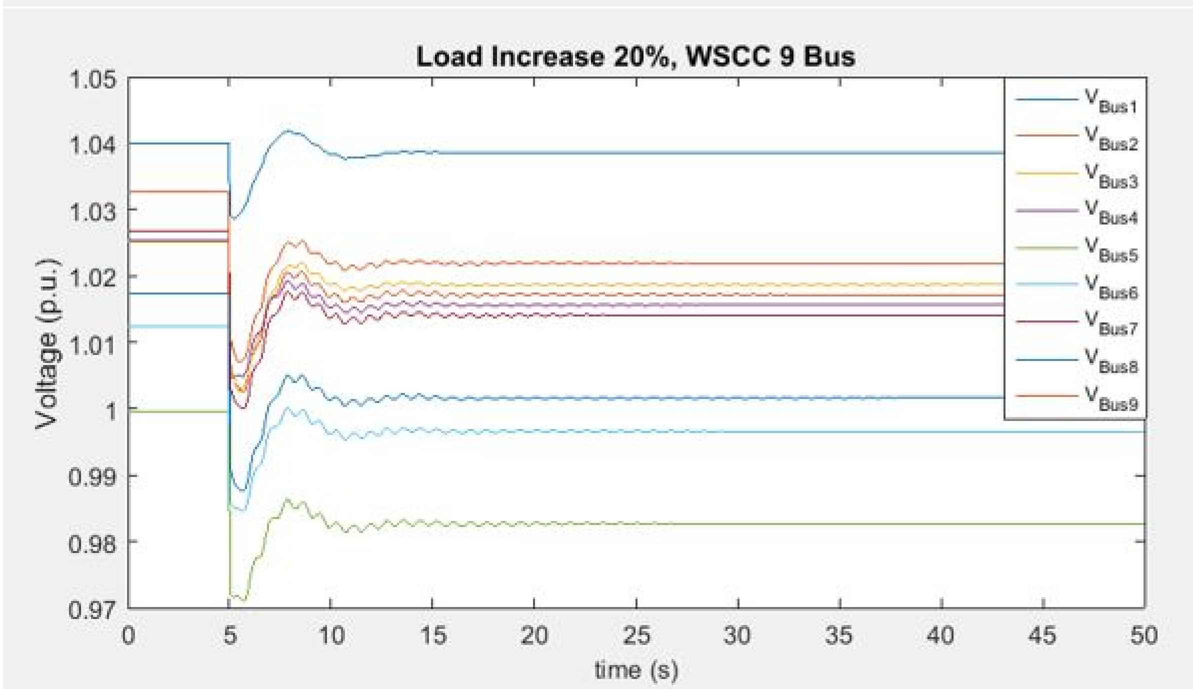


Figure 5.29: Load Increase 10%, 20% at t=5 s: WSCC 9 Bus

It can be seen that there is a sharper rise in voltage and a shorter recovery in voltage with the SVC when the small perturbation is applied.

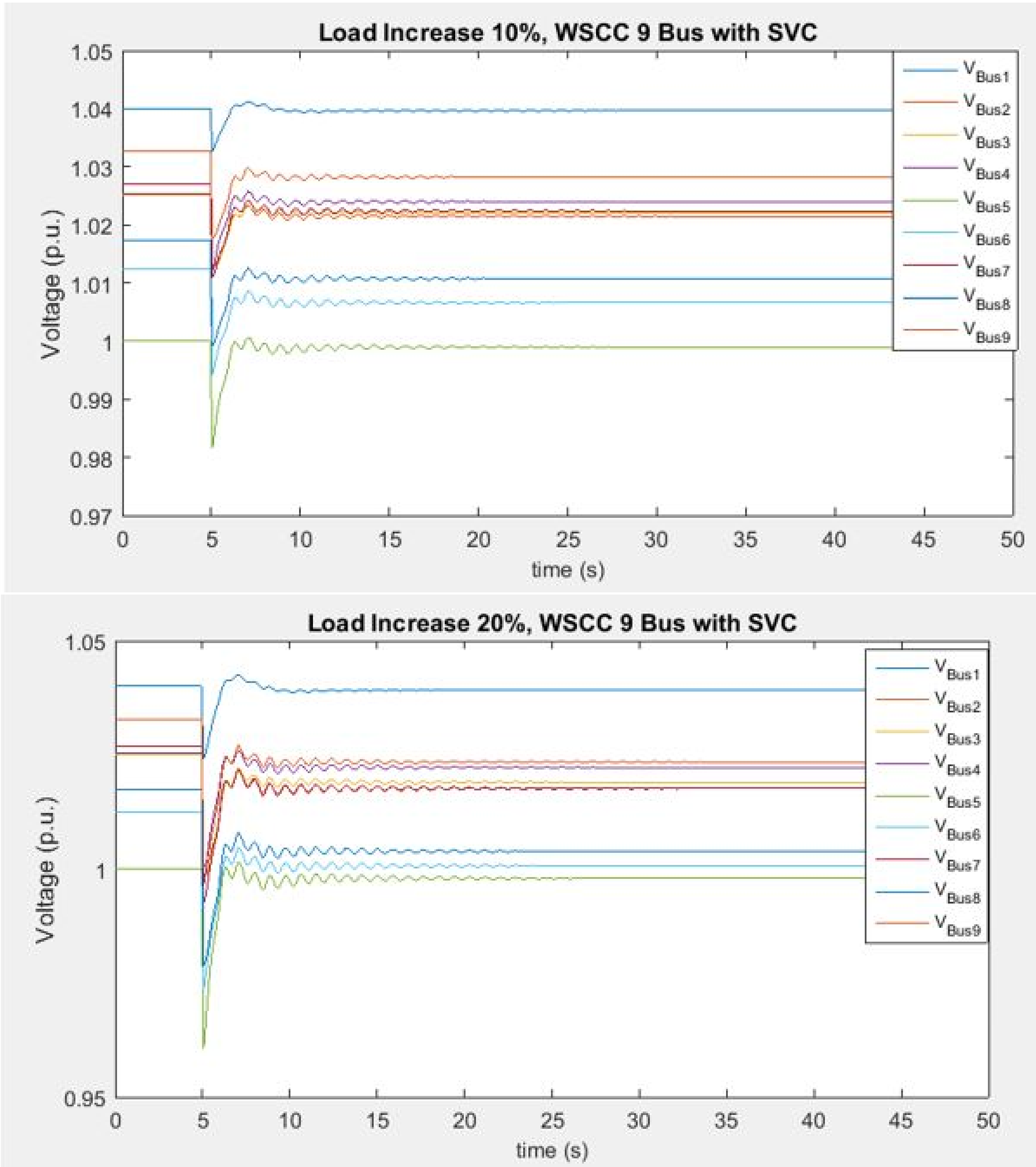


Figure 5.30: Load Increase 10%, 20% at t=5 s: WSCC 9 Bus with SVC in Bus 5

When TCSC is added the system becomes unstable, as seen from the positive eigenvalues. So, TCSC is not added.

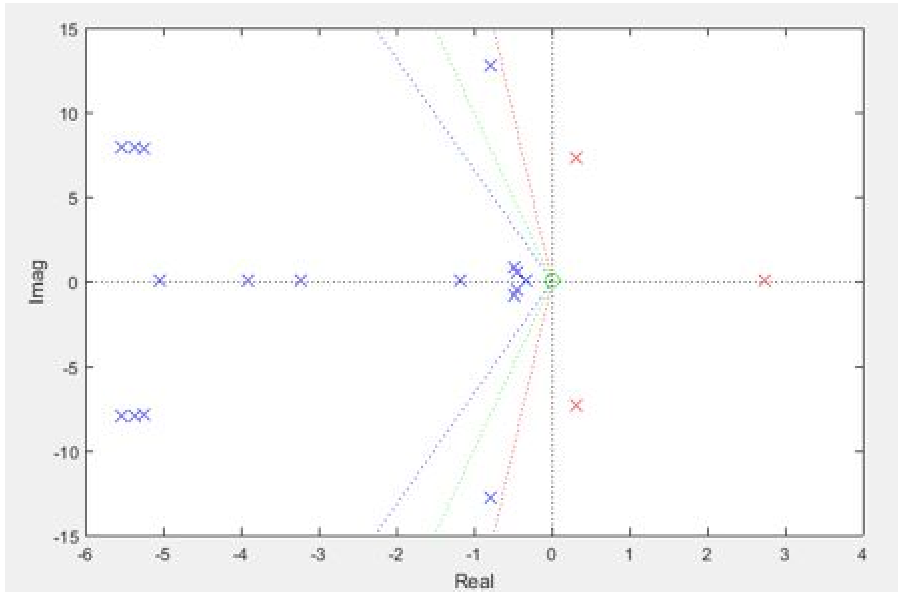


Figure 5.31: Eigenvalues in s-plane: WSCC 9 Bus with SVC and TCSC

Dynamic order:	27
Buses	9
Posistive eigs:	3
Negative eigs:	22
Complex pairs:	8
Zero eigs:	2

Figure 5.32: Signs of Eigenvalues: WSCC 9 Bus with SVC and TCSC

(b) Fault in Line 7-8

The system can handle the large disturbance with and without SVC.

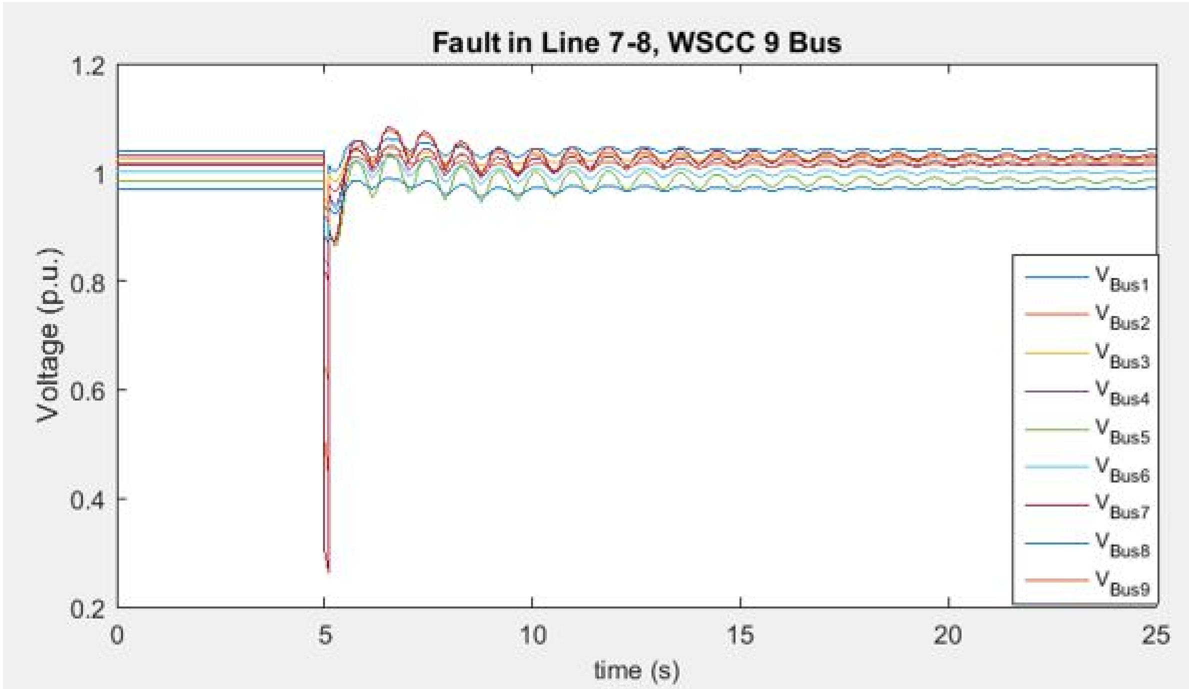


Figure 5.33: Three Phase Fault: WSCC 9 Bus

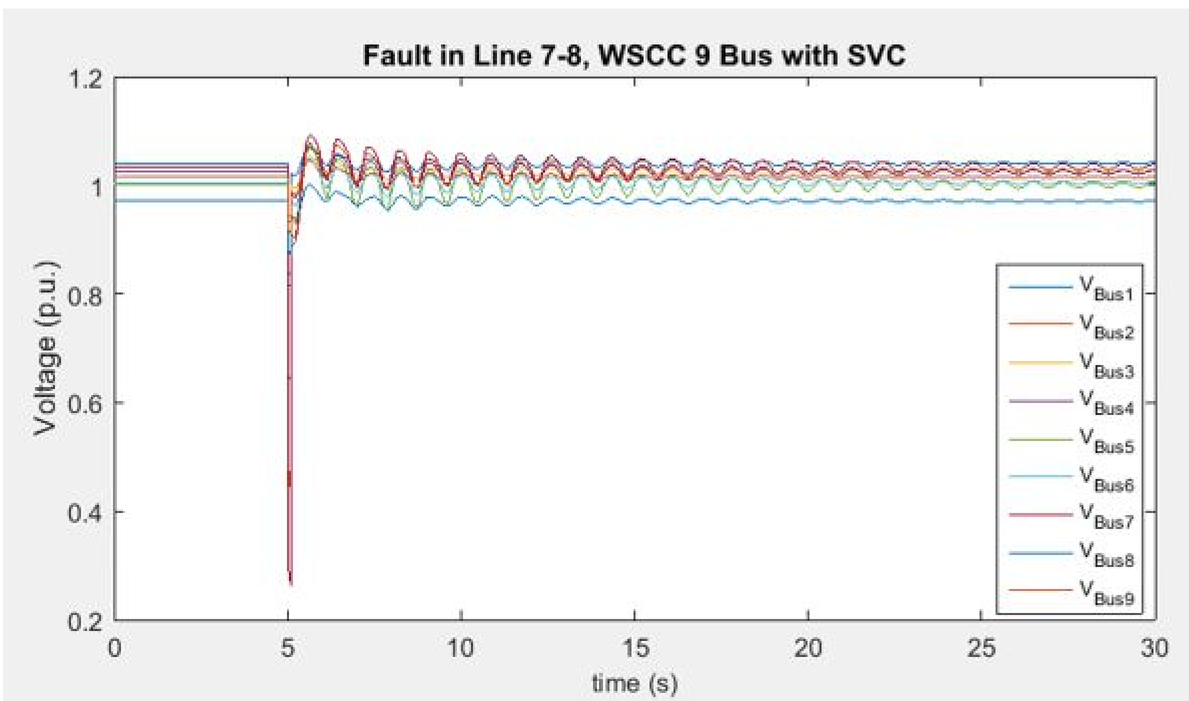


Figure 5.34: Three Phase Fault: WSCC 9 Bus with SVC in Bus 5

5.2 IEEE BUS 14

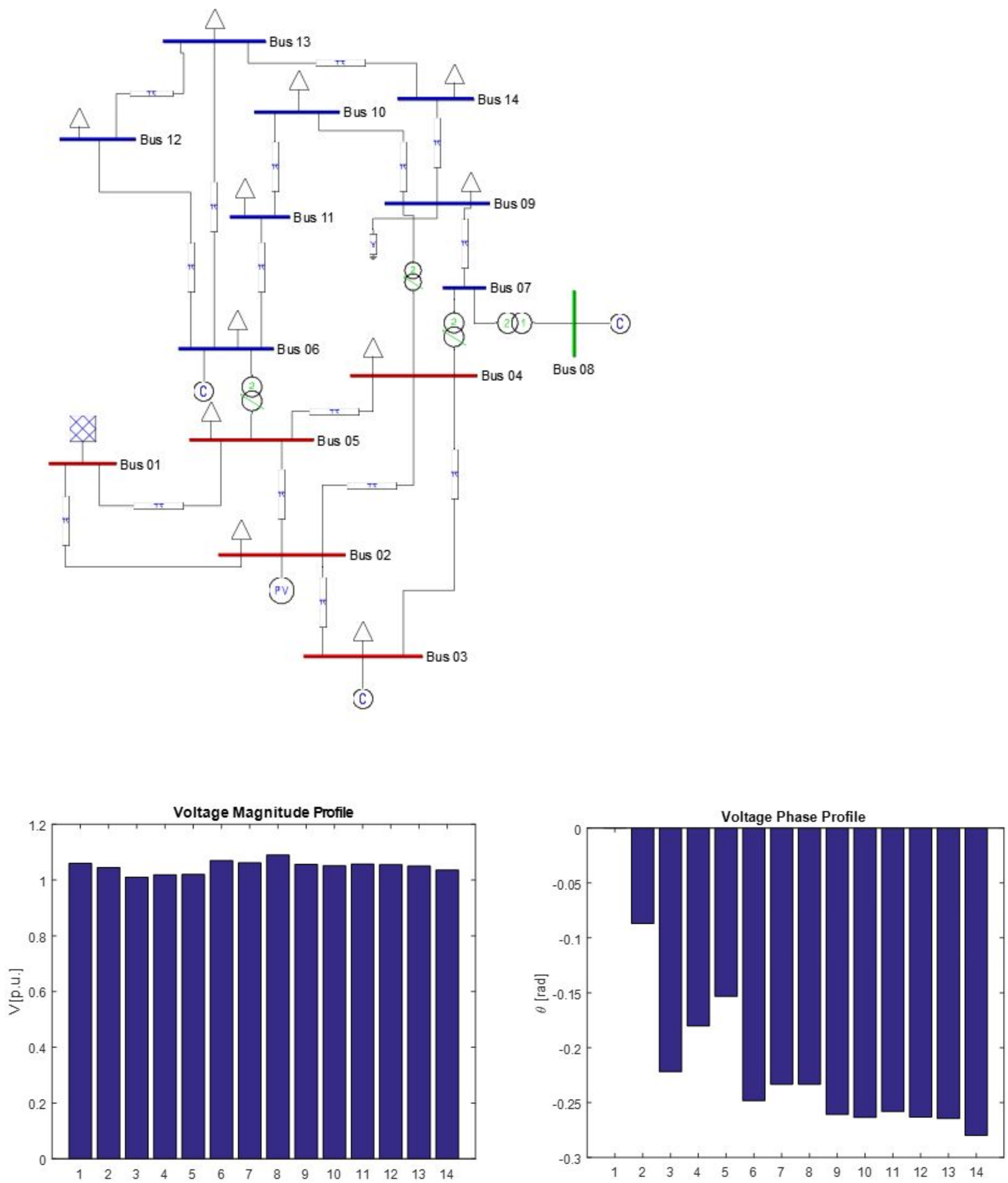


Figure 5.35: Power Flow of IEEE 14 Bus: Model, Voltage and Phase Angle

5.2.1 Static Model

(a) Without FACTS

1. *Generator Outage*

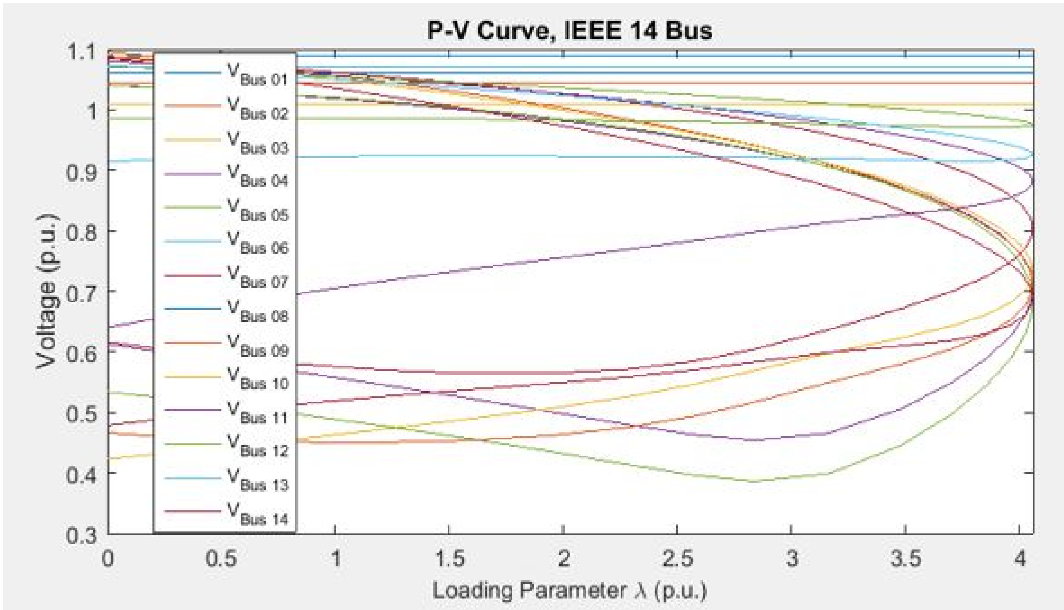


Figure 5.36: Base Case P-V Curve, IEEE 14 Bus

Generator Outage Case	Lambda Max Values		Generator Bus
	At Base Load	At 20% Load Increase	
1	4.0591	4.0591	Pre-Contingency
2	2.9577	2.8991	3
3	2.5852	2.4941	6
4	3.5541	3.4077	8
5	2.8419	2.7388	2

Table 5.26: Loading Parameter for Generator Outages: IEEE 14 Bus

Worst outage is for Case 3 (outage of generator 6). But, voltages are within limits for all cases.

Case 3:

At Base Load		At 20% Load Increase	
V [p.u.]	Phase [rad]	V [p.u.]	Phase [rad]
1.06	0	1.06	0
1.045	-0.0872	1.045	-0.09077
1.01	-0.22286	1.01	-0.23097
1.0145	-0.17987	1.0131	-0.18614
1.0151	-0.15212	1.0137	-0.15742
1.0458	-0.24738	1.0429	-0.25592
1.0561	-0.23487	1.0545	-0.24302
1.09	-0.23487	1.09	-0.24302
1.046	-0.26356	1.0434	-0.27272
1.0385	-0.26597	1.0355	-0.27522
1.0386	-0.25925	1.0355	-0.26824
1.0318	-0.26302	1.0283	-0.27213
1.0279	-0.26495	1.0243	-0.27414
1.0199	-0.2822	1.0162	-0.29204

Table 5.27: Case 3 - Outage of Generator in Bus 6: IEEE 14 Bus

2. *Line Outage*

Line Outage Case	Lambda Max Values		Outage Line
	At Base Load	At 20% Load Increase	
1	4.0591	3.4608	Pre-Contingency
2	4.0007	3.328	6-12
3	4.0489	3.3664	12-13
4	3.2722	2.7199	6-13
5	3.5821	2.9824	6-11
6	3.7819	3.1473	11-10
7	4.0263	3.3504	9-10
8	3.7018	3.0847	9-14
9	3.321	2.766	14-13
10	2.9388	2.4481	7-9
11	1.343	1.0876	1-2
12	2.2671	1.8952	3-2
13	3.9633	3.2996	3-4
14	3.6801	3.0655	1-5
15	3.9533	3.2914	5-4
16	3.302	2.7463	2-4
17	3.9665	3.2996	4-9
18	2.3411	1.9484	5-6
19	3.6215	3.0145	4-7
20	3.5498	2.9544	8-7
21	3.4435	2.8654	2-5

Table 5.28: Loading Parameter for Line Outages: IEEE 14 Bus

Worst outage is for Case 11 (outage of line 1-2). But, voltages are within limits for all cases

Case 11:

At Base Load		At 20% Load Increase	
V [p.u.]	Phase [rad]	V [p.u.]	Phase [rad]
1.06	0	1.06	0
1.045	-0.63646	1.045	-0.913
1.01	-0.72265	1.01	-1.0181
1.0028	-0.62592	0.97715	-0.88778
0.99431	-0.5603	0.9579	-0.79885
1.07	-0.67084	1.07	-0.94159
1.0539	-0.67329	1.0386	-0.94482
1.09	-0.67329	1.09	-0.94482
1.0472	-0.69768	1.0285	-0.97395
1.0436	-0.69791	1.0264	-0.97417
1.0529	-0.68667	1.0433	-0.96043
1.0547	-0.68686	1.0504	-0.96105
1.0489	-0.68916	1.0424	-0.9636
1.0298	-0.7116	1.0123	-0.99117

Table 5.29: Case 11 - Outage of Line 1-2: IEEE 14 Bus

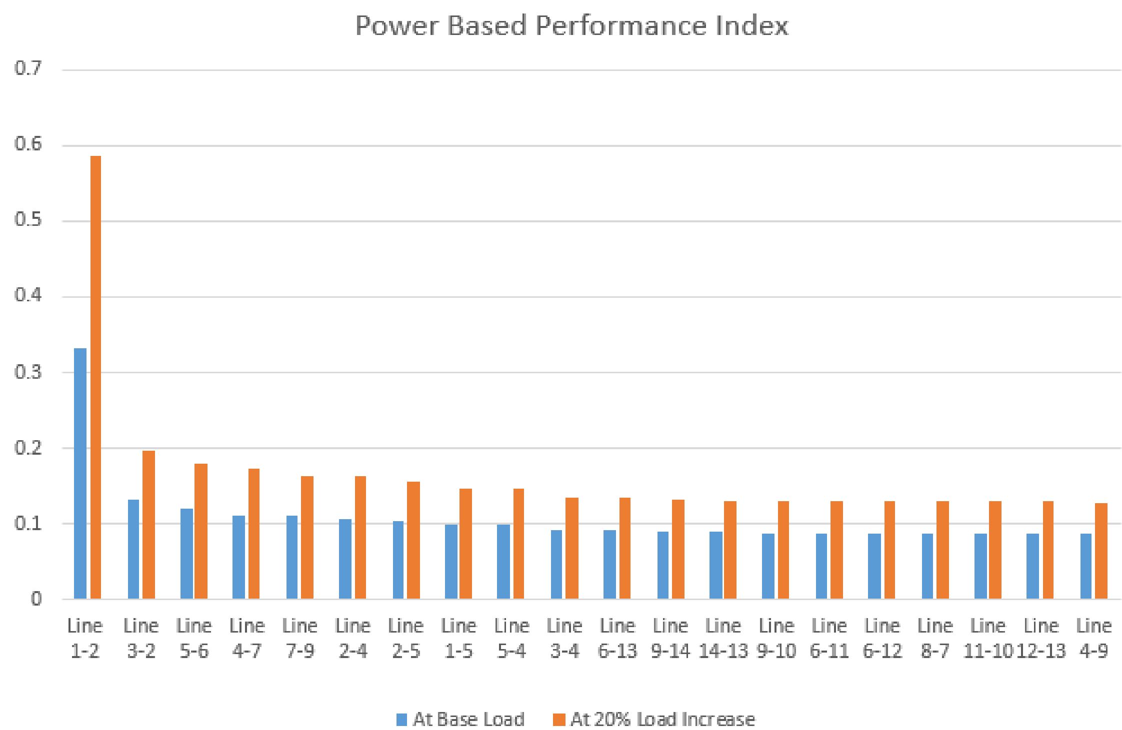


Figure 5.37: PI_P Ranking for Line Outages: IEEE 14 Bus

Line Power within limits. Highest risk is for the outage of line 1-2.

Maximum Load Increase within Limits

	Percentage (%)
Maximum Load Increase	131
Maximum Load Increase with outage of line 1-2	22.5

Table 5.30: Secure Loading Range: IEEE 14 Bus

Load can be increased by 131% with voltages within limits. Load can be increased by 22.5%, with no line outage causing the voltages to drop below the limits.

(b) Adding a TCSC

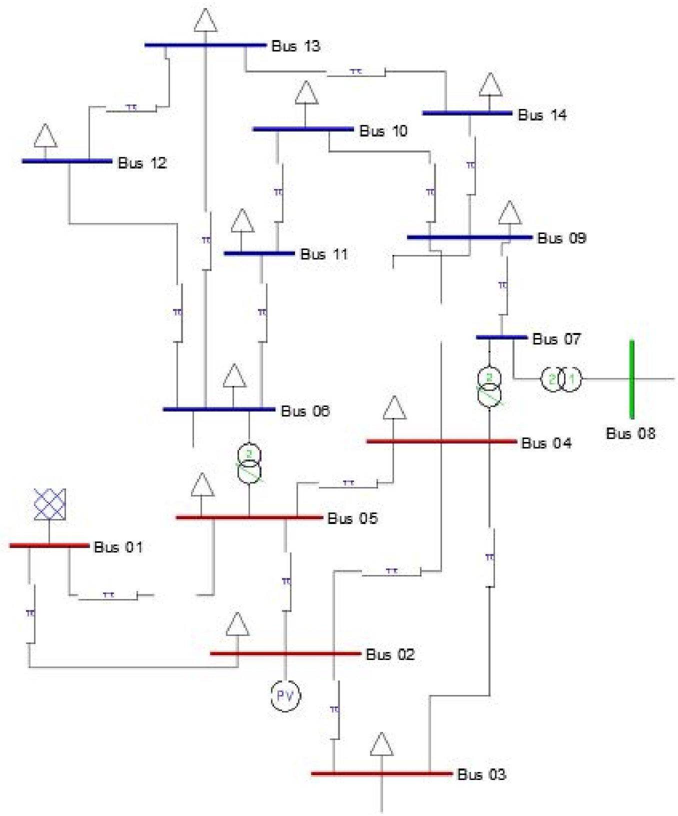


Figure 5.38: IEEE 14 Bus with TCSC in Line 1-5

TCSC Placement Line	PI_P
4-7	0.1164
7-9	0.1163
8-7	0.1159
9-10	0.1157
12-13	0.1156
9-14	0.1156
11-10	0.1155
2-4	0.1154
6-12	0.1154
6-11	0.1152
6-13	0.1151
14-13	0.1151
2-5	0.1132
4-9	0.1127
5-4	0.1124
3-4	0.1112
3-2	0.1108
5-6	0.1078
1-5	0.0979

Table 5.31: Adding TCSC Alternately to Each Line: IEEE 14 Bus

TCSC is placed in line 1-5 as it will give the smallest PI_P value.

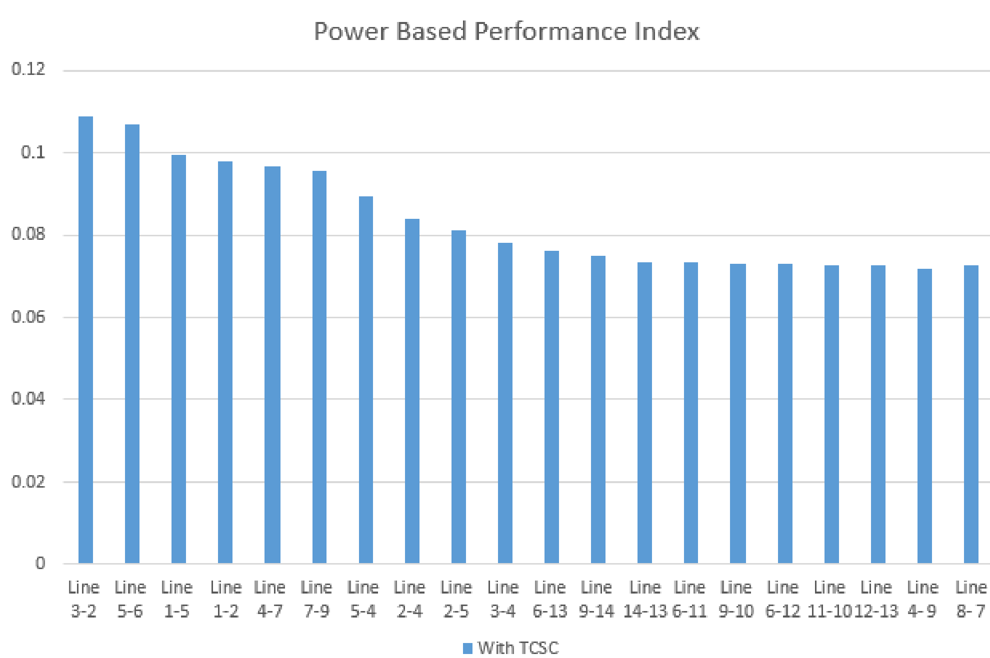


Figure 5.39: PI_P Ranking for Line Outages: IEEE 14 Bus with TCSC

Worst case outage was initially for outage of line 1-2. Outage of line 1-2 will cause excess current flow through line 1-5 instead so it makes sense that TCSC is placed in line 1-5. Series compensation of TCSC was taken randomly as -50%. The values of performance index has improved for every outage case. Line Power is still within limits. Highest risk is now for outage of line 3-2.

Maximum Load Increase within Limits

	Percentage (%)
Maximum Load Increase	133.5
Maximum Load Increase with outage of line 1-2	19.1

Table 5.32: Secure Loading Range: IEEE 14 Bus with TCSC

Load can be increased by 133.5% with voltages within limits. Load can be increased by 19.1%, with no line outage causing the voltages to drop below the limits.

Optimal Power Flow

	Cost Function [$/h]	PI_v	Total Losses [MW]
Base Case:	1047.6779	0.030	4.665
With Outage of Line 1-2	1061.0248	0.0280	7.889
TCSC added to Line 1-5:	1047.9985	0.0290	4.741
With Outage of Line 1-2	1060.9235	0.027	7.863
SVC added to Bus 5:	962.932	0.0229	4.939
With Outage of Line 1-2	976.3323	0.0284	8.089

Table 5.33: Optimal Power Flow Solution: IEEE 14 Bus

Addition of neither TCSC or SVC is crucial but the cost is less with addition of SVC however losses increases with addition of either.

5.2.2 Dynamic Model

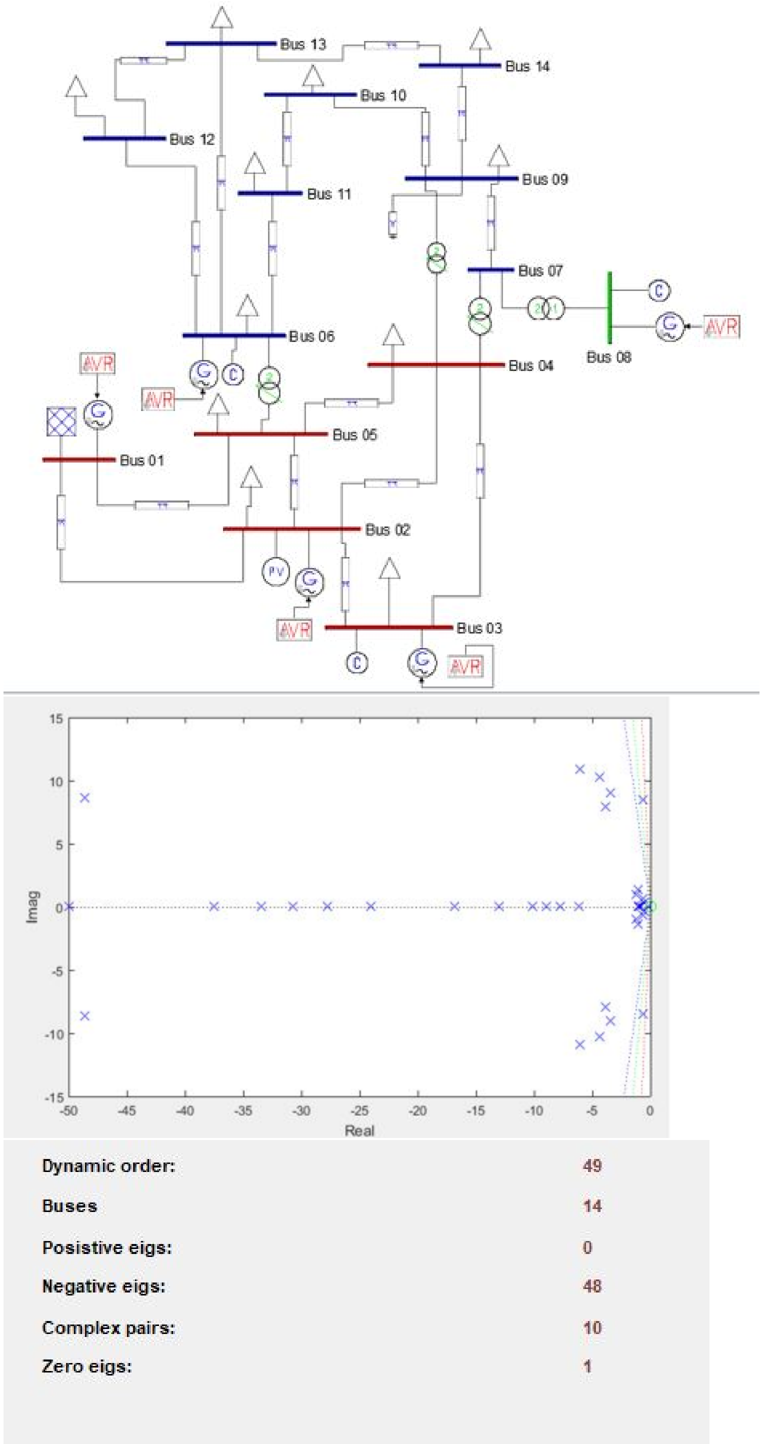


Figure 5.40: Dynamic Model and Eigenvalues: IEEE 14 Bus

With TCSC in Line 1-5

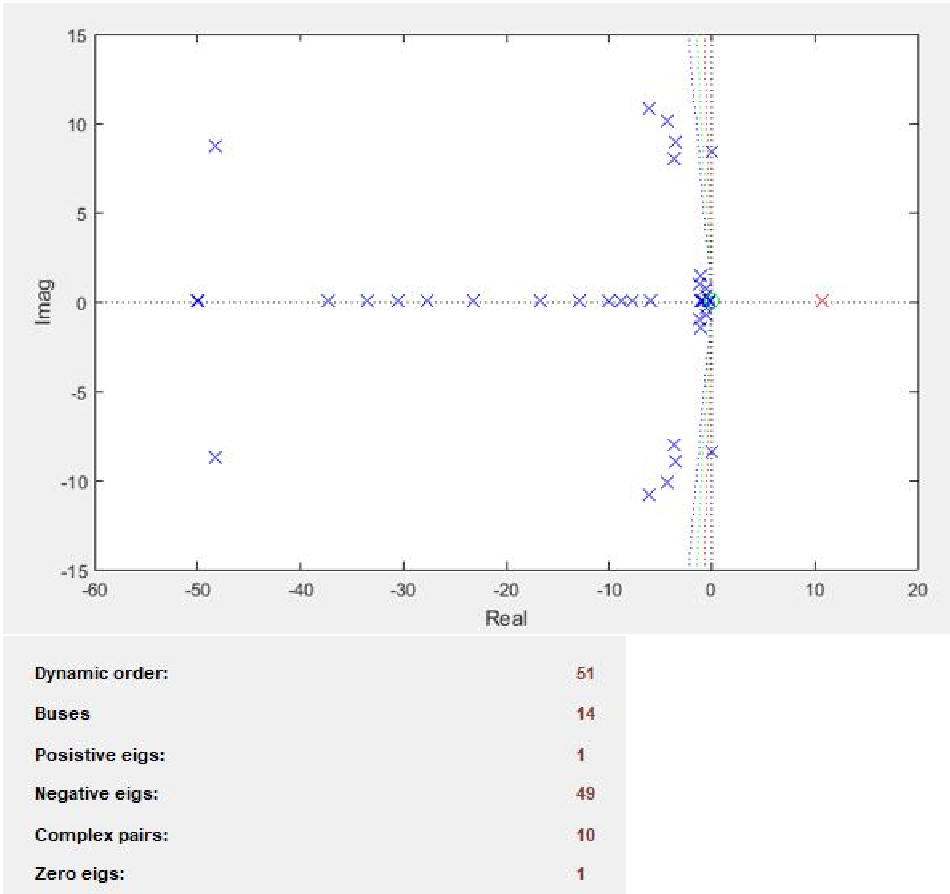
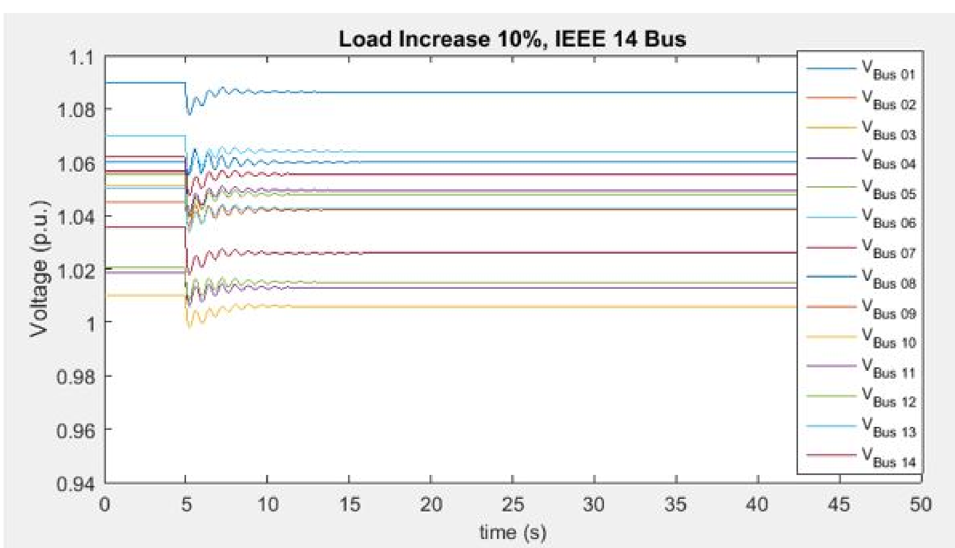


Figure 5.41: Eigenvalues: IEEE 14 Bus with TCSC

(a) Load Increase



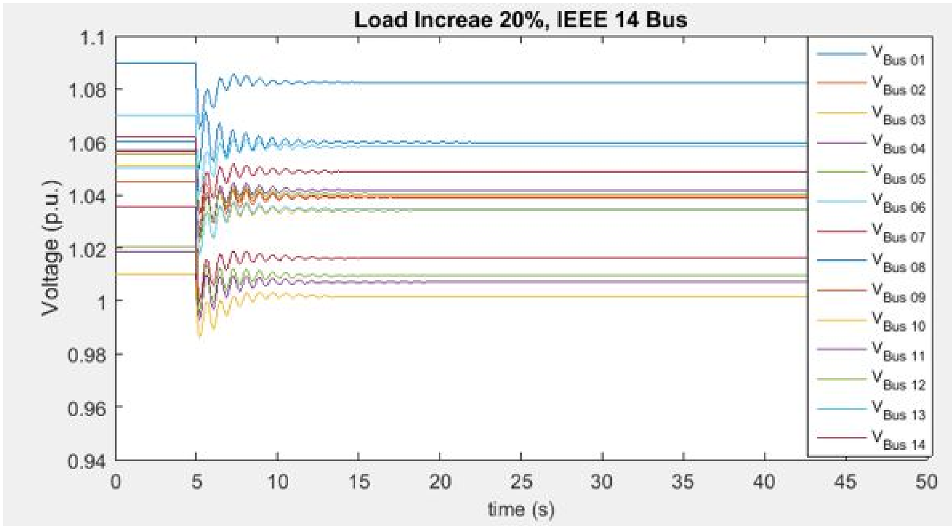


Figure 5.42: Load Increase 10%, 20% at t=5 s: IEEE 14 Bus

Load Increased at t=5 s. As load increases, the oscillation amplitude increases.

(b) Fault in Line 1-2

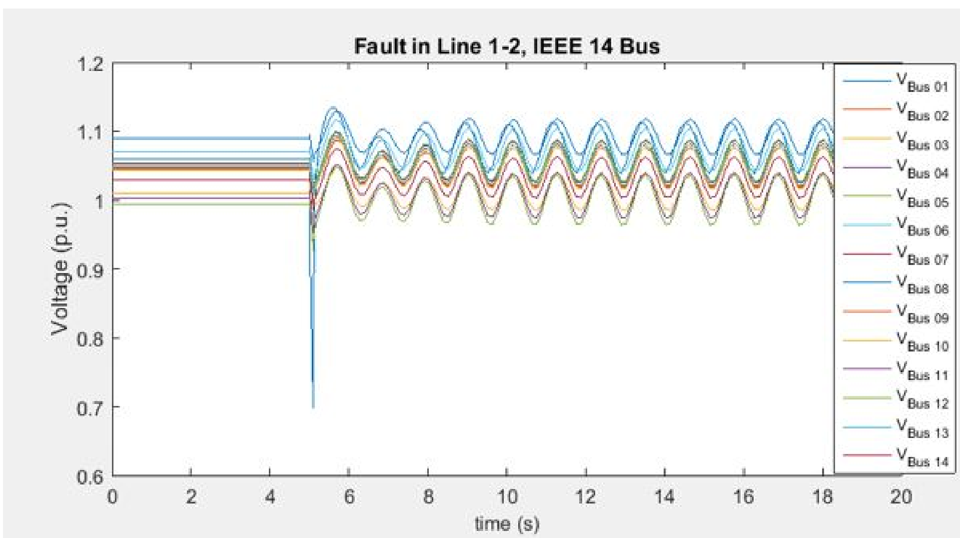


Figure 5.43: Three Phase Fault at Line 1-2: IEEE 14 Bus

Fault occurs at t=5s and cleared at t=5.1s.

The system must be modified so that the system is stable under the fault condition but even the addition of the SVC won't make the system stable for the most severe line fault. Therefore, the system is unstable for this large disturbance.

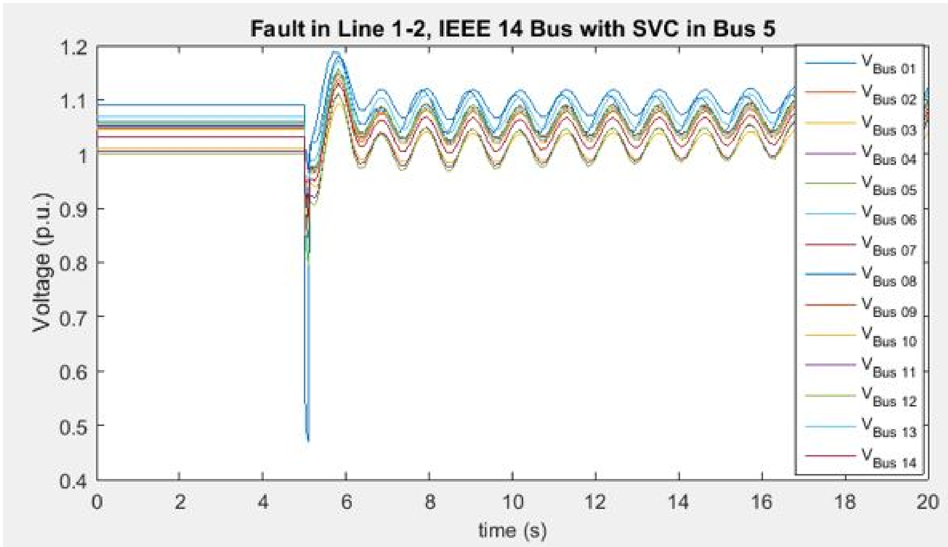


Figure 5.44: Three Phase Fault at Line 1-2: IEEE 14 Bus With SVC

5.3 IEEE 30 Bus

5.3.1 Static Model

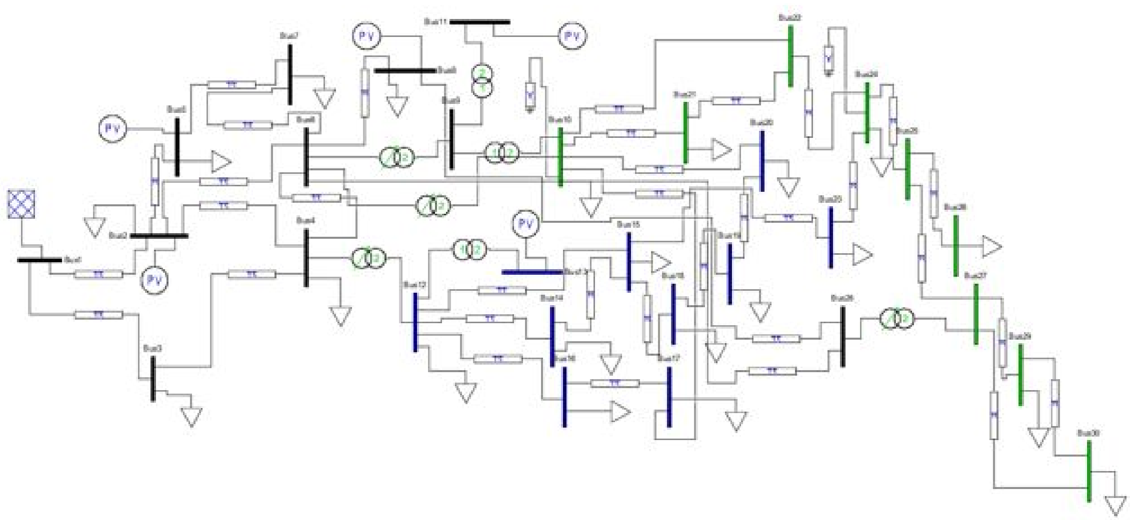


Figure 5.45: IEEE 30 Bus Model

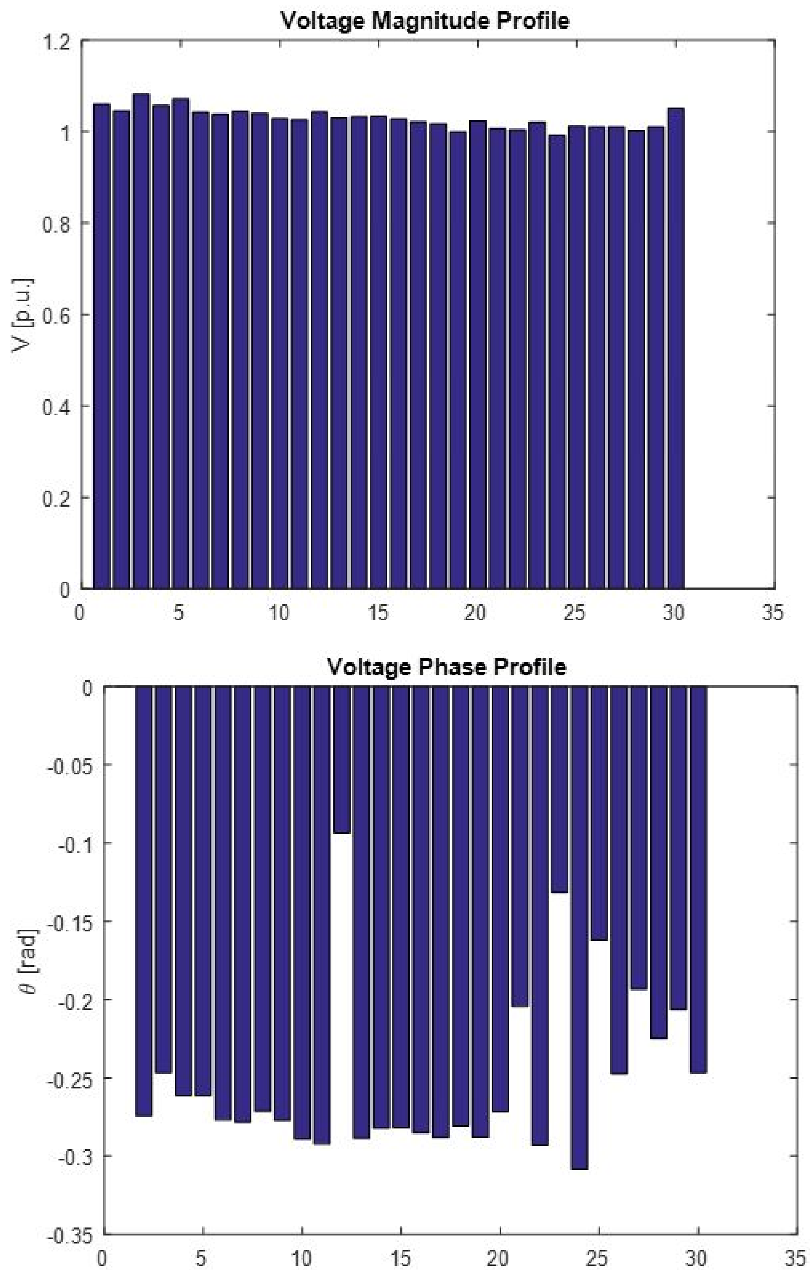


Figure 5.46: Power Flow Voltage, Phase Angle Results: IEEE 30 Bus

1. *Generator Outage*

Generator Outage Case	Lambda Max Values		Generator Bus
	At Base Load	At 20% Load Increase	
1	2.9565	2.5821	Pre-Contingency
2	2.7872	2.3219	5
3	2.781	2.3162	11
4	2.3891	1.9897	8
5	2.6307	2.1909	13
6	2.6895	2.2412	2

Table 5.34: Loading Parameter for Generator Outages: IEEE 30 Bus

Worst generator outage case is Case 4, which is still within limits.

At 20% load increase, bus 30 voltage is below limits for Case 4.

Case 4:

At Base Load		At 20% Load Increase	
V [p.u.]	Phase [rad]	V [p.u.]	Phase [rad]
1.06	0	1.06	0
1.043	-0.09393	1.043	-0.12001
1.0117	-0.12957	1.0005	-0.16016
1.0006	-0.15988	0.9878	-0.1982
1.01	-0.24961	1.01	-0.31111
0.99323	-0.18982	0.97859	-0.23508
0.99221	-0.22373	0.98154	-0.27779
0.97931	-0.19949	0.96121	-0.24697
1.0414	-0.24472	1.0283	-0.30273
1.0347	-0.27307	1.0164	-0.33777
1.082	-0.24472	1.082	-0.30273
1.0509	-0.26103	1.0394	-0.32364
1.071	-0.26103	1.071	-0.32364
1.0353	-0.27673	1.0197	-0.34296
1.03	-0.27803	1.0128	-0.34433
1.0364	-0.27063	1.0202	-0.33504
1.0302	-0.27619	1.0114	-0.34179
1.0194	-0.28861	0.99901	-0.35738
1.0163	-0.2915	0.99473	-0.36092
1.0201	-0.28791	0.99917	-0.35638
1.022	-0.28096	1.0007	-0.34755
1.0225	-0.28071	1.0013	-0.34721
1.0178	-0.28456	0.99668	-0.35214
1.01	-0.28718	0.98557	-0.35498
1.0022	-0.27879	0.97709	-0.34519
0.9842	-0.28634	0.95487	-0.35477
1.006	-0.26897	0.98259	-0.33328
0.98699	-0.20028	0.97015	-0.24776
0.98574	-0.2912	0.95764	-0.36109
0.97405	-0.30717	0.94335	-0.38113

Table 5.35: Case 4- Outage of Generator at Bus 8: IEEE 30 Bus

2.*Line Outage*

Worst outage cases are Case 42 (outage of line 1-2), Case 38 (outage of line 28-27), Case 25 (outage of line 27-30), Case 28 (outage of line 5-2) and Case 24 (outage of line 27-90) respectively. The rest of the outages are within limits. Case 42 is within limits for the base load.

Line Outage Case	Lambda Max Values		Outage Line
	At Base Load	At 20% Load Increase	
1	2.9565	2.5821	Pre-Contingency
2	2.8848	2.4071	1-3
3	2.9171	2.43	14-12
4	2.7418	2.2839	15-12
5	2.9022	2.4174	16-12
6	2.9486	2.4559	14-15
7	2.8512	2.3745	2-4
8	2.9297	2.4399	17-16
9	2.9191	2.4331	18-15
10	2.9479	2.455	18-19
11	2.9129	2.426	19-20
12	2.8024	2.3201	20-10
13	2.9624	2.4672	17-10
14	2.8066	2.3381	21-10
15	2.9157	2.4287	22-10
16	2.9588	2.4641	22-21
17	2.7848	2.3193	15-23
18	2.8963	2.4136	3-4
19	2.7032	2.252	24-22
20	2.8723	2.3922	23-24
21	2.8455	2.3703	25-24
23	2.9016	2.4174	27-25
24	2.231	1.8588	27-29
25	2.0302	1.6925	27-30
26	2.5792	2.1496	29-30
27	2.8405	2.3656	28-8
28	2.2069	1.8385	5-2
29	2.8018	2.3345	28-6
30	2.8068	2.3376	6-2
31	2.8773	2.3939	4-6
32	2.9243	2.4354	7-5
33	3.0038	2.5022	6-7
34	2.6625	2.2172	8-6
35	2.8728	2.3928	6-10
36	2.411	2.0094	4-12
37	2.7876	2.3221	6-9
38	1.5165	1.2635	28-27
39	2.7808	2.3163	9-11
40	2.6307	2.1909	12-13
41	2.3939	1.9943	9-10
42	1.2574	1.0209	1-2

Table 5.36: Loading Parameter for Line Outages: IEEE 30 Bus

Case 42:

V [p.u.]	Phase [rad]
1.06	0
1.043	-1.0667
0.89788	-0.7444
0.92958	-0.92677
1.01	-1.1904
0.9762	-1.0356
0.97909	-1.1112
1.01	-1.0619
1.0231	-1.0942
1.0065	-1.1248
1.082	-1.0942
1.0219	-1.0843
1.071	-1.0843
1.0035	-1.1073
0.99683	-1.1124
1.0048	-1.1074
0.99996	-1.1242
0.98484	-1.1325
0.98176	-1.1402
0.98691	-1.1376
0.99076	-1.1342
0.99137	-1.1337
0.98341	-1.1272
0.97625	-1.1395
0.97344	-1.1379
0.95113	-1.1475
0.98262	-1.1309
0.97868	-1.0505
0.95767	-1.1587
0.94337	-1.1787

Table 5.37: Case 42- Outage of Line 1-2: IEEE 30 Bus

Voltages are below limit for Bus 3, 4 and 30.

Case 38:

V [p.u.]	Phase [rad]
1.06	0
1.043	-0.09302
1.0197	-0.13176
1.0105	-0.16244
1.01	-0.24623
1.01	-0.19123
1.0022	-0.22302
1.01	-0.20278
1.0469	-0.25852
1.0377	-0.29375
1.082	-0.25852
1.0534	-0.27696
1.071	-0.27696
1.0364	-0.29519
1.0286	-0.29851
1.0389	-0.28858
1.0331	-0.29599
1.0196	-0.30916
1.0174	-0.31209
1.0217	-0.30852
1.0212	-0.30591
1.0204	-0.30702
1.0081	-0.3146
0.98964	-0.3305
0.93876	-0.37303
0.92073	-0.38113
0.91784	-0.39751
1.0113	-0.19425
0.8983	-0.42097
0.88717	-0.43768

Table 5.38: Case 38 - Outage of Line 28-27: IEEE 30 Bus

Voltages are below limit for Bus 25, 26, 27, 29 and 30.

Case 25:

V [p.u.]	Phase [rad]
1.06	0
1.043	-0.09352
1.0206	-0.13168
1.0116	-0.16232
1.01	-0.24751
1.0101	-0.19342
1.0023	-0.22483
1.01	-0.20655
1.0507	-0.24691
1.0448	-0.27473
1.082	-0.24691
1.0569	-0.26155
1.071	-0.26155
1.042	-0.27713
1.0373	-0.27872
1.0441	-0.27171
1.0396	-0.27756
1.0278	-0.28945
1.0253	-0.29248
1.0294	-0.28904
1.0323	-0.28247
1.0328	-0.28222
1.0266	-0.28554
1.0207	-0.28862
1.0154	-0.28114
0.99766	-0.28849
1.0207	-0.27197
1.0064	-0.20428
0.97592	-0.31913
0.93944	-0.36554

Table 5.39: Case 25 - Outage of Line 27-30: IEEE 30 Bus

Bus 30 voltage is below limits.

Case 24:

V [p.u.]	Phase [rad]
1.06	0
1.043	-0.09358
1.0206	-0.13176
1.0116	-0.16242
1.01	-0.2476
1.0101	-0.19355
1.0023	-0.22495
1.01	-0.20669
1.0507	-0.24706
1.0448	-0.27488
1.082	-0.24706
1.0569	-0.26168
1.071	-0.26168
1.042	-0.27728
1.0373	-0.27888
1.0441	-0.27186
1.0396	-0.27771
1.0278	-0.2896
1.0253	-0.29263
1.0294	-0.2892
1.0323	-0.28264
1.0328	-0.2824
1.0266	-0.28573
1.0208	-0.28887
1.0156	-0.28158
0.99789	-0.28893
1.021	-0.27253
1.0064	-0.20447
0.94672	-0.35307
0.95708	-0.34352

Table 5.40: Case 24 - Outage of Line 27-29: IEEE 30 Bus

Bus 29 voltage is below the limit.

Overall, based on the power flow solution we see that we would need a minimum of 3 SVCs at bus 25, 29 and 30 for all voltages to be within limits. This number will decrease once dispatch is considered for optimal power flow.

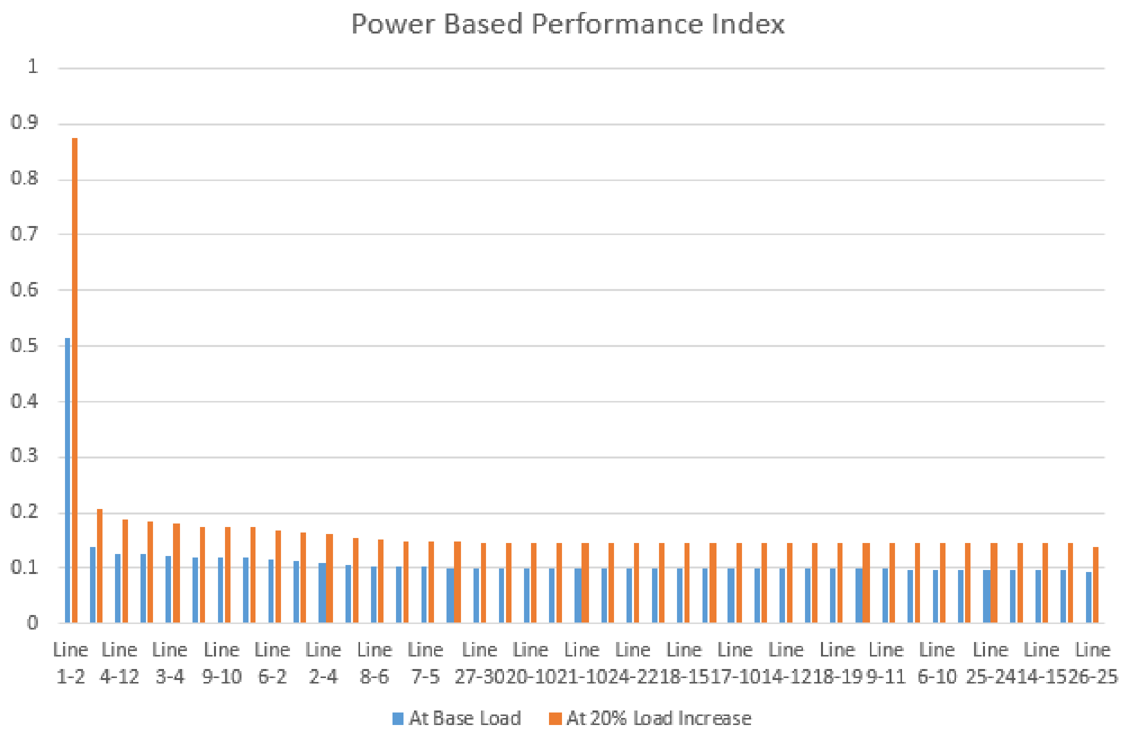


Figure 5.47: PI_P Ranking for Line Outages: IEEE 30 Bus

Line powers are within limits. Highest risk is for outage of line 1-2.

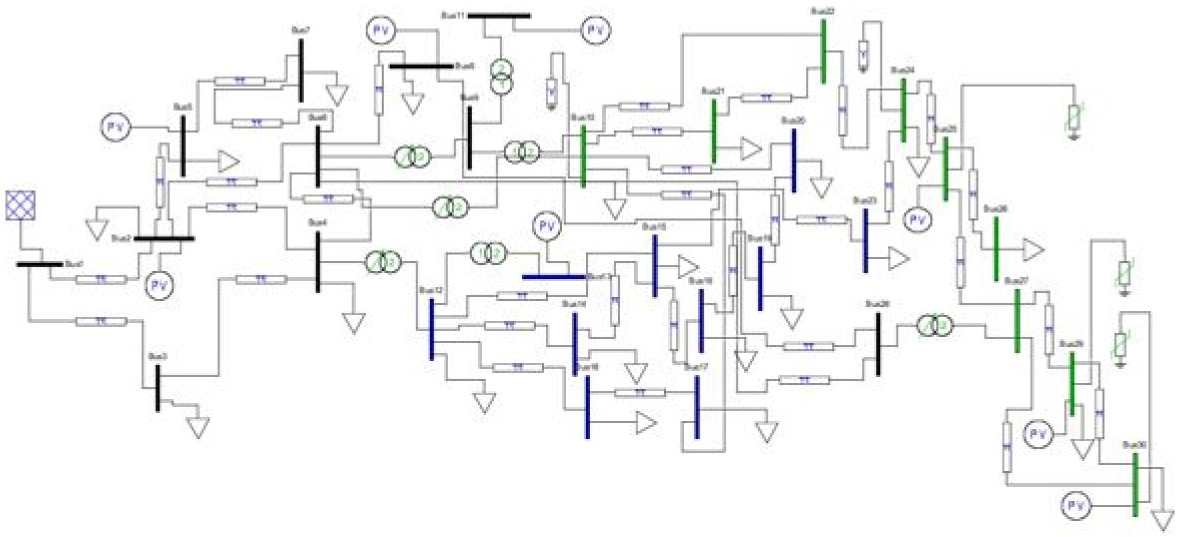
Maximum Load Increase within Limits

	Percentage (%)
Maximum Load Increase	39.1
Maximum Load Increase with outage of line 1-2	-5

Table 5.41: Secure Loading Range: IEEE 30 Bus

Load can be increased by 39.1% with voltages within limits. Load must be decreased by 5%, so that no line outages cause the voltages to drop below the limits.

(b) Modified form where SVC is added to Bus 25, 29 and 30



1. *Generator Outage*

Generator Outage Case	Lambda Max Values	Generator Bus
1	3.7753	Pre-Contingency
2	2.8731	5
3	3.4598	11
4	3.0586	8
5	3.106	13
6	2.7713	2

Table 5.42: Loading Parameter for Generator Outages: IEEE 30 Bus with SVCs

No voltages are below the limit. Worst outage case is Case 6 (outage of generator in bus 2).

Case 6:

V [p.u.]	Phase [rad]
1.06	0
1.022	-0.10875
1.015	-0.14383
1.0049	-0.17758
1.01	-0.26923
1.0056	-0.21112
0.99959	-0.24422
1.01	-0.22559
1.0471	-0.26466
1.0398	-0.29251
1.082	-0.26466
1.0533	-0.27872
1.071	-0.27872
1.0379	-0.29442
1.0328	-0.29584
1.0399	-0.28913
1.0348	-0.29528
1.023	-0.30691
1.0204	-0.31012
1.0245	-0.30673
1.0266	-0.30006
1.0269	-0.29972
1.0204	-0.30222
1.0123	-0.30466
1	-0.29346
0.982	-0.30105
1.0154	-0.28951
1.0028	-0.22216
1	-0.31355
1	-0.33487

Table 5.43: Case 6 - Outage of Generator in Bus 2: IEEE 30 Bus with SVCs

2. *Line Outage*

Line Outage Case	Lambda Max Values	Outage Line
1	3.7753	Pre-Contingency
2	3.5185	1-3
3	3.6793	14-12
4	3.4072	15-12
5	3.6835	16-12
6	3.7716	14-15
7	3.3282	2-4
8	3.7528	17-16
9	3.4392	18-15
10	3.6951	18-19
11	3.2865	19-20
12	3.008	20-10
13	3.5274	17-10
14	3.6219	21-10
15	3.7524	22-10
16	3.7496	22-21
17	3.7646	15-23
18	3.5483	3-4
19	3.7558	24-22
20	3.7732	23-24
21	3.396	25-24
23	3.4455	27-25
24	3.7297	27-29
25	3.7304	27-30
26	3.7622	29-30
27	3.7259	28-8
28	2.244	5-2
29	3.6977	28-6
30	3.0982	6-2
31	3.3951	4-6
32	3.7118	7-5
33	3.3868	6-7
34	3.248	8-6
35	3.6149	6-10
36	2.7799	4-12
37	3.3831	6-9
38	2.6111	28-27
39	3.4636	9-11
40	3.1012	12-13
41	2.8672	9-10
42	1.261	1-2

Table 5.44: Loading Parameter for Line Outages: IEEE 30 Bus with SVCs

Worst outage case is Case 42 (outage of line 1-2). All voltages are within limits.

Case 42:

V [p.u.]	Phase [rad]
1.06	0
1.043	-0.69629
0.97244	-0.48637
0.9795	-0.60437
1.01	-0.79816
0.99811	-0.6802
0.99475	-0.73801
1.01	-0.69689
1.0418	-0.72784
1.0327	-0.75261
1.082	-0.72784
1.0456	-0.72323
1.071	-0.72323
1.0306	-0.74109
1.0252	-0.74467
1.0317	-0.74039
1.0275	-0.75266
1.0155	-0.75988
1.0129	-0.76552
1.017	-0.76333
1.0198	-0.76004
1.0202	-0.75962
1.0139	-0.7555
1.0074	-0.76388
1	-0.75888
0.982	-0.76646
1.0139	-0.75627
0.99761	-0.69158
1	-0.78115
1	-0.80249

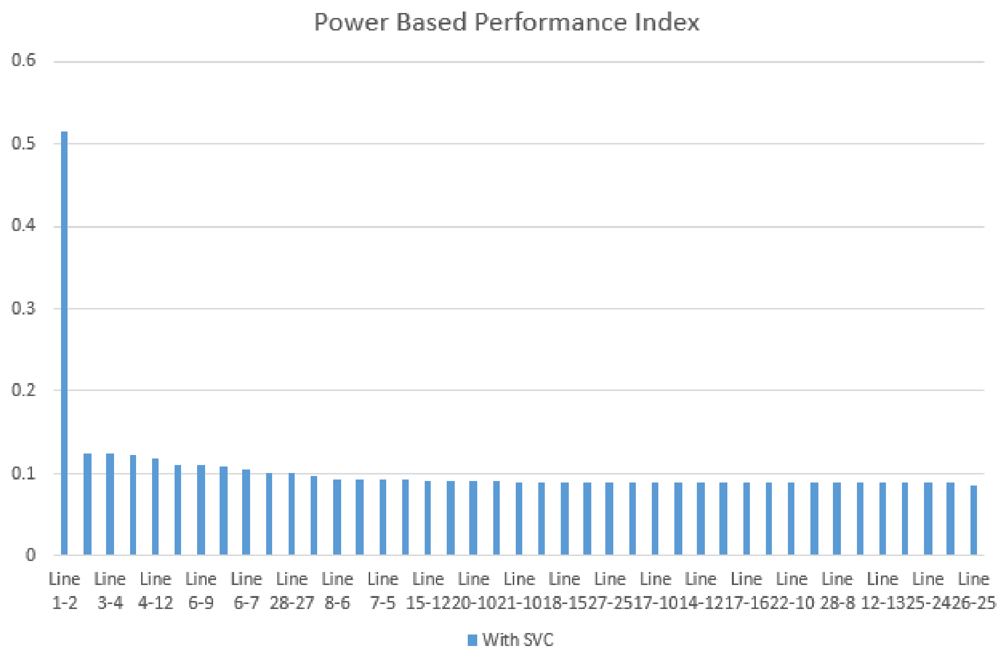


Figure 5.48: PI_P Ranking for Line Outages: IEEE 30 Bus with SVC

Line powers are within limits. Highest risk is for outage of line 1-2.

Maximum Load Increase within Limits

	Percentage (%)
Maximum Load Increase	97.1
Maximum Load Increase with outage of line 1-2	8.8

Table 5.45: Secure Loading Range: IEEE 30 Bus with SVCs

Load can be increased by 97.1% with voltages within limits. Load can be increased by 8.8%, for no line outage to cause the voltages to drop below the limits.

(c) Adding TCSC to line 1-3 of the modified form including SVC

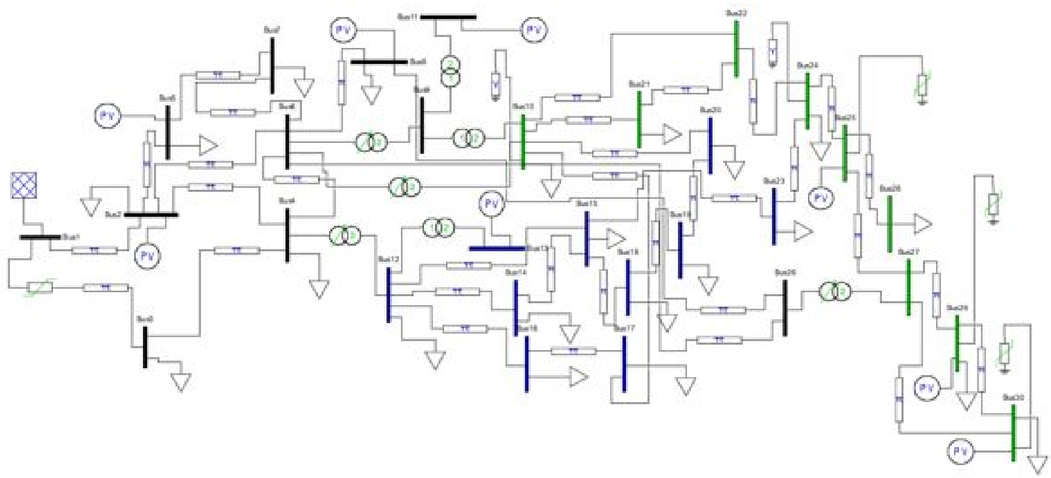


Figure 5.49: IEEE 30 Bus with SVCs and TCSC

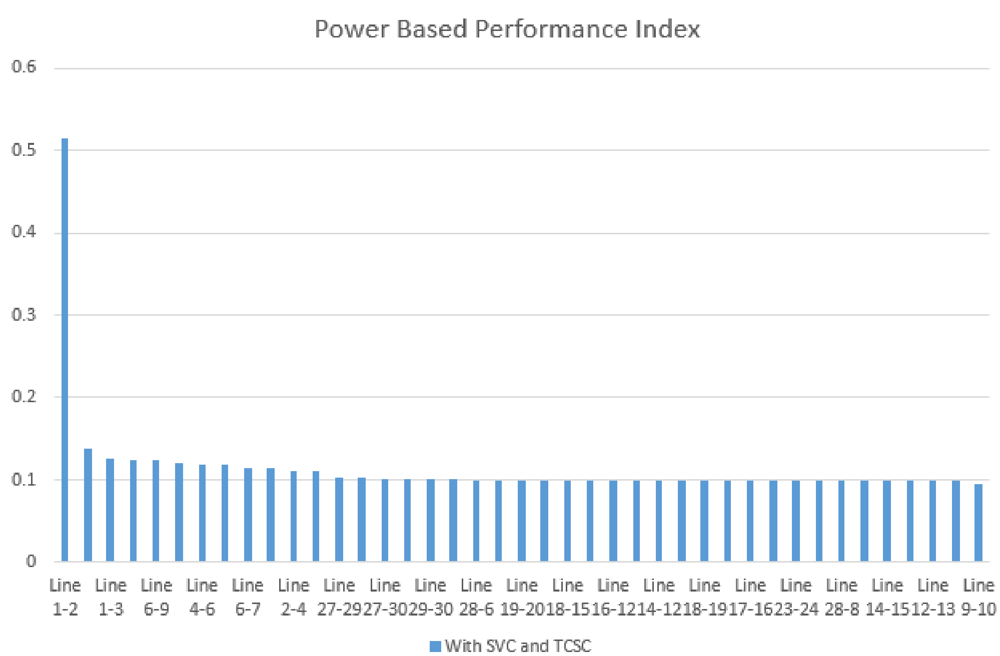


Figure 5.50: PI_P Ranking for Line Outages: IEEE 30 Bus with SVC and TCSC

Worst case outage was initially for outage of line 1-2. Outage of line 1-2 will cause excess current flow through line 1-3 instead so TCSC is placed in line 1-3. Series compensation of TCSC was taken randomly as -50%. The values of performance index has improved for every outage case. Line Power is still within limits. Highest risk is still for outage of line 1-2.

Maximum Load Increase within Limits

	Percentage (%)
Maximum Load Increase	101.2
Maximum Load Increase with outage of line 1-2	14.9

Table 5.46: Secure Loading Range: IEEE 30 Bus with SVCs and TCSC

Load can be increased by 101.2% with voltages within limits. Load can be increased by 14.9%, with no line outages causing the voltages to drop below the limits.

Optimal Power Flow

	Cost Function [$/h]	PIv	Total Losses [MW]
Base Case:	802.1483	0.0393	9.426
With Outage of Line 1-2	842.8509	0.0323	13.01
With Outage of Line 27-28	-	-	-
SVC added to Bus 29:	802.2703	0.0368	9.469
With Outage of Line 1-2	842.8558	0.0308	13
With Outage of Line 27-28	808.1483	0.0390	11.167

Table 5.47: OPF Solution: IEEE 30

OPF does not converge for outage of line 27-28 so at least one SVC must be added. SVC must be added to bus 29 so that only one SVC is needed.

5.3.2 Dynamic Model

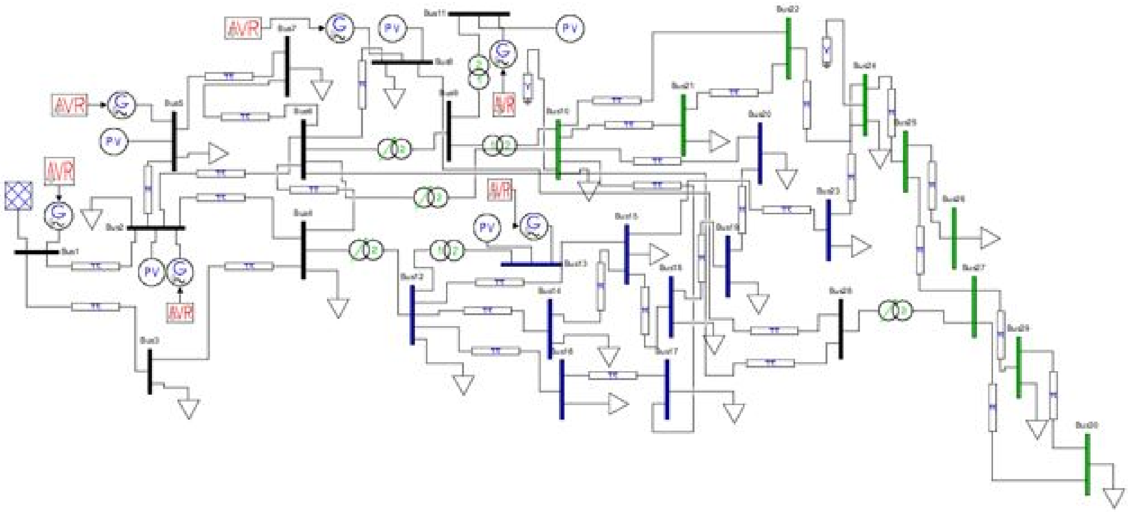


Figure 5.51: Dynamic Model: IEEE 30 Bus

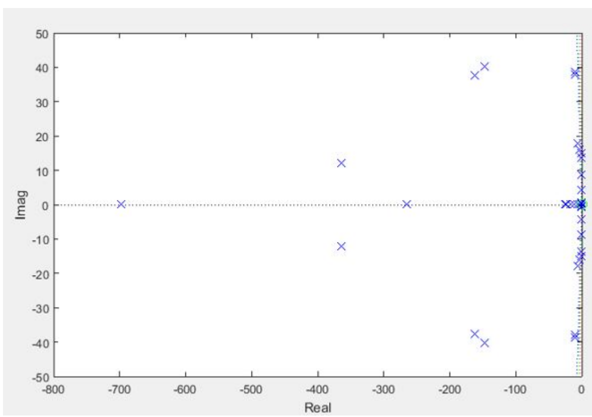


Figure 5.52: Eigenvalues in s-plane: IEEE 30 Bus

Dynamic order:	59
Buses	30
Posistive eigs:	0
Negative eigs:	58
Complex pairs:	20
Zero eigs:	1

Figure 5.53: Sign of Eigenvalues: IEEE 30 Bus

(a) Load Increase

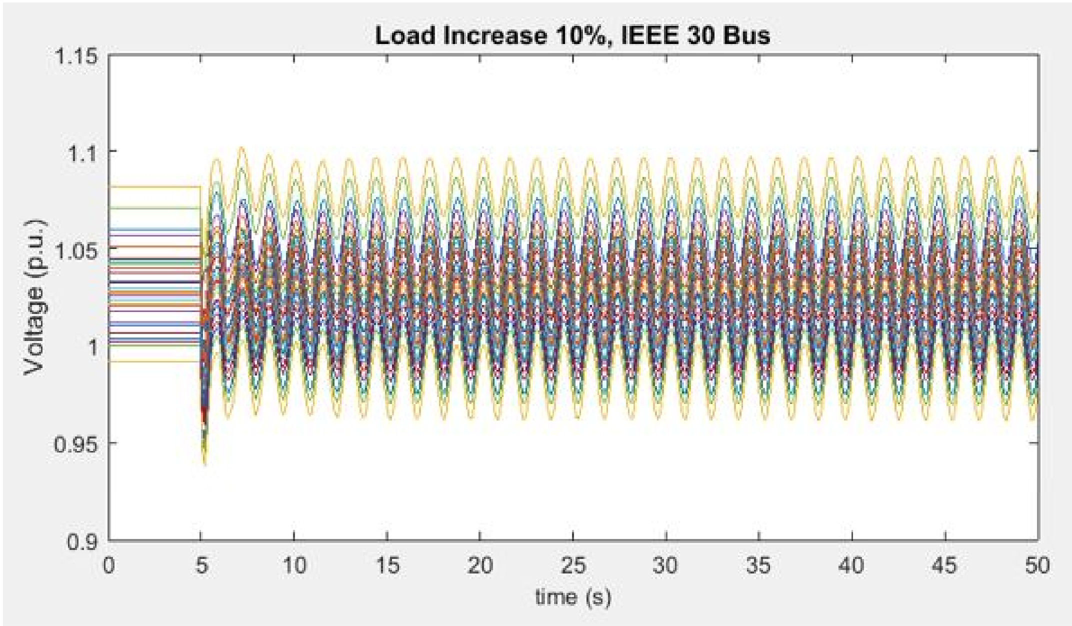


Figure 5.54: Load Increase 10% at t=5 s: IEEE 30 Bus

System becomes unstable for such a large disturbance despite being small-signal stable. So, perturbation is reduced.

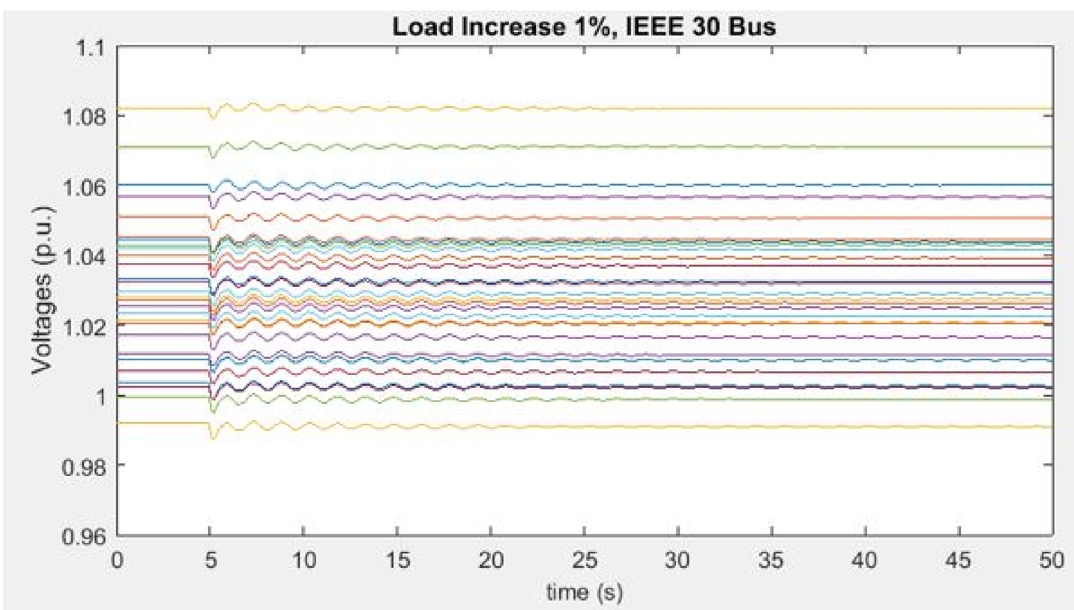


Figure 5.55: Load Increase 1% at t=5 s: IEEE 30 Bus

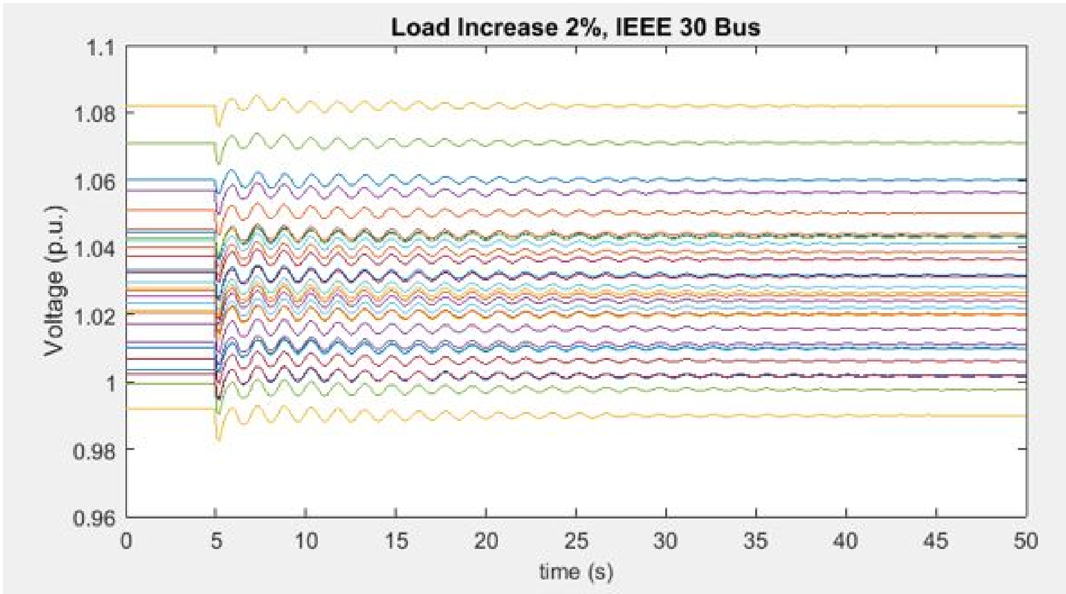


Figure 5.56: Load Increase 2% at t=5 s: IEEE 30 Bus

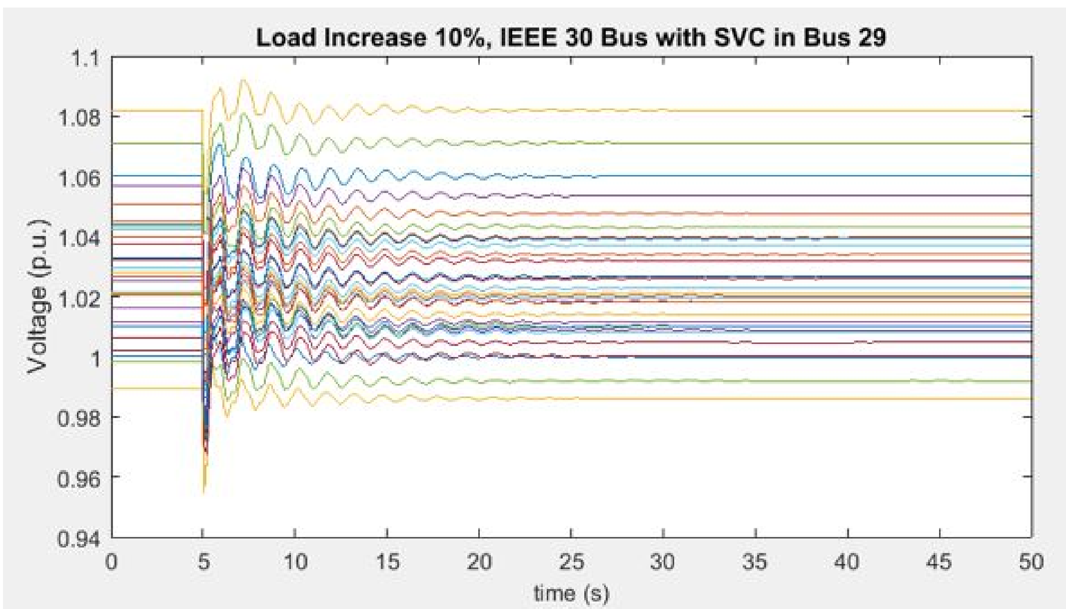


Figure 5.57: Load Increase 10% at t=5 s: IEEE 30 Bus with SVC

Addition of SVC improves stability so system can handle larger load changes.

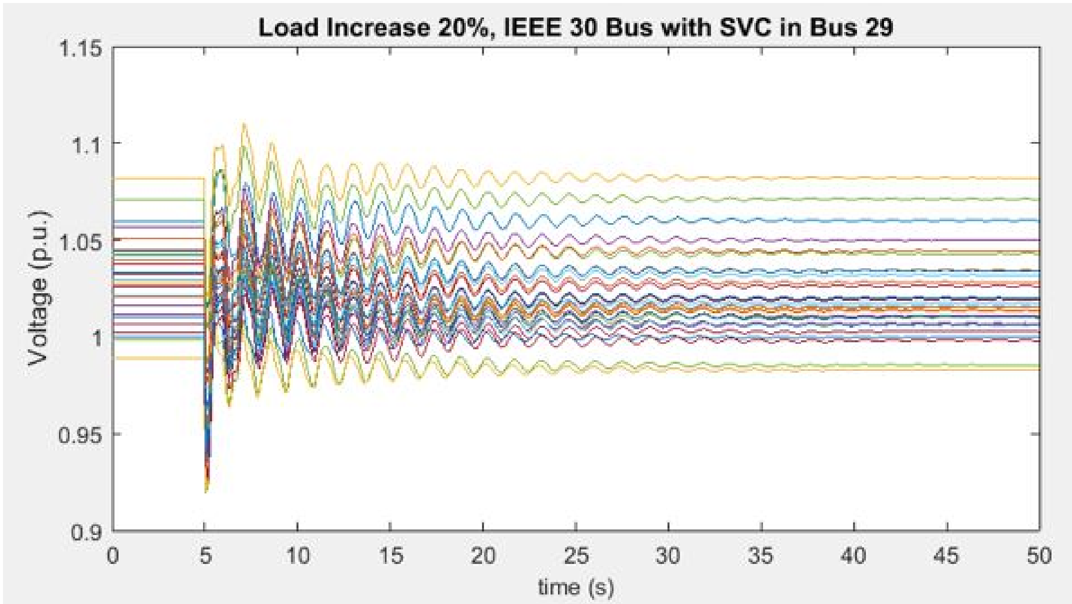


Figure 5.58: Load Increase 20% at t=5 s: IEEE 30 Bus with SVC

(b) Fault in Line 1-2

The system is unstable for this fault as it is too severe.

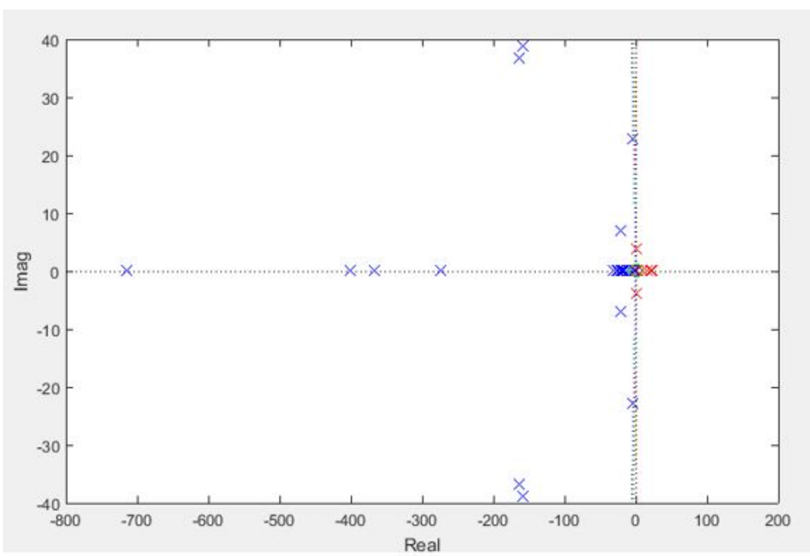


Figure 5.59: Eigenvalues in s-plane: IEEE 30 Bus

Dynamic order:	59
Buses	31
Posistive eigs:	11
Negative eigs:	47
Complex pairs:	5
Zero eigs:	1

Figure 5.60: Sign of Eigenvalues: IEEE 30 Bus

With SVC in Bus 29

Dynamic order:	59
Buses	31
Posistive eigs:	11
Negative eigs:	47
Complex pairs:	5
Zero eigs:	1

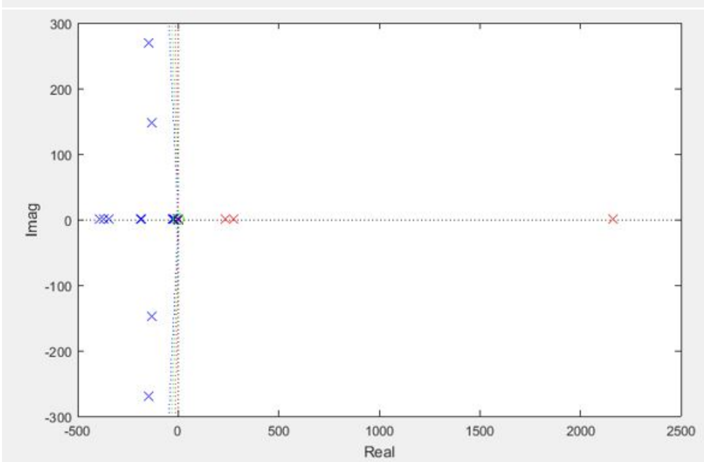


Figure 5.61: Eigenvalues: IEEE 30 Bus with SVC

The number of positive eigenvalues has not dropped so the system is still unstable.

Chapter 6

Conclusion and Discussion

In this research work, the main objective is to assess the security and the optimal placement of FACTS devices using several IEEE bus test cases. We initially relied on continuation power flow to rank contingencies in order of their severity in terms of the voltage values. The most severe cases were simulated using power flow and the weak buses were identified. Using fast-decoupled load flow the power based performance index was calculated and ranked to find the most severe contingencies in terms of line power flow. The same was done at 120percent loading to show the extent to which the severity of the contingencies are influenced with a change of loading.

Relying only on power flow solutions we determined how many SVCs and TCSCs would be required at minimum to fulfil the given security constraints: line power limits and voltages within the range $0.95<V<1.05$. However, this only narrowed down the placement regions as power flow is only a subset of the optimal power flow. Next, optimal power flow was performed for each severe contingency. This was done to show the necessity of FACTS placement and also to determine which of the FACTS device placements found from the power flow solution is actually necessary.

For example, for IEEE 30 Bus it was found that 3 SVCs were required at bus 25, 29 and 30 according to the power flow solution. Optimal power flow without any SVCs showed that the most severe contingency in terms of bus voltages gave a diverging solution. This proves that at least one SVC is required in the bus system to be N-1 secure. Out of the 3 SVC placements only 1 was required at bus 29 for the system to be N-1 secure. If the SVC were placed at bus 30 or 25 instead we would end up needing 2 SVCs. The reason that we did not simply add the SVC to the weak bus using CPF is seen for the IEEE 30 bus. The weak bus was bus 30 but because bus 29 was connected to both bus 25 and 30 it was a more ideal location to place the SVC. The SVC improves the voltage profile for all neighboring buses.

Next, we checked the small signal stability of the system and gauged the response of the system under disturbances such as load increase and line fault to see how the system were to respond to such disturbances and contingencies in real time.

The choice of SVC over STATCOM was done due to the more widespread usage of SVC and also the availability of the cost function. However, STATCOM shows much better response in terms of stability. In time domain, the oscillations show much stronger damping with STATCOM.

Chapter 7

Future Scope

Based on this work further investigations can be extended:

- Using UPFC instead for improvement of both voltage and line flow profiles simultaneously instead of considering them separately as we have done.

- Using Power System Stabilizers (PSS) for further improvement in stability.

- Integrating renewable energy into the systems to take the advantage of the placement of FACTS devices.

- Taking the algorithmic approach, as is being done, in order to find the optimal placement and sizing of FACTS devices and PSS.

- Investigate the effect of multiple outages.

- Investigating the security response to real-time changes in system conditions throughout normal operation in terms of predicting severe contingencies and ensuring secure dispatch.

Chapter 8

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Appendix A
Cost Functions for Optimal Power Flow

IEEE 5 Bus [22]

Bus No.	a ($/MW^2 h)	b ($/MW h)	c ($/h)	Pmin (MW)	Pmax (MW)
1	0.004	3.4	60	10	200
2	0.004	3.4	60	10	200

WSCC 9 Bus

Bus No.	a ($/MW^2 h)	b ($/MW h)	c ($/h)	Pmin (MW)	Pmax (MW)
1	0.004	3.4	60	10	200
2	0.004	3.4	60	10	200
3	0.004	3.4	60	10	200

IEEE 14 Bus [29]

Bus No.	a ($/MW^2 h)	b ($/MW h)	c ($/h)	Pmin (MW)	Pmax (MW)
1	0.00375	2.00	95	50	500
2	0.01750	1.75	30	20	200
3	0.06250	1.00	45	20	300
6	0.00834	3.25	55	20	150
8	0.02500	3.00	65	20	200

IEEE 30 Bus [30-31]

Bus No.	a ($/MW^2 h)	b ($/MW h)	c ($/h)	Pmin (MW)	Pmax (MW)
1	0.00375	2.00	0	50	200
2	0.01750	1.75	0	20	80
5	0.06250	1.00	0	15	50
8	0.00834	3.25	0	10	35
11	0.02500	3.00	0	10	30
13	0.02500	3.00	0	12	40

SVC and TCSC [32]

$$C_{SVC} = 0.0003s^2 - 0.3051s + 127.38(US\$/KVAR) \tag{A.1}$$

$$C_{TCSC} = 0.0015s^2 - 0.713s + 153.75(US\$/KVAR) \tag{A.2}$$

where, s is the range of operation in MVAR and the operating lifetime of the device is assumed to be 3 years.