Application of FACTS Devices in Transmission Networks under Demand Uncertainty for Performance Improvement

Muhammad Ammar Hafeez
01-244202-011

A thesis submitted in fulfilment of
requirements for the award of degree of
Masters of Sciences in Electrical Engineering

Department of Electrical Engineering

BAHRIA UNIVERSITY ISLAMABAD

AUGUST 2022

Approval of Examination

Scholar Name: Muhammad Ammar Hafeez
Registration Number: 01-244202-011
Program of Study: MS (EE)
Thesis Title: Application of FACTS Devices in Transmission Networks under Demand Uncertainty for Performance Improvement

It is to certify that the above scholar's thesis has been completed to my satisfaction and, to my belief, its standard is appropriate for submission for examination. I have also conducted plagiarism test of this thesis using HEC prescribed software and found similarity index ___ that is within the permissible limit set by the HEC for the MS degree thesis. I have also found the thesis in a format recognized by the BU for the MS thesis.

Principal Supervisor Signature: ____________________
Date: _______ August 2022
Principal Supervisor Name: Dr. ASAD WAQAR

Author's Declaration

I, **Muhammad Ammar Hafeez,** hereby state that MS thesis titled "**Application of FACTS Devices in Transmission Networks under Demand Uncertainty for Performance Improvement**" is totally my own work and has not been submitted previously by me for taking any degree from Bahria University or anywhere else in the country/world. At any time if my statement is found to be incorrect even after my graduation, the University has full right to cancel my research work and withdraw my degree.

Name of Scholar: Muhammad Ammar Hafeez
Date: ____________________

Plagiarism Undertaking

I, Muhammad Ammar Hafeez, Registration No. 01-244202-011, a student of MS (EE), solemnly declare that research work presented in the dissertation titled "**Application of FACTS Devices in Transmission Networks under Demand Uncertainty for Performance Improvement**" is solely my research work with no significant contribution from any other person. Minor contribution or help wherever taken in this research work has been duly acknowledged and that complete thesis has been written by me. I completely understand and respect the zero-tolerance policy of HEC and Bahria University towards plagiarism. Therefore, I as an author of the above titled thesis declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred / cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled thesis even after award of MS degree, the university reserves the right to withdraw / revoke my MS degree and that HEC and the University has the right to publish my name on the HEC / University website on which names of scholars are placed who submitted plagiarized thesis.

Scholar/ Author's Sign: _________________

Name of Scholar: Muhammad Ammar Hafeez

Dedication

This Thesis is dedicated to my Parents, Spouse and Teachers
For their support, endless love and encouragement.

ACKNOWLEDGEMENT

All the acclimations and gratitude is for Allah Almighty, the compassionate and benevolent who knows better the mysteries and the secrets of the universe and His Holy Prophet (S.A.W) whose teachings serve as a inspiration for humanity in the hours of despair and darkness.

I would like to present my warmest thanks to the Head of Department (EE) Dr. Junaid Imtiaz and my dear supervisor Dr. Asad Waqar, who encouraged and made me able to complete this research work. Their valuable guidance carried me through all the stages of writing my thesis. I would also like to thank all my thesis committee members who encouraged me throughout the research journey and letting my defense enjoyable moment, and for your brilliant comments and suggestions.

My Mother and father, who are always praying for my success. Without their guidance this was not possible for me to reach at this stage, my wife and my sister who supported me morally and my two little champs – Musfirah Ammar (My Daughter) and Muhammad Rayyan (My Son) whose smile brings an eminent energy in myself.

I would also like to thank National Transmission and Dispatch Company, Chief Engineer, Project Director and other colleagues who were a source of continuous help, support and suggestions. Special thanks to my colleague and friend Mr. Salman Shakeel, who continuously guided me during the research and simulation work.

Abstract

The Transmission System is the backbone of the power utility of a country which contributes to the provision of uninterrupted power supply to the consumers. The power dispersal is the primary role of the transmission system which is operating at high voltages to avoid losses. The conventional method of strengthening the transmission system is to build more transmission lines to ensure reliability, redundancy and at least N-1 contingency. However, due to the growing population, the new constructions have several limitations, therefore utilization of the existing transmission system up to the maximum possible extent is of prime importance.

To ensure the utilization of existing system, FACTS devices play a pivotal role. These not only enhance the power transfer capability but also increase the performance of transmission line. Moreover, by managing the impedance factor of the FACTS devices, the power can be controlled to flow in a certain direction.

In the current study, cases are developed to study the effect of installation of Static VAR Compensators (SVC) and Series Compensation (Fixed). For the study, IEEE systems of 14 and 39 Bus are utilized.

Contingency analysis is performed to calculate the performance parameter (PP) during contingency of transmission line tripping. Performance parameter is summation of Number of overloaded transmission lines and Number of buses underwent voltage violation when transmission lines are tripped. Based on the value of PP, the ranking is done regarding the severity of effects whenever contingency occurred, and line is tripped.

FACTS devices (SVC and Series Compensators) are installed at weak buses present in the system and then load flow analysis using Power System Simulator for Engineering (PSSE) has be carried out. The results would be compared with the scenario when FACTS are not installed. This would be applied to two standard systems of IEEE of sufficient sizes and in the end chunk of transmission system of Pakistan would be studied and remedies would be proposed if time permits.

Table of Contents

Chapter 1

Chapter 2

Chapter 5

List of Tables

List of Figures

List of Abbreviations

FACTS	Flexible Alternating Current Transmission Systems
PSS/E	Power System Simulator for Engineering
IEEE	Institute of Electrical & Electronics Engineering
SVC	Static VAR Compensator
VI-PFC	Variable Impedance Power Flow Control
CCT	Critical Clearing Time
TCR	Thyristor Controlled Reactor
STATCOM	Static Synchronous Compensator
UPFC	Unified Power Flow Controlled
IPC	Interphase Power Flow Controller
TCSC	Thyristor Controlled Series Capacitor
SSSC	Static Synchronous Series Compensator
EHV	Extra High Voltage
SLD	Single Line Diagram
NEPRA	National Electric Power Regulatory Authority
NTDC	National Transmission & Despatch Company
PESCO	Peshawar Electric Supply Company

CHAPTER 1

INTRODUCTION

1.1 Background

The Transmission System is the backbone of the power utility of a country which contributes to the provision of uninterrupted power supply to the consumers. The power dispersal is the primary role of the transmission system which is operating at high voltages to avoid losses. The conventional method of strengthening the transmission system is to build more transmission lines to ensure reliability, redundancy and at least N-1 contingency. However, due to the growing population, the new constructions have several limitations, therefore utilization of the existing transmission system up to the maximum possible extent is of prime importance.

To ensure the utilization of existing system, FACTS devices play a pivotal role. These not only enhance the power transfer capability but also increase the performance of transmission line. Moreover, by managing the impedance factor of the FACTS devices, the power can be controlled to flow in a certain direction.

In the current study, the FACTS devices would be allocated to the weak buses present in the system and then load flow analysis using Power System Simulator for Engineering (PSS/E) would be carried out. The results would be compared with the scenario when FACTS are not installed. This would be applied to two standard systems of IEEE of sufficient sizes and in the end chunk of transmission system of Pakistan would be studied and remedies would be proposed if time permits.

1.2 Motivation

The integration of renewable energy resources power electronic devices at grid level causes a lot of disturbances which result in voltage instability [21]. There are many causes of voltage instability which include configuration of power system, pattern of generation and load. [22-26].

To stabilize the system, reactive power sources are added in the system. Shunt capacitors or Flexible AC Transmission system devices can be used to address these issues. A lot of research is being done on FACTS devices as it can improve the stability of the system. It can also improves the maximum power transfer capability and Total Harmonic distortion (THD) [27]. In the present study, Static VAR Compensators and Series Compensation will be installed in the system and the impact will be studied. The simulations are done on IEEE 14, IEEE 39 and IEEE 118 bus system. Voltage violation and overload percentage with and without installation of Compensation devices stated above are observed on different buses in the system.

1.3 Problem Statement

The construction of new transmission infrastructure to strengthen the existing transmission network is constrained due to Right of way problems, hence the existing transmission lines should be utilized to the best possible extent. The power flow could be controlled/enhanced using the installation of FACTS devices.

Table 1.1: Problem Statement

Element	**Description**
The problem of …	The reduced Power Transmission/Dispersal Capacity due to Ferranti Effect, Low/Over Voltage issues etc.
Affects…	Low Voltage due to Transmission Overloading, Over voltage due to the Ferranti effect, decrease in active power flow due to increase in reactive loading.
And result in…	Instability of power system and decrease in power dispersal capacity of Transmission Network.
Benefits of solution…	In the present research, the issues will be pointed out in respect of low dispersal of power & low voltages and remedies would be suggested to not only increase the power transmission capability but also control the flow of power in transmission line by using FACTS.

1.4 Objectives & Significance

- The research will highlight the issues in transmission system which bar the full utilization of the infrastructure and solution will be proposed to enhance the utilization of the system.
- FACTS devices will be proposed and their working to enhance the controllability of power flow in transmission line would be studied besides the improvement of performance during the varying load conditions.
- The study will be applied to real system to find solution of the problem faced in Pakistan. Thus the study will also be beneficial with respect to regional application keeping in view the recent power blackouts in the country.

1.5 Thesis Contribution

In pursuit of aforementioned objectives, the following contributions have been made in the research:

- The location for installation of compensation is found using contingency analysis on 14, 39 and 118 bus IEEE power systems.
- A comparison is built for the cases with and without compensation i.e., installation of SVC both in steady state and dynamic state during the fault condition.
- The effect of installation of FACTS device was studied on the stability of the nearby buses and lines during the fault on bus and it was concluded that the system remained stable in fault conditions after installation of FACTS device.
- The improvements of installation of the FACTS device have been represented using the steady state load flow exhibits and dynamic simulation on PSS/E.

1.6 Thesis Organization

The thesis document is organized in a way given below:

- A comprehensive literature review has been done in chapter 2 in which background of FACTS devices is given. The models and types are discussed and problems faced in the power system are identified.
- In chapter 3, the proposed approach to include the compensation in the system has been discussed and explained. Moreover, the introduction of the software used i.e., Power System Simulator for Engineering (PSS/E) has been given.
- In chapter 4, simulations and results are discussed. The simulations were performed on IEEE system of 14, 39 and 118 buses. Moreover, the comparison of the results is also shown before and after installation of FACTS device.
- At the end, conclusion based on the research findings and future recommendations/work are included in chapter 5**.**

CHAPTER 2

LITERATURE REVIEW

2.1 Background

The power system in a country is driven by transmission system operator who is responsible for secure and efficient operation. Due to the growth of industrial sector worldwide, the consumption of electricity has increased manifold. For providing the electricity to consumers, transmission system of the country is very important as generation is done in remote areas while load is located in far off cities [1].

There are various threats to the power system which can cause blackouts [2]. The transmission network has different constraints in supplying the desired power to the consumers which include line impedance, thermal capacity, etc. One important issue is system overloading [3]. Due to excessive overloading, the protection mechanism may operate to trip the transmission line and flow of power is disturbed.

Overloading of transmission system is mainly due to increased load demand and low investment in new construction of utilities, transmission system constraints have rapidly increased which have severe economic impact [4]. Uncontrolled 'loop flow' in ring connected power system causes congestion and reliability problems. Loop flows in a transmission system impact the full utilization transmission lines infrastructure, limiting power transfer capacity [5].

Power grid failure has been experienced by all the major countries due to such transmission and distribution issues. Analysis of electrical networks of different countries in [6] has helped in identification of different problems which include maximum frequency deviation, critical clearing time (CCT) and minimum voltage recovery period. [7]

To study the issues, power flow analysis is used. It is also used to plan the desired expansion of generation and transmission infrastructure. Load Flow studies ensures optimal performance and also help in maintaining safety standards [8].

2.2 Voltage Stability

P. Kundur in [9] has defined Voltage stability as the ability of power system to ensure a constant voltage level within tolerable limits, both in normal and contingency conditions. Under normal conditions, a power grid should maintain its steady state and in case of outage or disturbance, system shall return to its steady state in least possible time. Stability Issues may cause collapse if necessary steps are not taken to reinstate the system to its normal state.

As per [10], when voltage decreases gradually due to disturbances, the network comes under instability mode. Voltage instability usually occurs in case of fault, sudden load increase, and inappropriate protection switching etc. on a generator or a power line [11]. It can also be present due to uncontrolled VAR demand and supply [12].

If the instability is not resolved, it will ultimately result in voltage collapse and system blackout. This is a threat to power system security and therefore cause hindrance in achieving the objective of ensuring a continuous and consistent supply of power to consumers [13]. The collapse normally occurs when the system is heavily burdened. The decrease in voltage is gradual at start but the decline in voltage profile become steeper leading to collapse [14].

Voltage stability has resulted in several blackouts in many countries. Particularly in 2003, 6 major blackouts occurred affecting the US, Britain, Sweden, Denmark and Italy. There is due to continuous rise in power demand, which can increase exceptionally in future with the establishment of electrical vehicles [15].

Voltage Stability analysis is done Voltage Stability Indices (VSI) which are numerical levels that can be observed while system parameters vary. These indices can be used to know the proximity of system collapse due to voltage instability. The L- index is used to describe the stability of system [15]. It uses load flow values that incorporates both load side parameters and and generator control characteristics [16]. Based on the results, the weak areas can be identified and solutions can be proposed accordingly [17].

The popular solutions to the congestion and stability problems include network reconfiguration, which is also known as topology control (TC). Other solution are transmission switching (TS) [18] and utilization of flexible AC transmission system (FACTS) [19]. These solutions can reduce network overloading, warrant reliable and robust operation of power system [20].

2.3 Constraints in Upgradation of Transmission Infrastructure

It has been suggested in [21] that by upgrading transmission infrastructure, the power system stability can be increased. However, presently new lines are not easy to be constructed due to right of ways issues. The construction may also provoke environment and safety issues. Many residents feel that the transmission line has negative effects on their health and safety, property values and aesthetics.

Therefore, the existing system should be utilized efficiently by installing compensation mechanism which means to regulate the existing lines [3]. The sending/receiving side voltages can be held constant for every load by using passive elements like capacitors, inductors etc.

Moreover, the uncertain power demand, fuel prices, renewable energy supply, etc., also inhibit the additional investments in transmission reinforcement including construction and rehabilitation [19]. The increasing use of renewable energy make the system more stressed due to their dynamic behavior. Moreover, with the increase in cross-border/regional trades, the situation has further worsened. [15]

Thus, a more flexible solution which has incremental investments is required to protect the system such that it can be proficiently operated with bulk amounts of unpredictable renewable power/energy [19].

2.4 Flexible AC Transmission System (FACTS) Devices

N.G. Hingorani in 1988 had introduced FACTS Devices. It is a HVAC semiconductor device which has the potential to manage different factors including voltage, phase angle, reactance, current, etc. [16]

Flexible AC transmission systems (FACTS) have ability to maneuver power flow in transmission network to improve system utilization, limit loop power flows and avoid congestion and. FACTS devices control power flows on ac systems through large power converters (10–300 MW) [22]. However, due to exorbitant costs, the use of FACTS is restricted.

Due to techno-economic benefits, the interest in FACTS devices has yielded significant technological developments. Several kinds of FACTS devices have been installed worldwide. The most popular as per [23] are: load tap changers, Series/Shunt VAR compensators, phase-angle regulators [24], UPFC, etc. Author of [23] has listed following main objectives of FACTS:

- Regulate the flow of power in the power system.
- Operate transmission lines near to their thermal capacity.
- Avoidance of series/cascaded tripping of transmission lines and avoiding blackouts.
- Damping of oscillations to stabilize the system.

Following roles of FACTS devices have also been listed in [25]:

Table 2.1: Comparison of Different FACTS Devices

Operating Problems	**Corrective Action**	**FACTS Type**
Voltage Limits		
Low Voltage at Peak Load	Provide VARs	SVC, STATCOM
High Voltage at Small Load	Absorb VARs	SVC, STATCOM, TCR
High Voltage due to tripping	Absorb VARs and manage loading	STATCOM, TCR, SVC
Low Voltage due to tripping	Provide VARs and manage loading	SVC, STATCOM
Thermal Limits		
Transmission Line overloading	Minimize Loading	SSSC, IPC, TCSC, UPFC
Fault on parallel Lines	Minimize Loading	SSSC, IPC, TCSC, UPFC
Loop Flows		
Load division in parallel circuits	Change series impedance	UPFC, SSSC, TCSC, IPC
Post-fault power flow distribution	Readjust network	SSSC, UPFC, IPC, TCSC
Reverse Power Flow	Regulate phase angle	UPFC, IPC, SSSC

2.4.1 Static VAR Compensators

It is a recognized principle to utilize reactive power compensation for controlling the voltage at a certain bus in an electrical power system. For the purpose, synchronous condensers and switched capacitors and inductors were used to control the system voltage [49]. After 1960, thyristor controlled reactors (TCR) along with fixed capacitors (FC) or thyristor switched capacitors (TSC) were utilized to inject or absorb reactive power.

In power systems, the control of voltage in bus network and power oscillation damping is a unique challenge. To smoothly run the power system having generation, transmission & distribution system, economically and reliably, the researchers are always looking for new control techniques. [52,53] The basic issues to be addressed are below:

- increasing power transmission capability
- improving transient stabilities
- damping of oscillations
- maintaining system voltage

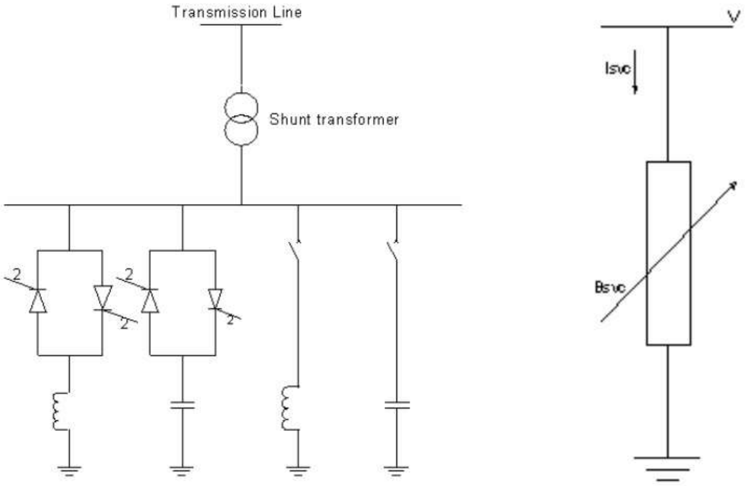
Unlike traditionally used shunt devices for reactive compensation, an SVC i.e., Static VAR Compensator is capable of smoothly compensating reactive power in a system by adjusting the firing angles of thyristors [48]. Its most important application in distribution system is to balance the abrupt reactive power changes due to the various equipment/loads. [51]. In addition to the system balancing ability, SVC can be used for power factor correction which can reduce losses and improve system security

It contain standard fixed shunt elements (reactors, capacitors), The fundamental circuit configurations for SVC systems can be divided into two categories [48]:

- Fixed capacitors and thyristor controlled reactors (FC/TCR types)
- Thyristor-switched capacitors and thyristor-controlled reactors (TSC/TCR types)

The combination enables the power system operator to set any desired operating point over a VAR range within the capacitive and inductive limits.

In [49,50], following model of Static VAR Compensator has been listed. SVC is built using reactors and capacitors, controlled by thyristor switches. It is connected in shunt with the transmission line through a shunt transformer [51]. The model is shown in the figure given below:



Functional diagram of SVC *Equivalent circuit of SVC*

Figure 1.

The model takes SVC as variable susceptance connected in Shunt, B_{SVC} which is adjusted automatically to achieve the desired voltage control. The resultant susceptance B_{eq} is determined by the thyristor's firing angle α [54]:

$$B_{eq} = B_L(\alpha) + B_c$$

where

$$B_L(\alpha) \;=\; -\frac{1}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin(2\alpha)}{\pi}\right), \quad B_c = \omega C \;\text{ and }\; 0^0 \le \alpha \le 90^0$$

If the real power consumed by the SVC is assumed to be zero, then:

$$P_{SVC} = 0$$
$$Q_{SVC} = -V^2 B_{SVC}$$

where *V* is the bus voltage magnitude.

With the changes in reactive power demand, susceptance is varied keeping in view the limits for optimum supply of reactive power. Equation states that reactive power is a proportional to square of bus voltage [53]. The low voltage result in decreased reactive power.

Most power flow simulations do not include a specific static VAR compensator model. These SVC devices are normally modeled as a conventional PV (generator) with certain reactive power limits [55].

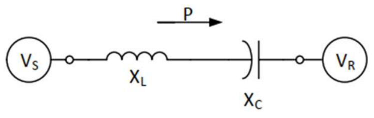
2.4.2 Series Compensation

A Series compensation has been known for resolution of several issues related to power system [56] such as:

- Improvement in dynamic system performance in normal as well as contingency condition by decreasing angle difference between generators;
- Providing reactive power in transmission lines to regulate system;
- Enhancing controllability of power between adjacent and parallel transmission lines by changing impedances/reactance.
- Damping of oscillations.

By solving the above issues with solutions requiring less capital cost such as series compensation, the capacity of existing transmission infrastructure can be increased. This will minimize the need for new transmission infrastructure and hence major investment is saved [57]. This also yield better risk management while preserving the right of ways and corridors for future needs. Moreover, overall asset utilization increases and losses are decreased. In addition to above, Series compensation also improves system reliability without any additional burden on consumers.

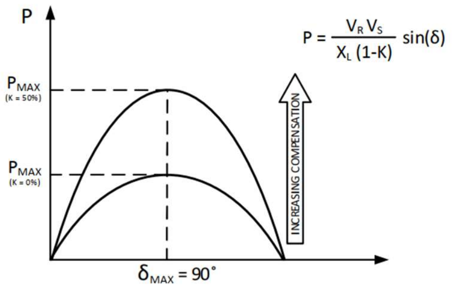
The power transfer equation, used to account for series capacitance, X_C, shows that level of compensation, K, increases the power transfer for a given angle δ. It is due to fact that capacitive impedance is negative with respect to inductive reactance which results in low overall impedance of the line [58]. The equation and a simplified network representation are shown in Figure 2-1 for illustrative purposes.



$$P_R = \frac{V_R V_S}{X_L - X_C} \sin\delta = \frac{V_R V_S}{X_L(1-K)} \sin\delta$$

Figure 2-1 - Power transfer equation

The effect of adding series compensation is shown in Figure given below where for a same angle δ_{MAX}, the maximum power transfer, P_{MAX}, doubles when compensation level, K, reaches 50%. [58]

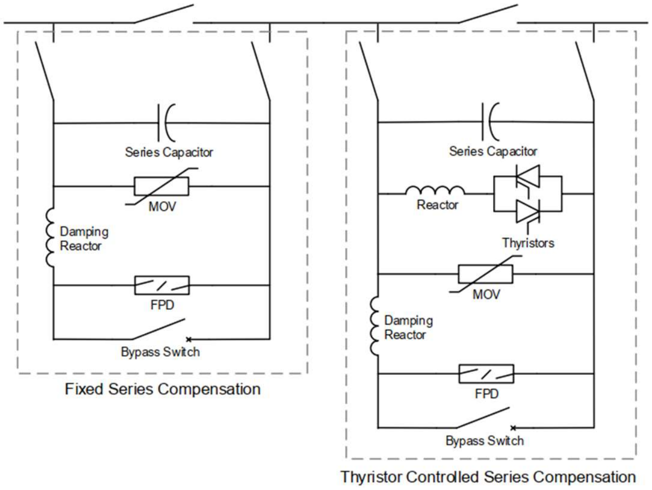


$$P_{max} = \frac{V_R V_S}{X_L - X_C} = \frac{V_R V_S}{X_L(1-K)}$$

Voltage stability is also improved due to the self-regulation by series compensators. In contract with shunt reactive devices where output is inversely proportional to inverse square of the voltage change, the power output of series elements increases with the square of the current [57].

The maximum power transfer from transmission line is increased due to the increased availability of reactive power which support bus voltage as power flow increases. It also means that sudden load variations due to nearby loads or generators switching on or off will have better regulation.

Following models of the Series compensation are developed [56]:



Fixed Series Compensation

Thyristor Controlled Series Compensation

A fixed series compensation consists of parallel arrangement of capacitors, protection devices and a bypass switch [56]. The bypass switch is normally in the open position and can be used to switch the series capacitor in or out of power system. It also bypass the series capacitor if the fault is not cleared within a certain time.

Series compensation partially compensates for the inductive reactance of transmission line and results in increased power transfer ability and system stability. Compensation levels typically range from 20% to 80% [56]. Consequently, the reactance due to the series capacitor (X_C) will always be less than the inductive reactance of the transmission line (X_L). [58]

Series compensation can be installed in the middle of a transmission line or either ends. For the most effective results, the optimal location for series capacitive compensation is at the mid of transmission line. [59].

2.4.3 Distributed Flexible AC Transmission System (D-FACTS) Devices

A device named D-FACTS was introduced based on distributed static series compensator (DSSC), which fastens directly to transmission conductors and hence no High Voltage insulation is required. These devices are distributed on transmission line to accomplish desired power flow control by managing the line impedance. [5]

Distributed static series compensator (DSSC) uses multiple single-phase low powered inverters that attach to the transmission line and manage the impedance of the transmission line dynamically. This arrangement allows the control of active power flow in the transmission line [26]. In addition, the DSSC device contain a single turn transformer (STT) that is physically clamped to the conductor. The conductor serves as secondary winding for STT, which can directly inject the desired voltage. The line induction is responsible to power the inverter as it injects orthogonal voltage to the line current. [5]

The system is low cost and overcomes some of restrictions of FACTS devices, and is a new approach to attain power flow control.

2.4.4 Modular Flexible AC Transmission System (M-FACTS) Devices

A new technique i.e., modular FACTS (M-FACTS) has been developed which is based on SSSC to deal with uncertainty in power system. These devices introduce a leading/lagging voltage perpendicular to the line current, which function as a series capacitor/reactor [19]. The elements added in series have highest impact to control the power flow on transmission lines [5].

These devices thus can elevate or lower the reactance and hence impedance of a line, thereby manage power through push/pull from/to the circuit on which it is installed. These devices are also known as variable impedance power flow control (VI-PFC) devices. [19]

VI-PFC can be used to control the power flow in the parallel paths in transmission network, which can in turn provide relief to transmission system. The method can be used both in normal and contingency conditions during overloading. It can most importantly increase or decrease impedance of transmission line and hence making it best suited as compared to fixed series reactors or capacitors. Multiple VI-PFC devices can be deployed in power system to resolve overloading issues [3].

2.5 Demand Uncertainty in Power System

The power system of today’s world is interconnected and forms a ring network and supply’s variety of loads to meet the consumer’s demands [33]. The load demand, of course, vary constantly based upon the requirements which leads to the variable loading of the system. These variations have certain undesirable effects, the most considerable of which are given below:

2.5.1 Generation becomes Costly

Generators give maximum efficiency at (or very close to) their rated capacity. Hence, when the load varies and becomes low, the generator will not be loaded up to its rated capacity and hence its working efficiency is reduced which results in increased cost of production.

2.5.2 Difficulty in system control

In sudden load variation, the frequency of the system varies. For proper operation, the frequency must be within the permissible limits for which additional control equipment are required which increase the cost. These include speed governors, voltage and frequency sensors, microcontrollers and other closed loop control equipment. Moreover, in case of additional load, the equipment can become overloaded as well which may result in tripping of transmission lines and grid equipment.

2.5.3 Increased Losses

Due to variation in loading conditions, various machines like transformers, electronic devices and other machines show increased losses due to magnetization characteristics, saturation and variation in parameters. This decreases the overall efficiency of the system.

The point 2.5.2 suggest that there should be a mechanism which can somehow compensate for the additional or decreased load demand and adjust its behavior to protect the power system from collapse. This can be done using the FACTS devices.

2.6 Work by Other Authors

From literature review, it is learnt that the research area has been chosen by many authors for finding the solution to the power transmission system congestions. Different authors have proposed different approaches to identify potential risk and their probable solutions. Some of these highly relevant works are discussed below:

Table 2.2: Work By Other Authors

Author	Research Work
Gogoi, K., & Chatterjee, S.	The constraints of transmission system are discussed in [6] including extreme frequency deviation, and the critical clearing time (CCT) and least voltage recovery period. Dynamic Simulation of Western Indian Grid is carried out and weak buses are identified using L-index algorithm. However, after determining the stability issues, steps to avoid breakdown and remedies are not provided. This can be done using FACTS implementation.
Gogoi, K., & Chatterjee, S.	Load flow study of Eastern region of India is carried out on PSSE in [7] and buses prone to Voltage collapse are identified. However, Remedial measures are not suggested and only analysis of the system is made. How the system can be improved is to be determined.
A. Soroudi	In the research work [3], demand uncertainty is considered and focus has been made to utilize the existing transmission infrastructure to meet consumer needs. The performance and controllability can be enhanced by using Modular FACTS. However, M-FACTS require at least one parallel path in order to push/pull power. The devices installed on various lines shall act in a coordinated manner. Moreover, the study is applied to IEEE systems and impact on actual power system are not discussed.
Divan, D., Brumsickle, et al	A low cost solution of Distributed FACTS has been presented in [5]. D-FACTS attach directly to EHV Line and are inexpensive and do not require HV insulation. These are numerous single phase low-powered inverters that clip on T/Line to dynamically control impedance and hence power flow. In the above scenario, The requirement to increase the impedance by small value requires multiple D-FACTS and to operate them in a coordinated manner requires extensive algorithm due to large number of devices when the power system of whole country is considered.

Table 2.2: Work By Other Authors	
Author	**Research Work**
Samuel, I. A., Katende, J., et al.	The paper [11] discusses the voltage instability issues of the power system, as these are responsible for system collapse. Novel Line Stability Index forecasts voltage collapse and has proven to be more computationally efficient than previously developed indicators like LMN and FVSI. In the study, the weakest bus has been determined using index, but the remedies to improve system reliability are not applied.
Adebayo, I. G., Jimoh, et al	In the study [14], the reactive power flow is varied at particular load bus to determine optimal point. Fast Voltage Stability Index has conventionally been utilized to evaluate weak bus. However, inherent structural characteristic theory can detect critical bus most advantageously. The method of finding weak bus has been optimized, however, the proposal of enhancing the stability has not been presented in the study.
Reddy, K. V. R., Lalitha, et al.	The paper [16] discusses that Blackouts are the result of voltage instability. Stability is determined using L-index and weak bus is thus identified. System is studied by installing SVC and TSCS and also fault conditions are evaluated.. A small standard system is considered. Moreover, controlling power flow using FACTS is not studied in detail. Through VI-PFC we can change the power flow in the system.
Pourbabak, H., Nudell, et al	The author has stressed in [19] on type of modular FACT (based on SSSC) i.e., Variable Impedance Power Flow Control (VI-PFC). It has ability to dynamically raise or reduce the line reactance and managing system overloading. Dispatch Settings of VI-PFC work to reduce post-fault/trip overloading in Power system. The author has worked with fixed location and size of M-FACT. Moreover, coordinated working of two M-FACTS is also not considered. The study also uses IEEE 39 bus system and the results are not applied on real power system of an area.
Georgilakis, P. S., & Vernados, P. G.	The benefits of FACTS devices in transmission system operation is studied in [23] and various types of FACTS which include STATCOM, SVC, TCR, UPFC, IPC are discussed. No Simulation results have been presented on software tools neither any scenario based proofs have been provided. Only review of benefits is stated.

2.7 Novelty

Although the research discusses the subject that has been the center of interest for many authors for quite a long time and the work is also being done recently. However, the application of FACTS in power system with respect to controllability of power is to be studied in much detail in addition to performance & stability enhancement of the overall system with the help of a simulation software, specifically designed for analysis of power system. In present study, the Siemens' Power System Simulator for Engineering would be used.

The study will also be applied to the scenario of Pakistan and the impact will be studied in normal and under contingency scenario. It will also be helpful in addressing the cascaded outage issues in Pakistan. The study will be performed keeping in view the NEPRA Grid Code that is being followed in Pakistan.

CHAPTER 3

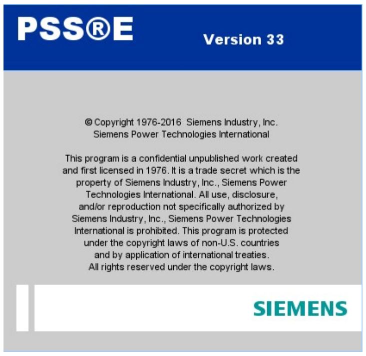
RESEARCH METHODOLOGY

3.1 Research Approach & Strategy

- Load Flow Studies are be carried out on IEEE networks of suitable size in Siemens Power System Simulator for Engineering (PSSE).
- The constraint/area where the compensation is required will be identified where the Grid Code Violations in respect of Voltage are present and where the system is prone to tripping due to excessive over/under loading.
- The effect of placement of FACTS Devices will be studied. The analysis would be carried out on before/after results, after Load Flow Study in PSSE.
- The Controllability of Power Flow using FACTS Devices installation is explored and studied that how flow of power can be altered from heavy loaded line to less loaded lines.
- The power system network of Pakistan has been studied and betterment is suggested.

3.2 Data Analysis Tool

Power System Simulation for Engineering (PSS/E) of SIEMENS will be utilized in the research. It is state of the art software for system studies of electrical power system in which both dynamic and steady state analysis can be carried out. The software is widely used by Electric Utilities operating in Pakistan including NTDC and other Distribution Companies.



© Copyright 1976-2016 Siemens Industry, Inc.
Siemens Power Technologies International

This program is a confidential unpublished work created and first licensed in 1976. It is a trade secret which is the property of Siemens Industry, Inc., Siemens Power Technologies International. All use, disclosure, and/or reproduction not specifically authorized by Siemens Industry, Inc., Siemens Power Technologies International is prohibited. This program is protected under the copyright laws of non-U.S. countries and by application of international treaties. All rights reserved under the copyright laws.

3.3 Contingency Analysis and Ranking

The Contingency analysis is being used to forecast the influence of a certain outage in the power system network such as tripping of equipment, generator, overhead transmission line, etc. [28].

Some of the critical contingencies will generate extreme circumstances in power systems. The method of identifying these dangerous contingencies is known to as contingency analysis and it can be obtained using the performance parameters for each transmission line of contingencies.

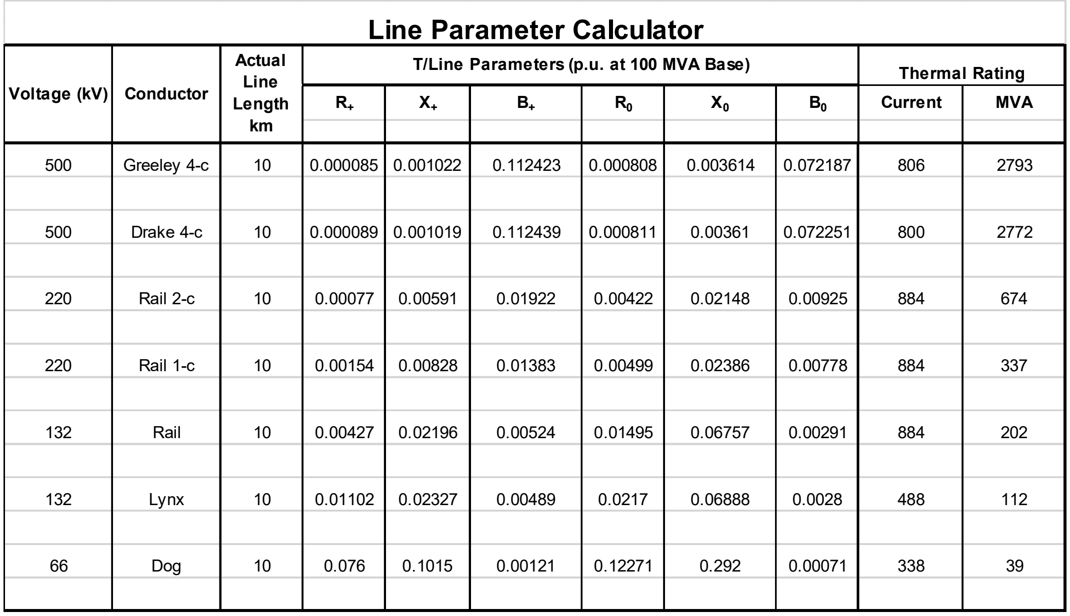
In the present study, we have considered single transmission line outage as "Performance Parameter" measurement. We identify the number of overloaded transmission lines (NOLL) and voltage violations on buses (NVVB) corresponding to each contingency.

Performance parameter = Number of Overloaded Transmission Line + Number of Voltage Violations recorded on Buses

As per the severity (NOLL + NVVB) for each case, we rank these transmission lines. After completing the contingency analysis for whole system and identifying the most critical area, compensation is applied in the form of FACTS device. The results have shown that installation of FACTS device on the location remove/reduce the overloadings and voltage violations while keeping the system stable in steady state and fault condition.

3.4 IEEE Bus Systems

The analysis is performed on IEEE bus system of 14, 39 and 118 buses. The system was constructed from available data of branches provided in [34-36]. MVA/Current ratings were not available and hence overloading on transmission line could not be studies. The conductor was then assumed to be rail conductor on 132kV line for 14 and 39 bus system and lynx conductor on 118 bus system. The R, X & B values were calculated from the sheet of data available with the power system planners in Pakistan [37]. The sheet for calculation of R, X, B values of the conductor is as follows:



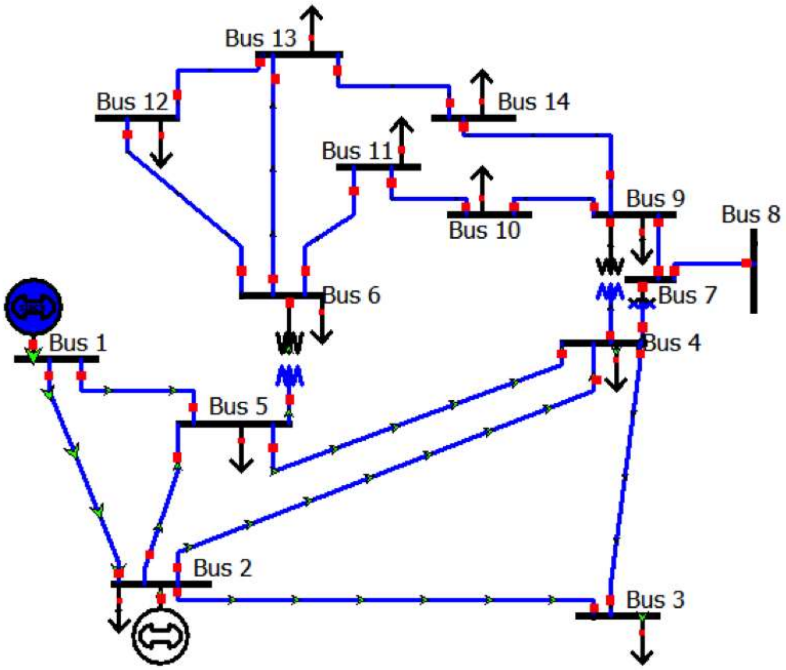
Line Parameter Calculator

Voltage (kV)	Conductor	Actual Line Length km	T/Line Parameters (p.u. at 100 MVA Base)						Thermal Rating	
			R_+	X_+	B_+	R_0	X_0	B_0	Current	MVA
500	Greeley 4-c	10	0.000085	0.001022	0.112423	0.000808	0.003614	0.072187	806	2793
500	Drake 4-c	10	0.000089	0.001019	0.112439	0.000811	0.00361	0.072251	800	2772
220	Rail 2-c	10	0.00077	0.00591	0.01922	0.00422	0.02148	0.00925	884	674
220	Rail 1-c	10	0.00154	0.00828	0.01383	0.00499	0.02386	0.00778	884	337
132	Rail	10	0.00427	0.02196	0.00524	0.01495	0.06757	0.00291	884	202
132	Lynx	10	0.01102	0.02327	0.00489	0.0217	0.06888	0.0028	488	112
66	Dog	10	0.076	0.1015	0.00121	0.12271	0.292	0.00071	338	39

The load flow analysis is conducted using Newton-Raphson method in which standard load flows are investigated and power flows are studied [90]. Afterwards, the contingency analysis was performed on PSS/E using Newton Raphson.

3.4.1 IEEE 14 Bus Systems

The IEEE 14-bus test case **represents a simple approximation of the American Electric Power system as of February 1962** [38]. The basic construction of IEEE system is as follows:



IEEE standard test system of 14 buses was utilized with minor adjustments. The system included following elements in the system:

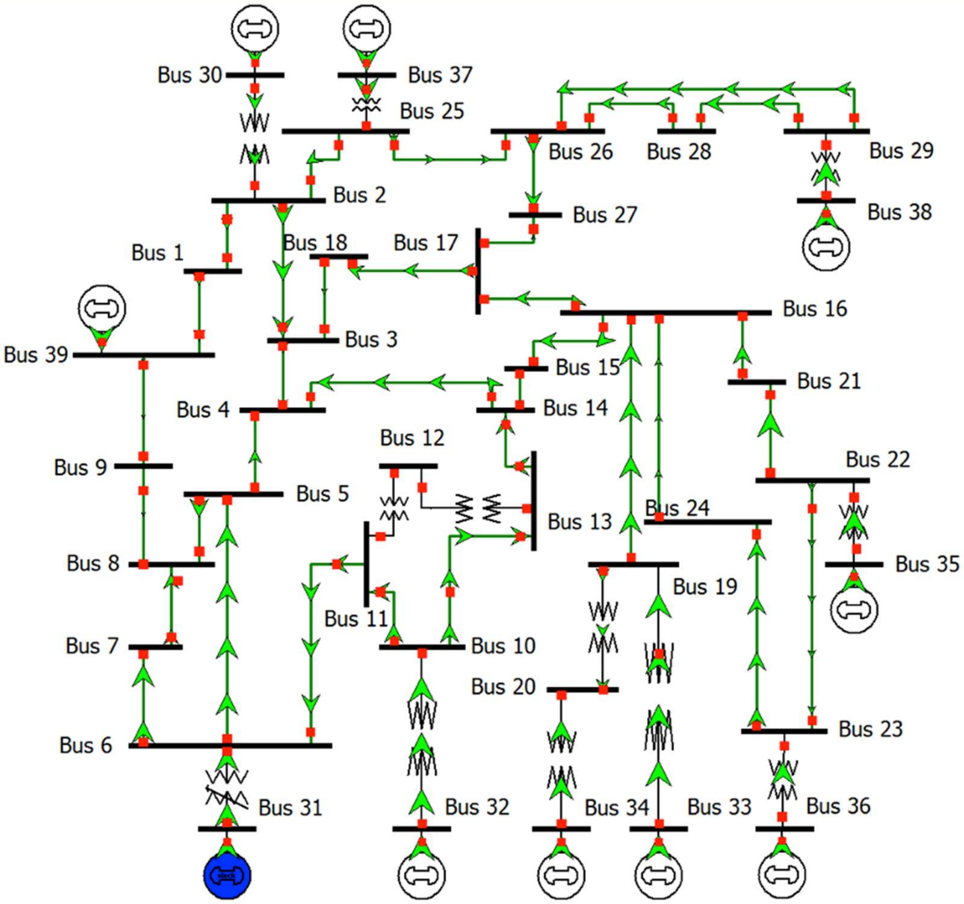
Table 3.1: IEEE 14-Bus System Components

Type	No.
Bus	14
Branches (T/Lines)	17
Transformers	03
Generators	02
Loads	11
Fixed Shunts	01

The parameters of 132kV Lynx Conductor are used for setting R, X and B values of transmission lines with MVA capacity of 112 MVA.

3.4.2 IEEE 39 Bus Systems

The IEEE 39-bus test case is know as the 10-machine New-England Power System [39] The basic construction of IEEE system is as follows:



EEE standard test system of 39 buses was utilized with minor adjustments. The system included following elements in the system:

Table 3.2: IEEE 39-Bus System Components

Type	No.
Bus	39
Branches (T/Lines)	34
Transformers	12
Generators	10
Loads	27
Fixed Shunts	03

The parameters of 132kV Rail Conductor are used for setting R, X and B values of transmission lines with MVA capacity of 202 MVA.

3.4.3 IEEE 118 Bus Systems

The IEEE 118-bus test case is simple approximation of the American Electric Power **system** (in the U.S. Midwest) as of December 1962 [40]. The basic construction of IEEE 118 bus system is as follows:

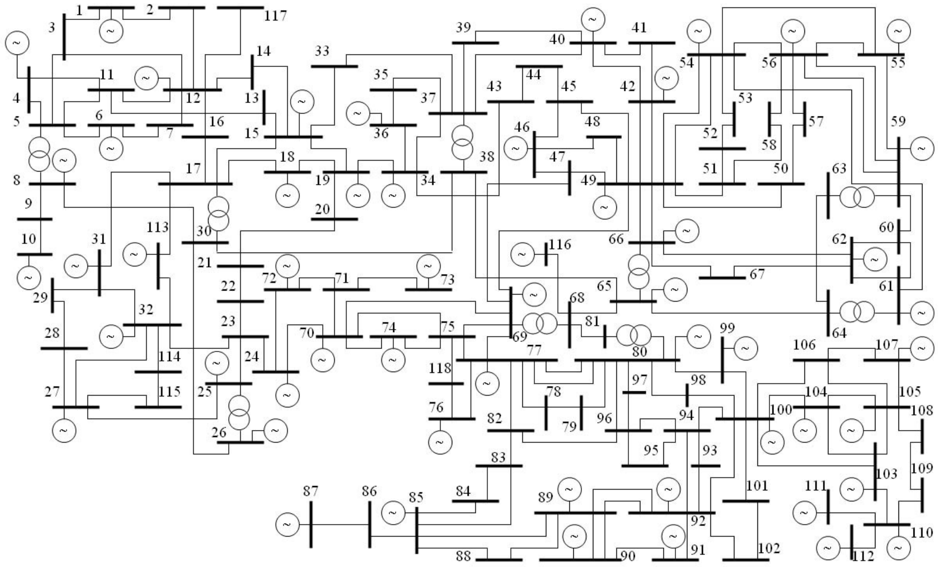


Рис.1. IEEE тестовая схема, состоящая из 118 узлов

IEEE standard test system of 118 buses was utilized with minor adjustments. The system included following elements in the system:

Table 3.3: IEEE 118-Bus System Components	
Type	**No.**
Bus	118
Branches (T/Lines)	170
Transformers	09
Generators	19
Loads	99
Fixed Shunts	15

The parameters of 132kV Rail Conductor are used for setting R, X and B values of transmission lines with MVA capacity of 202 MVA.

3.5 Real Time System of Pakistan modelled in PSSE

The recent Real time system of NTDC (the transmission utility of Pakistan) [37] was used for analysis. The system modelled in PSSE included 4297 buses including 500kV, 220kV, 132kV and 11kV. The areas where low voltage issues are significant were identified. The system is modelled with the actual parameters of transmission lines and grid stations.

In the system of Pakistan, the transmission lines are mostly constructed using Greely & Drake Conductor at 500kV level, Rail at 220kV level, Rail & Lynx at 132kV level etc. The parameters of lines used in system are as follows [37]:

Line Parameter Calculator

Voltage (kV)	Conductor	Actual Line Length km	T/Line Parameters (p.u. at 100 MVA Base)						Thermal Rating	
			R_+	X_+	B_+	R_0	X_0	B_0	Current	MVA
500	Greeley 4-c	10	0.000085	0.001022	0.112423	0.000808	0.003614	0.072187	806	2793
500	Drake 4-c	10	0.000089	0.001019	0.112439	0.000811	0.00361	0.072251	800	2772
220	Rail 2-c	10	0.00077	0.00591	0.01922	0.00422	0.02148	0.00925	884	674
220	Rail 1-c	10	0.00154	0.00828	0.01383	0.00499	0.02386	0.00778	884	337
132	Rail	10	0.00427	0.02196	0.00524	0.01495	0.06757	0.00291	884	202
132	Lynx	10	0.01102	0.02327	0.00489	0.0217	0.06888	0.0028	488	112
66	Dog	10	0.076	0.1015	0.00121	0.12271	0.292	0.00071	338	39

The parameters of the transformers are shown below [37]:

Transformer	Rated MVA	Base MVA	X at own base		X at 100 MVA base
			Per Cent	Per Unit	
132/11 kV	10/13	10	10	0.1	1.0000
132/11 kV	20/26	20	11	0.11	0.5500
132/11 kV	31.5/40	40	14.1	0.141	0.3525
66/11 kV	10/13	10	10	0.1	1.0000
132/66 kV	40	40	14	0.14	0.3500
220/132 kV	160	160	15	0.15	0.0938
220/132 kV	250	250	16	0.16	0.0640
500/220 kV	450	450	12.5	0.125	0.0278
500/220 kV	600	600	12.5	0.125	0.0208

CHAPTER 4

SIMULATIONS & RESULTS

In this research, simulations have been carried out on Siemens Power System Simulator for Engineer (PSS/E) which is being used in the power sector of Pakistan. It is state of the art software for system studies of electrical power system in which both dynamic and steady state analysis can be carried out. The studies have been conducted on three case scenarios of IEEE bus system i.e., IEEE-14, IEEE-39 and IEEE-118 bus system. The data for power systems of both the case scenarios have been taken from [34-36] respectively. However, the data did not included the MVA capacity of the transmission lines and correct R, X & B parameters. The parameters for rail conductor were added to the software and analysis was carried out based on the values of Rail conductor [37].

Moreover, the analysis was performed on the real time system of Pakistan [37] and potential areas were identified for installation of FACTS device.

The observations were recorded as no. of overloaded lines and no. of voltage deviation buses. The buses with more than 100% loading were considered overloaded and bus voltage out of range of 0.95pu to 1.05pu were considered voltage deviations as per NEPRA Grid Code. The performance parameter was calculated as:

Performance parameter = Number of Overloaded Transmission Line + Number of Voltage Violations recorded on Buses

Performance parameter is used to identify the weakest transmission line in the system based on the ranking. The branch with zero value of performance parameter is the most strongest link that causes no disturbance on system during contingency.

4.1 Simulations on IEEE 14 bus System:

In IEEE- 14 bus system, firstly, performance parameters are calculated through the contingency analysis in PSSE. Then compensation is applied on the selected area and then the results are compared.

4.1.1 Contingency Analysis on Normal IEEE 14 bus System:

Based on outage of each transmission line, contingency cases were built based on outages of transmission lines. The observations were recorded as no. of overloaded lines and no. of voltage deviation buses. The performance parameter was calculated for the system using contingency analysis. The detailed contingency analysis.

Appendix I shows the results of complete process. The results are:

Table 4.1: Contingency Analysis on IEEE-14

Contingency	Flow Violations #	Low Range Voltage Violations #	Performance Parameter
From 1-5	2	9	11
From 2-3	1	8	9
From 4-7	0	9	9
From 5-6	0	9	9
From 7-9	0	7	7
From 2-4	1	5	6
From 1-2	2	1	3
From 2-5	1	2	3
From 9-14	0	3	3
From 6-13	0	2	2
From 9-10	0	2	2
From 4-9	0	1	1
From 6-12	0	1	1
From 12-13	0	1	1
From 13-14	0	1	1
From 3-4	0	0	0
From 4-5	0	0	0
From 6-11	0	0	0
From 7-8	0	0	0
From 10-11	0	0	0
		Overall Performance Index	**68**

Based on highest values of performance parameters and contingency cases with harsh results, region with buses 1, 2, 3, 4 & 5 is most volatile and tripping in the area result in overloading and low voltages in whole system. The system results in 68 no. overloading and voltage violations when contingency analysis was performed.

Now from the analysis, we conclude that we should provide VAR support in the above stated area.

4.1.2 Analysis on IEEE 14 bus System with SVC at Bus 4:

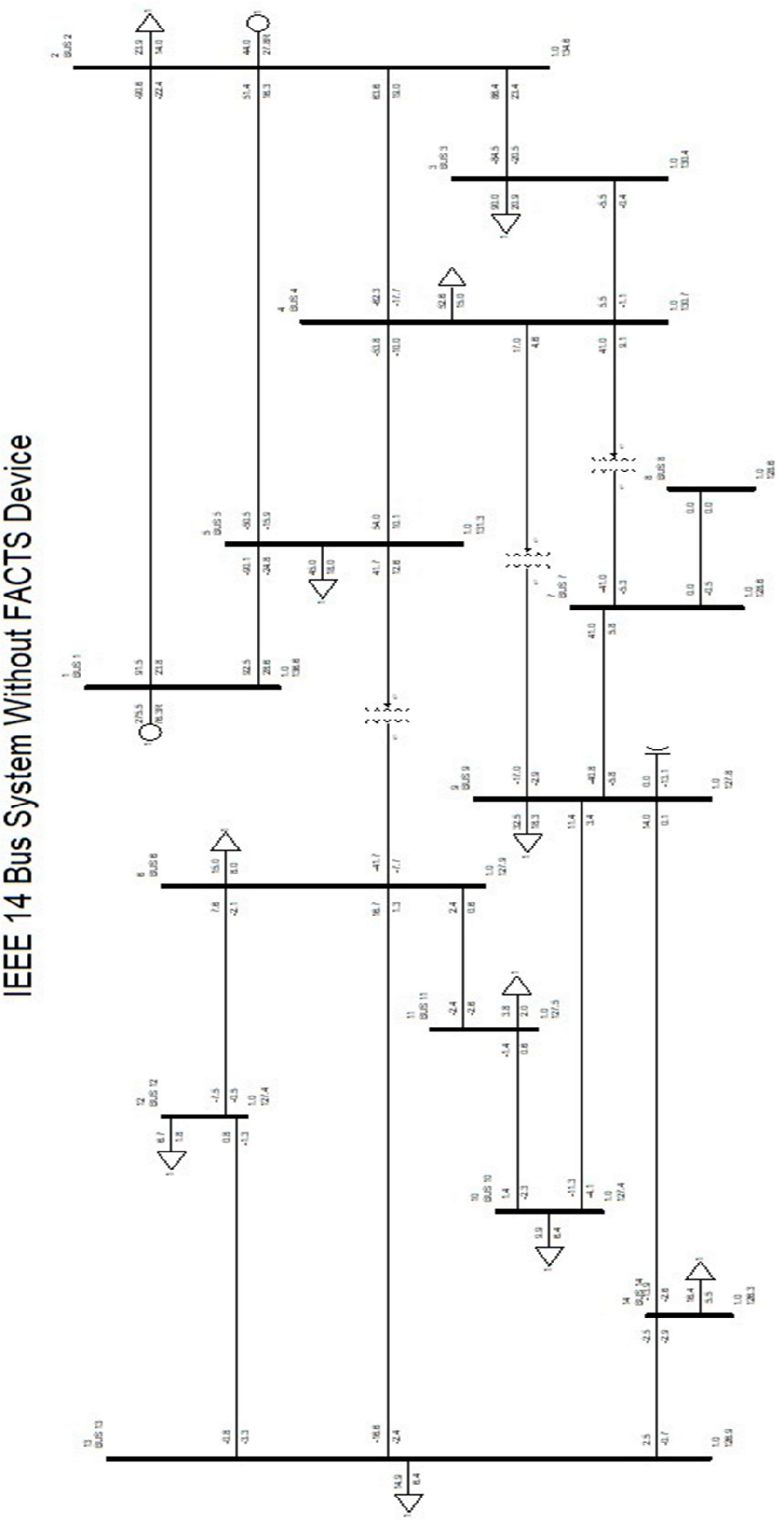
A Static VAR Compensator with Max Limit of 150MVAR is installed on Bus no. 4 and then contingency analysis is performed to study the improvements.

Table 4.2: Contingency Analysis on IEEE-14 after SVC

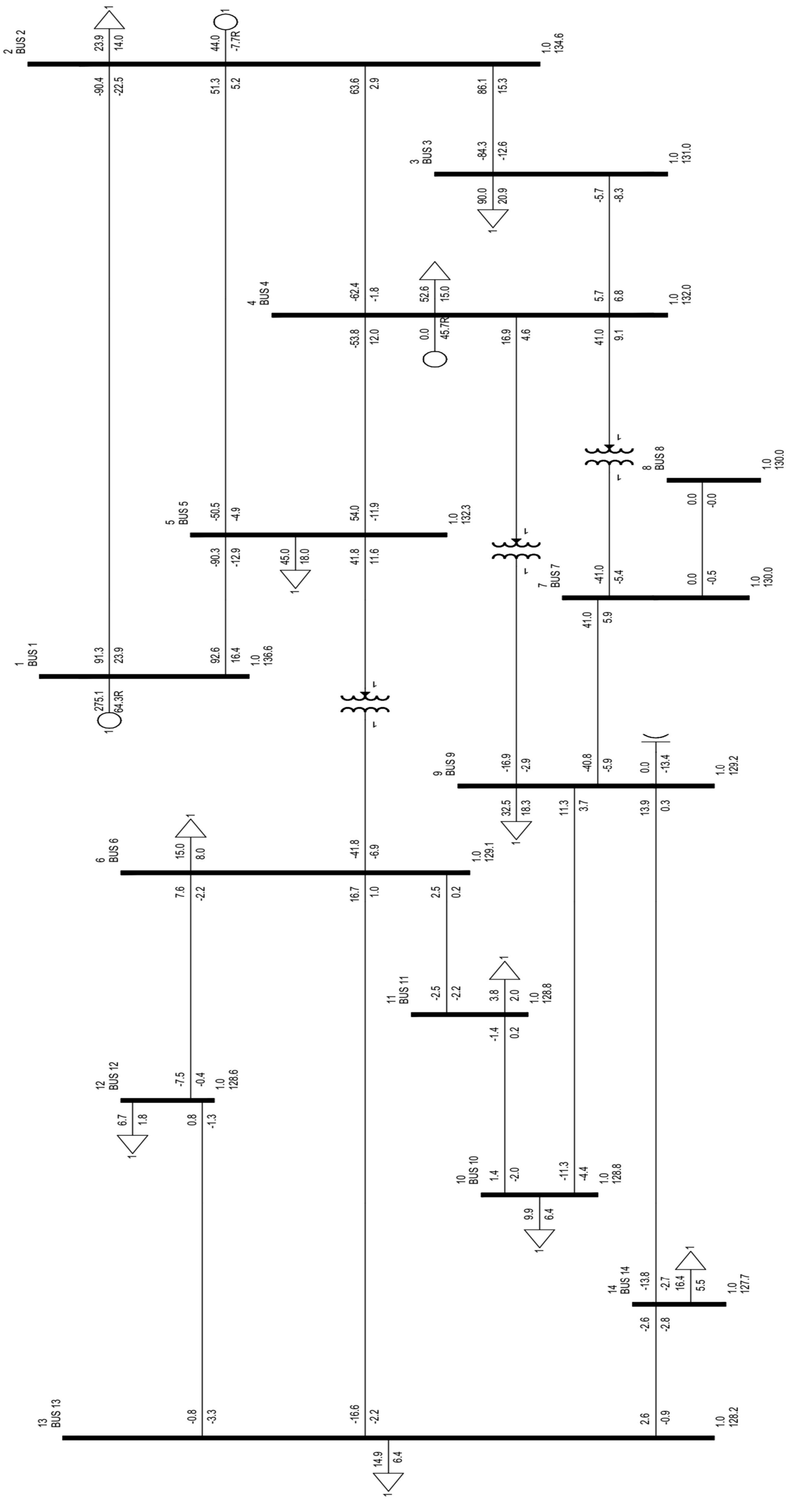
Contingency	Flow Violations #	Low Range Voltage Violations #	Performance Parameter
From 4-7	0	7	7
From 5-6	0	7	7
From 7-9	0	6	6
From 1-2	2	0	2
From 1-5	2	0	2
From 2-3	1	1	2
From 2-4	1	0	1
From 2-5	1	0	1
From 6-13	0	1	1
From 9-10	0	1	1
From 9-14	0	1	1
From 3-4	0	0	0
From 6-12	0	0	0
From 4-5	0	0	0
From 4-9	0	0	0
From 6-11	0	0	0
From 6-12	0	0	0
From 10-11	0	0	0
From 12-13	0	0	0
From 13-14	0	0	0
		Overall Performance Index	**31**

From the above results, it can be observed that the system has resulted in less voltage and flow violations after the installation of SVC and the same have been reduced to more than half i.e., 31 against the original value of 68.

The Single Line diagrams of the system developed in PSSE with the load flow values are shown:



IEEE 14 Bus System With SVC at Bus 4



Based on the simulation results, we compare the improvement in voltages at buses before and after installation of SVC in normal condition i.e., without contingency.

Table 4.3: Voltage Comparison Before/After SVC Installation on IEEE-14

Bus No.	Voltage before installation of SVC	Voltage after installation of SVC	Improvement
1	136.6 kV	136.6 kV	-
2	134.6 kV	134.6 kV	-
3	130.4 kV	131.0 kV	0.6 kV
4	130.7 kV	132.0 kV	1.3 kV
5	131.3 kV	132.3 kV	1.0 kV
6	127.9 kV	129.1 kV	1.2 kV
7	128.6 kV	130.0 kV	1.4 kV
8	128.6 kV	130.0 kV	1.4 kV
9	127.8 kV	129.2 kV	1.4 kV
10	127.4 kV	128.8 kV	1.4 kV
11	127.5 kV	128.8 kV	1.3 kV
12	127.4 kV	128.6 kV	1.2 kV
13	126.9 kV	128.2 kV	1.3 kV
14	126.3 kV	127.7 kV	1.4 kV

The above results show the considerable improvement in bus voltage after installation of SVC at the position identified through contingency analysis.

4.1.3 Dynamic Fault Analysis on Normal IEEE 14 bus System:

Various cases with bus fault on different buses were studied in normal scenario. The dynamic data of generators, exciters & rotors was taken from NTDC base cases [37]. This data is based on the actual models of generators (salient and non-salient poles).

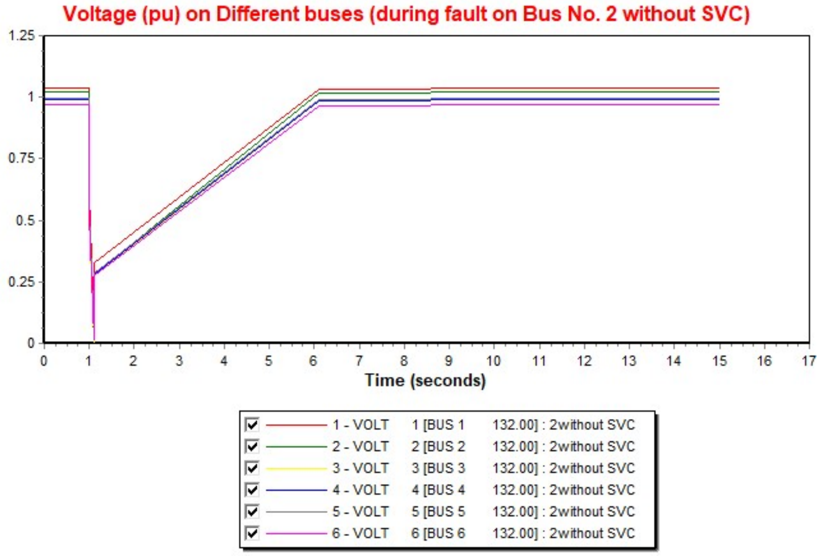
The dynamic simulations were run as per following steps:

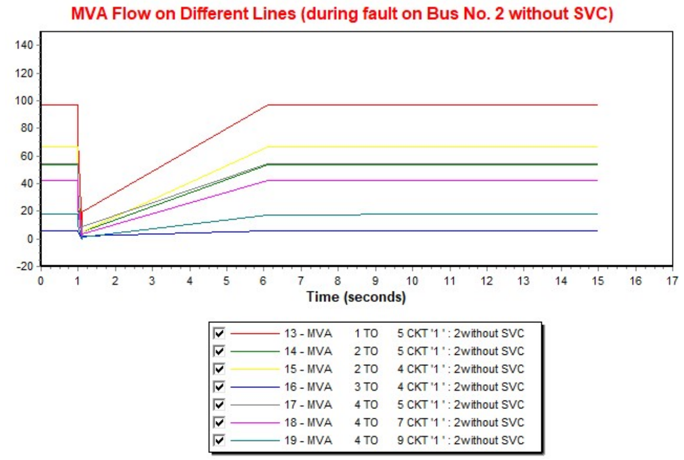
- System was initialized on dynamic parameters of generators.
- Simulation was run for 1 second.
- Fault on bus was introduced at t=1sec.
- Fault was cleared at t=1.1sec with/without outage of transmission line.
- Simulation was run till t=15sec to study Load flow on nearby transmission lines.

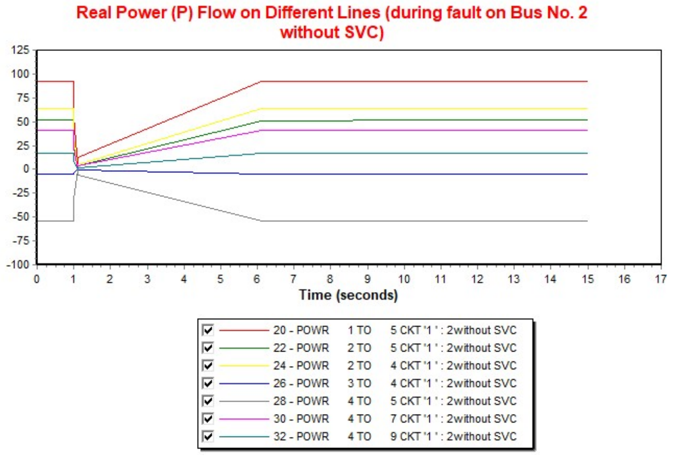
The case scenarios are discussed as under:

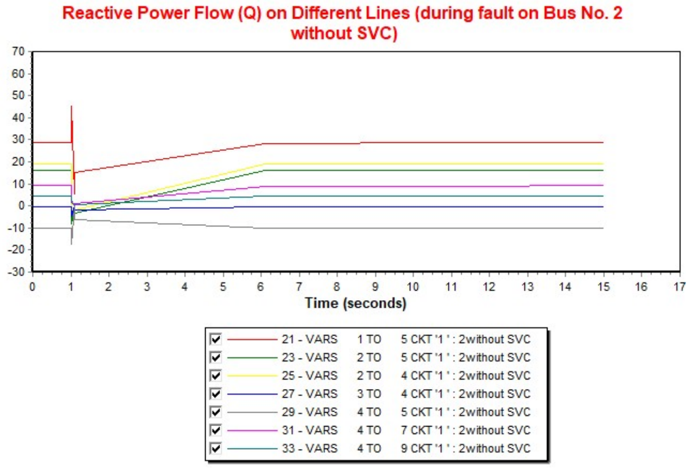
4.1.3.1 Fault on Bus 2 without line tripping & without FACTS Device:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown below:





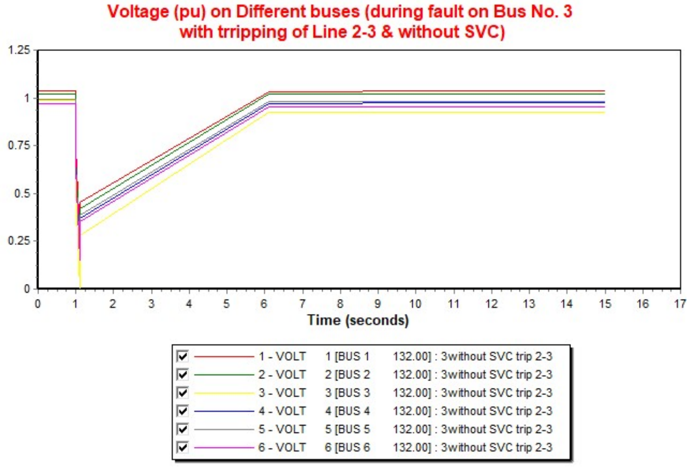


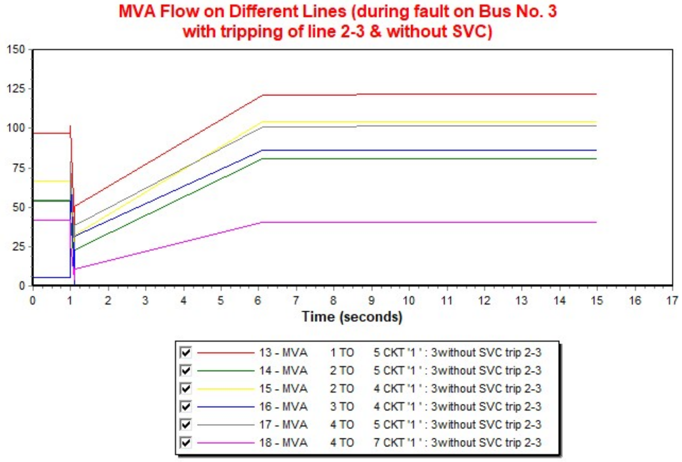


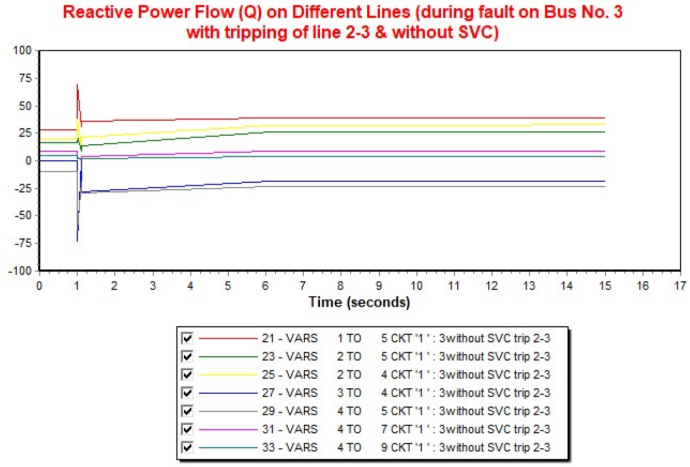
The results depict that system normalizes to its pre-fault position in the steady state after fault introduction and clearing.

4.1.3.2 Fault on Bus 3 with tripping of line from bus 2-3 & without FACTS Device:

The fault was introduced at t=1sec and cleared at 1.1sec with outage of line 2-3. The results were plotted which show response of system after fault clearing:


Voltage (pu) on Different buses (during fault on Bus No. 3 with trripping of Line 2-3 & without SVC)

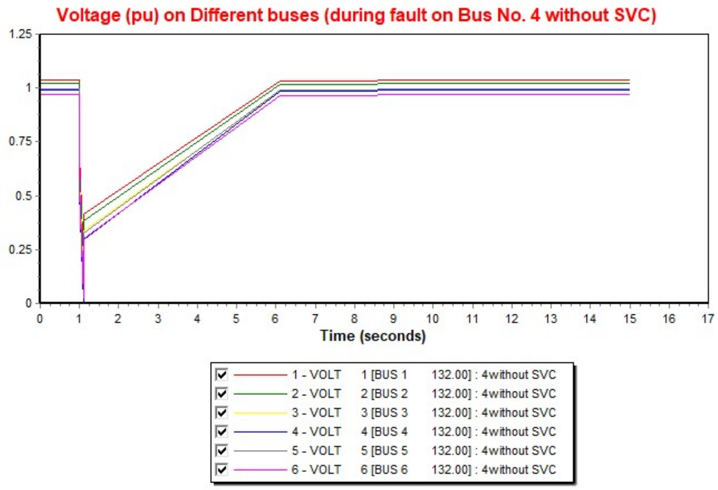

MVA Flow on Different Lines (during fault on Bus No. 3 with tripping of line 2-3 & without SVC)

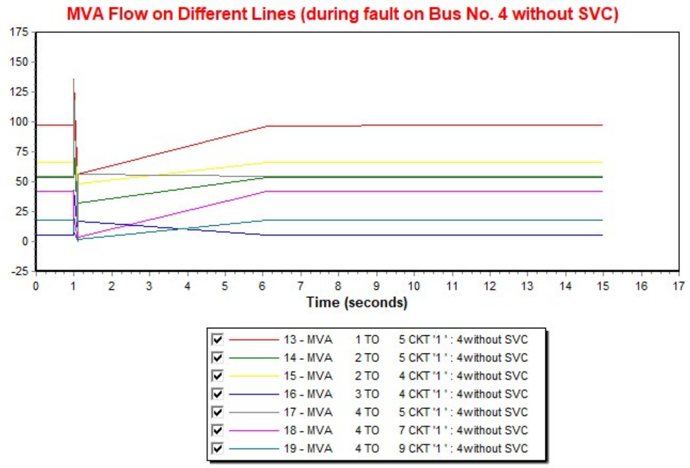

Reactive Power Flow (Q) on Different Lines (during fault on Bus No. 3 with tripping of line 2-3 & without SVC)

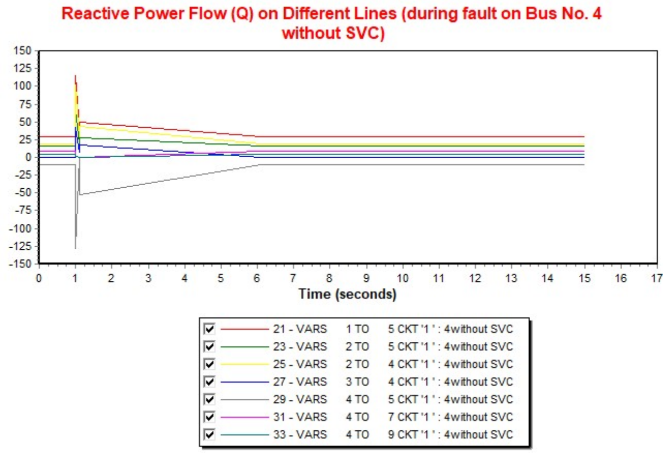
The results depict that system normalizes to its pre-fault position in the steady state after fault introduction and clearing.

4.1.3.3 Fault on Bus 4 without line tripping & without FACTS Device:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown below:







The results depict that system normalizes to its pre-fault position in the steady state after fault introduction and clearing.

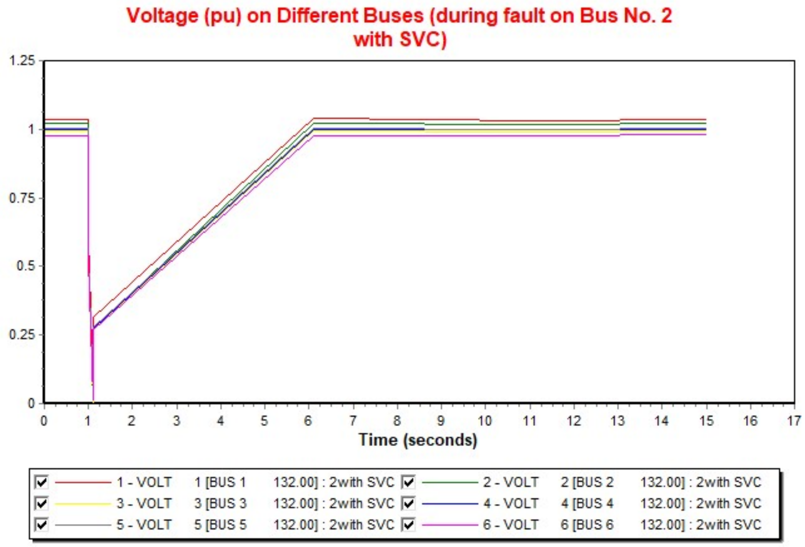
4.1.4 Dynamic Analysis on IEEE 14 bus System with SVC at Bus 4:

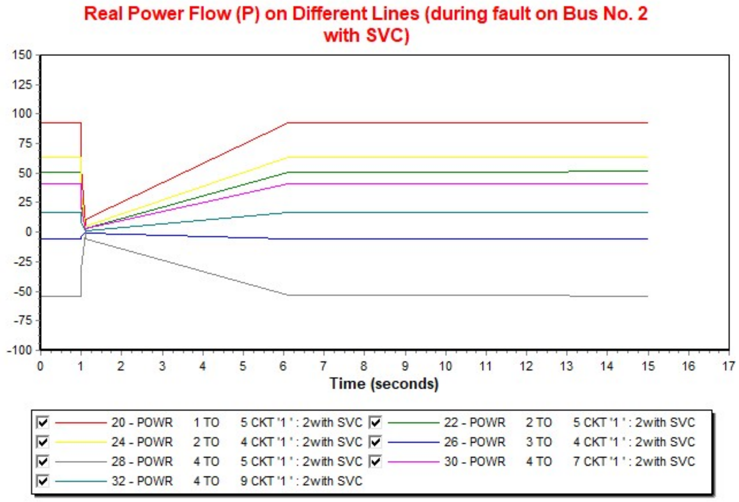
Various cases with bus fault on different buses were studied after installation of SVC in the system. The dynamic data of generators, exciters, SVC & rotors was taken from NTDC base cases [37]. This data is based on the actual models of generators (salient and non-salient poles).

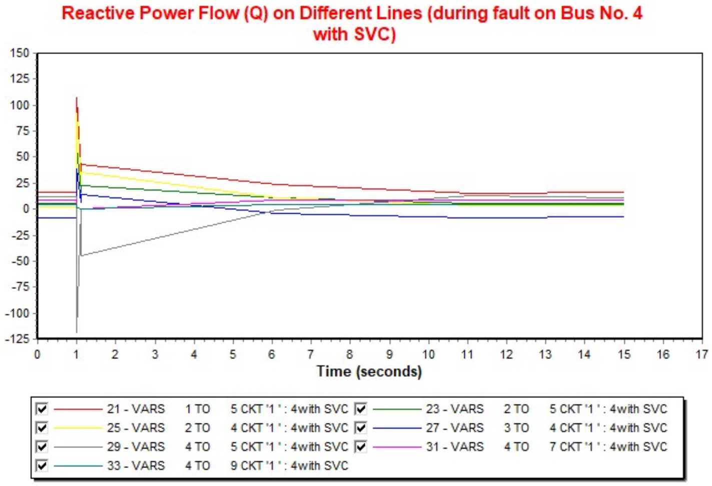
- The dynamic simulations were run as per following steps:
- System was initialized on dynamic parameters of generators.
- Simulation was run for 1 second.
- Fault on bus was introduced at t=1sec.
- Fault was cleared at t=1.1sec with/without outage of transmission line.
- Simulation was run till t=15sec to study Load flow on nearby transmission lines. The case scenarios are discussed as under:

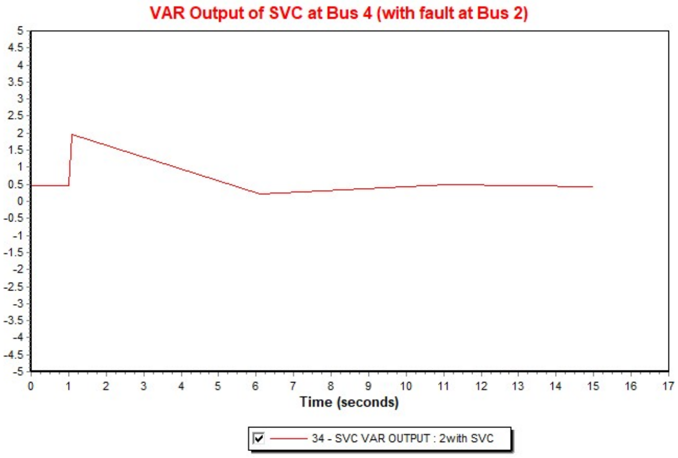
4.1.4.1 Fault on Bus 2 without line tripping & with SVC at Bus 4:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown.





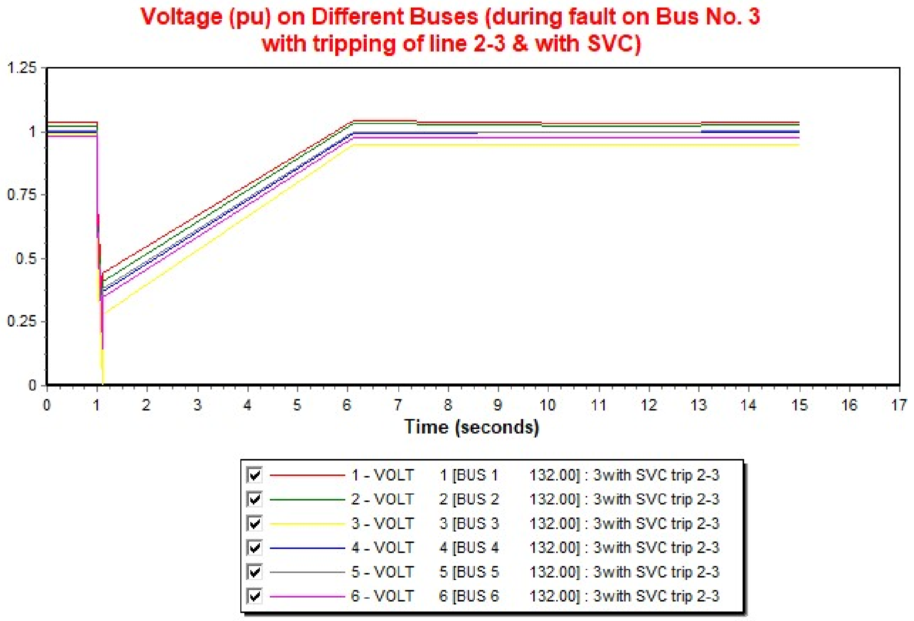


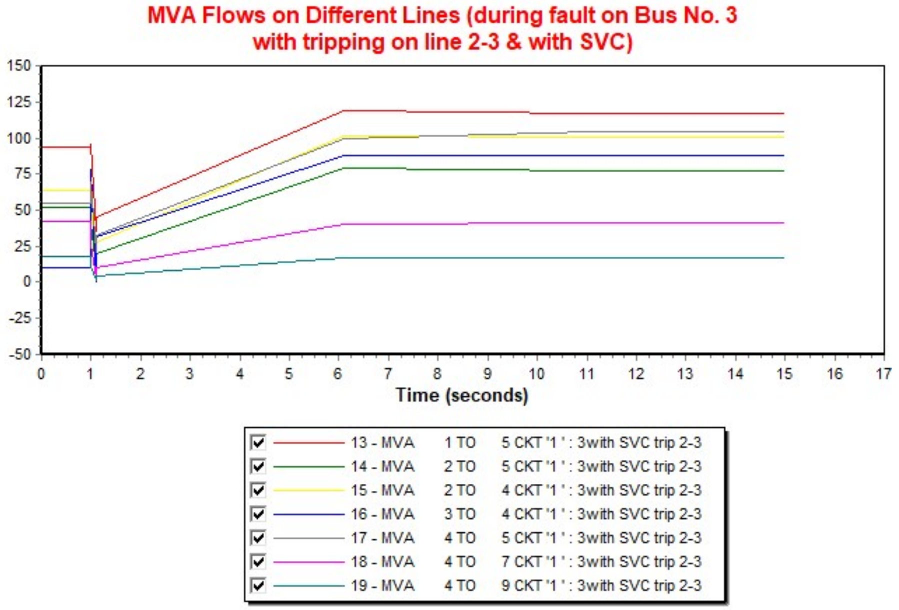


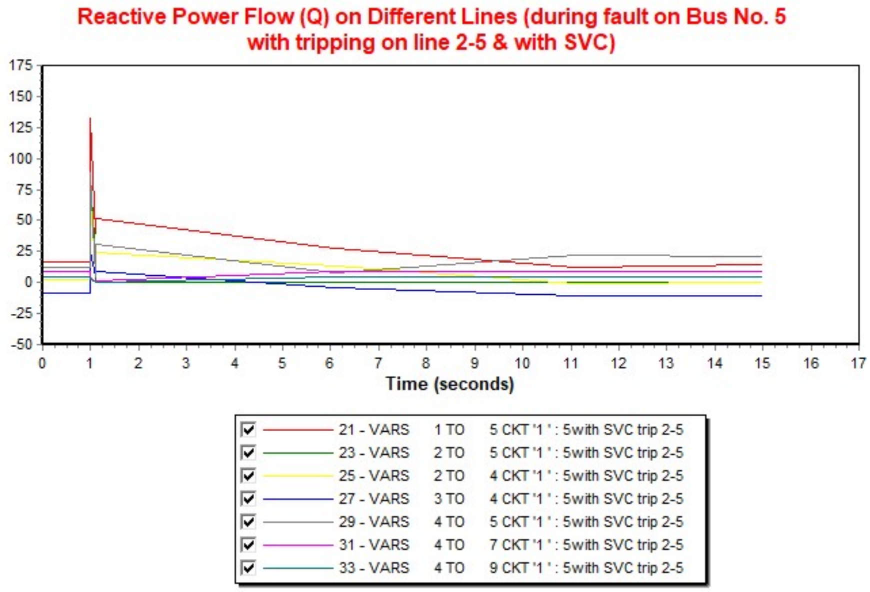
The results depict that system normalizes to its pre-fault position in the steady state after fault introduction and clearing. The SVC provide reactive power support during the fault up to the maximum limit and adjust its output accordingly.

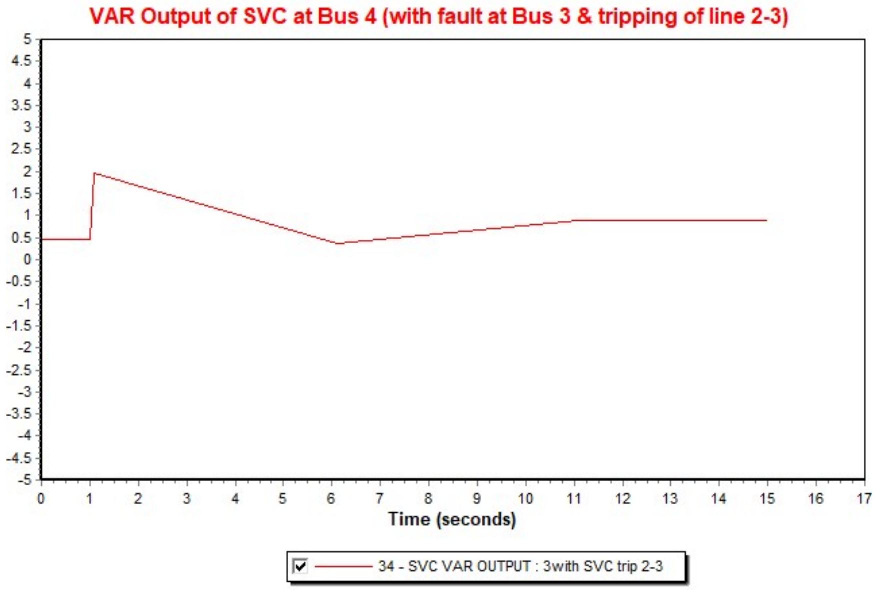
4.1.4.2 Fault on Bus 3 with tripping of line from bus 2-3 & with SVC at Bus 4:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown





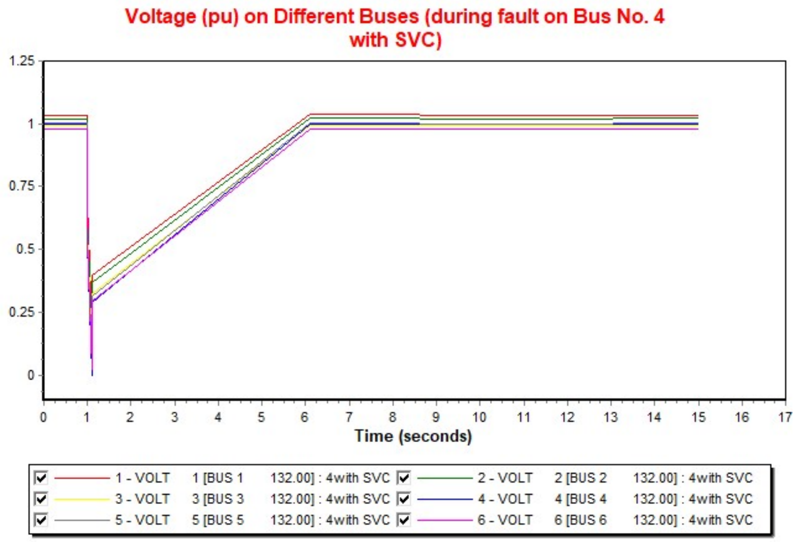


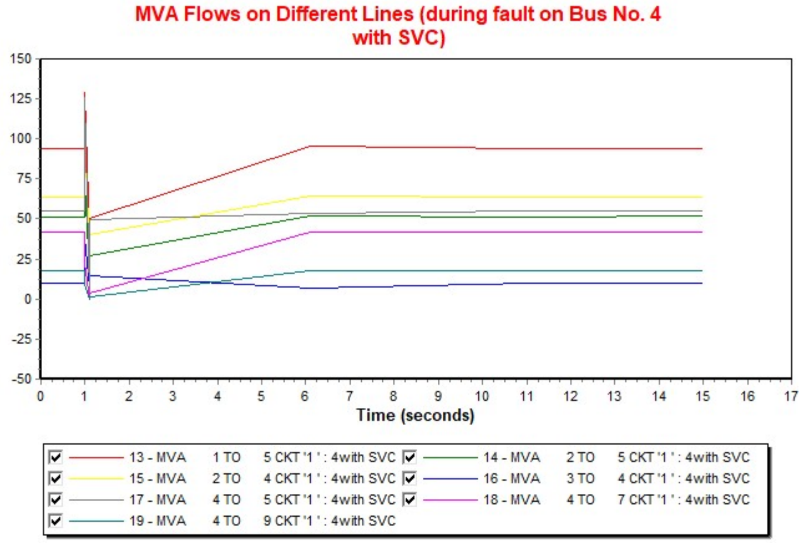


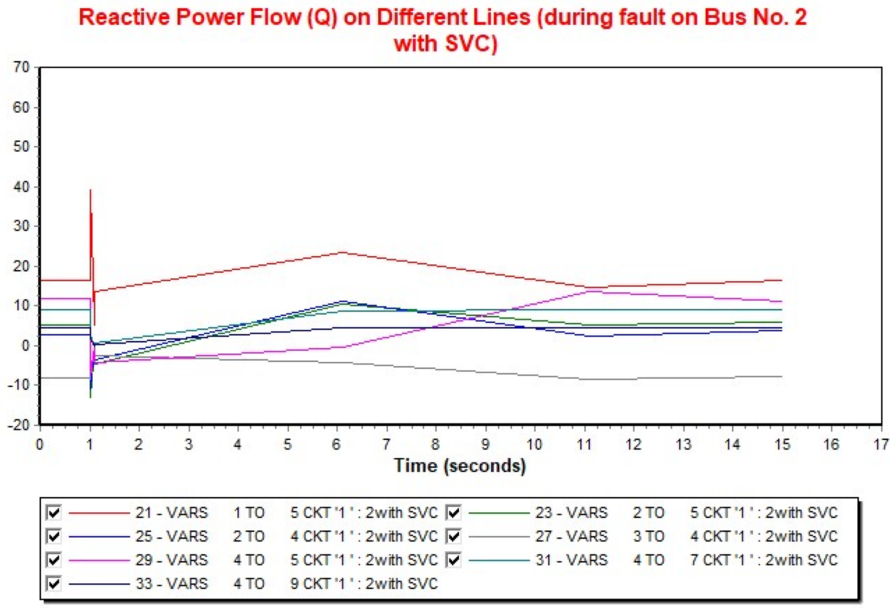
The results depict that system normalizes to its pre-fault position in the steady state after fault introduction and clearing. The SVC provide reactive power support during the fault up to the maximum limit and adjust its output accordingly. The real and reactive power flows change on the lines due to tripping/outage of a single circuit.

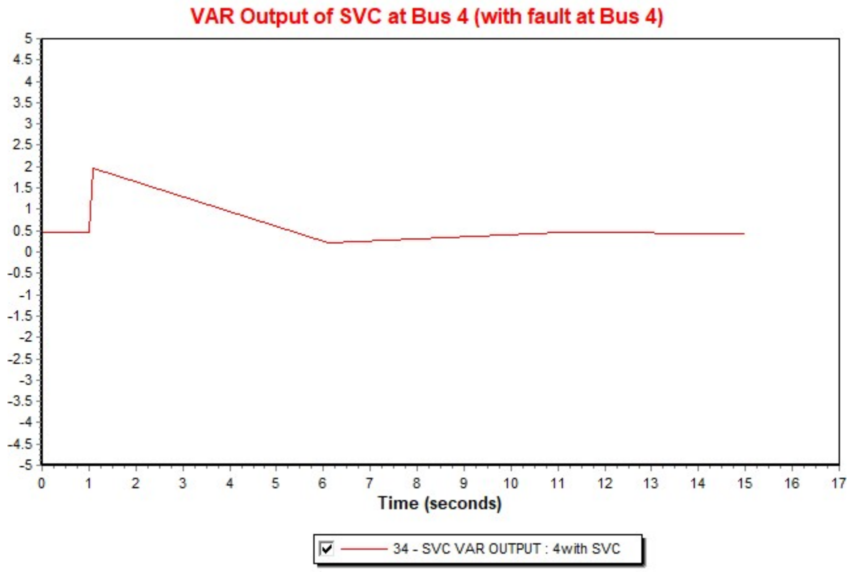
4.1.4.3 Fault on Bus 4 without line tripping & with SVC at Bus 4:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown









The results depict that system normalizes to its pre-fault position in the steady state after fault introduction and clearing. The SVC provide reactive power support during the fault up to the maximum limit and adjust its output accordingly. The real and reactive power flows change on the lines due to tripping/outage of a single circuit.

4.2 Simulations on IEEE-39 Bus System:

In network of IEEE-39 buses, contingency analysis was carried out to find the performance parameters. For 41 transmission lines, 41 contingency operations were performed which are listed in the table based on the ranking with respect to no. of overloaded lines and number of voltage violations. To minimize these overloading conditions in transmission lines and voltage deviations, compensation mechanism has been used.

The SVC was installed on Bus No. 3 and the response was observed. Moreover, the studies were also conducted by applying Series compensation to increase the transmission line capacity to carry the power. The results are presented in the respective sections below:

4.2.1 Contingency Analysis on Normal IEEE 39 bus System:

Based on the outage of each transmission line, contingency cases were built based on outages of transmission lines. The observations were recorded as no. of overloaded lines and no. of voltage deviation buses. The performance parameter was calculated for the system using contingency analysis. The detailed contingency analysis.

Appendix II shows the results of complete process. However, some top contingencies are shown below:

Table 4.4: Main Contingency Analysis on IEEE-39

Label	Flow Violation #	Flow Violation Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 2-3(1)	5	129.05	9	0.9003	14
SINGLE 22-35(1)	6	139.18	8	0.9302	14
SINGLE 20-34(1)	8	139	3	0.9487	11
SINGLE 21-22(1)	1	156.13	7	0.9282	8
SINGLE 2-25(1)	4	149.12	3	0.9253	7
SINGLE 2-30(1)	1	110.19	6	0.9219	7
SINGLE 10-32(1)	1	105	6	0.9381	7
SINGLE 9-39(1)	3	153.17	3	0.943	6
SINGLE 23-36(1)	6	130.44	0	0	6
SINGLE 25-37(1)	4	133.16	2	0.8878	6
Total of all contingencies					**150**

Based on highest values of performance parameters and contingency cases with harsh results, region around bus 2 is most volatile and tripping in the area result in overloading and low voltages. The system results in 150 no. overloading and voltage violations when contingency analysis was performed. Now from the analysis, we conclude that we should provide VAR support in the above stated area.

4.2.2 Analysis on IEEE 39 bus System with SVC at Bus 3:

A Static VAR Compensator with Max Limit of 300MVAR is installed on Bus no. 3 and then contingency analysis is performed to study the improvements. Appendix II shows the results of complete process. However, some top contingencies are shown below:

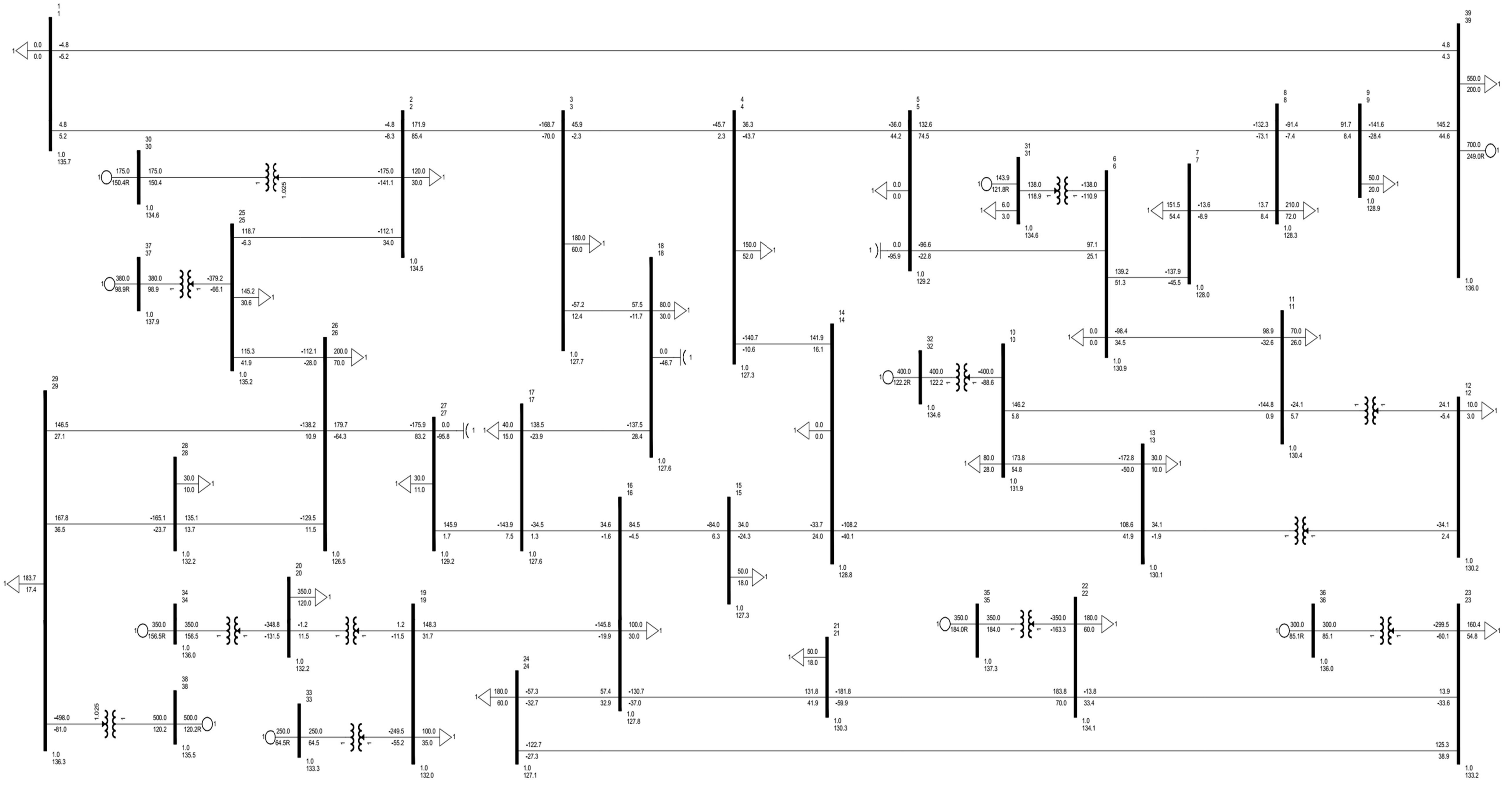
Table 4.5: Main Contingency Analysis on IEEE-39 after SVC

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 22-35(1)	5	136.37	3	0.9439	8
SINGLE 20-34(1)	6	136.83	0	0	6
SINGLE 25-37(1)	4	131.31	2	0.903	6
SINGLE 2-25(1)	4	151.55	1	0.9348	5
SINGLE 28-29(1)	2	164.58	3	0.8682	5
SINGLE 2-3(1)	4	129.35	0	0	4
SINGLE 23-36(1)	4	128.48	0	0	4
SINGLE 5-8(1)	1	139.09	2	0.9354	3
SINGLE 6-7(1)	2	146.46	1	0.9415	3
SINGLE 6-11(1)	3	117.53	0	0	3
Total of all contingencies					**91**

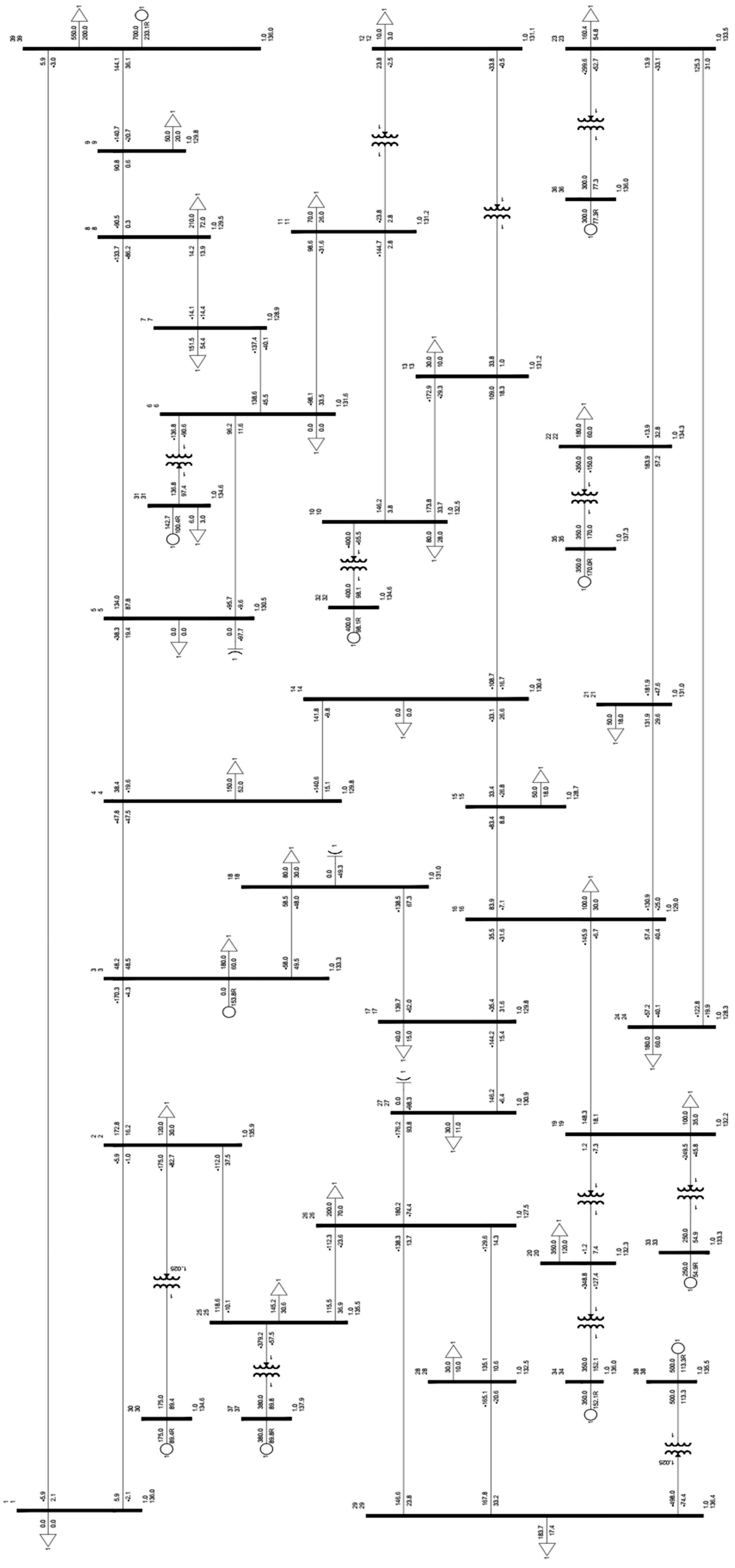
From the above results, it can be observed that the system has resulted in less voltage and flow violations after the installation of SVC and the same have been reduced to 91 against the original value of 150. Hence, the system has improved considerably.

The Single Line diagrams of the system developed in PSSE with the load flow values are shown:

IEEE 39 Bus System Without FACTS Device



IEEE 39 Bus System With SVC at Bus 3



Now we compare the improvement in voltages at some nearby buses before and after installation of SVC in normal condition i.e., without contingency.

Table 4.6: Comparison of Bus Voltage Before/After Installation of SVC in IEEE-39

Bus No.	Voltage before installation of SVC	Voltage after installation of SVC	Improvement
1	135.7 kV	136.0 kV	0.3 kV
2	134.5 kV	135.9 kV	1.4 kV
3	127.7 kV	133.3 kV	5.6 kV
4	127.3 kV	129.8 kV	2.5 kV
5	129.2 kV	130.5 kV	1.3 kV
6	130.9 kV	131.6 kV	0.7 kV
7	128.0 kV	128.9 kV	0.9 kV
8	128.3 kV	129.5 kV	1.2 kV
9	128.9 kV	129.8 kV	0.9 kV
10	131.9 kV	132.5 kV	0.6 kV
11	130.4 kV	131.2 kV	0.8 kV
12	130.2 kV	131.1 kV	0.9 kV
13	130.1 kV	131.2 kV	1.1 kV
14	128.8 kV	130.4 kV	1.6 kV
15	127.3 kV	128.7 kV	1.4 kV
16	127.8 kV	129.0 kV	1.2 kV
17	127.6 kV	129.8 kV	1.2 kV
18	127.6 kV	131.0 kV	3.4 kV
19	132.0 kV	132.2 kV	0.2 kV
20	132.2 kV	132.3 kV	0.1 kV
21	130.3 kV	131.0 kV	0.7 kV
22	134.1 kV	134.3 kV	0.2 kV
23	133.2 kV	133.5 kV	0.3 kV
24	127.1 kV	128.3 kV	1.2 kV
25	135.2 kV	135.5 kV	0.3 kV
26	126.5 kV	127.5 kV	1.0 kV
27	129.2 kV	130.9 kV	1.7 kV
28	132.2 kV	132.5 kV	0.3 kV
29	136.3 kV	136.4 kV	0.1 kV

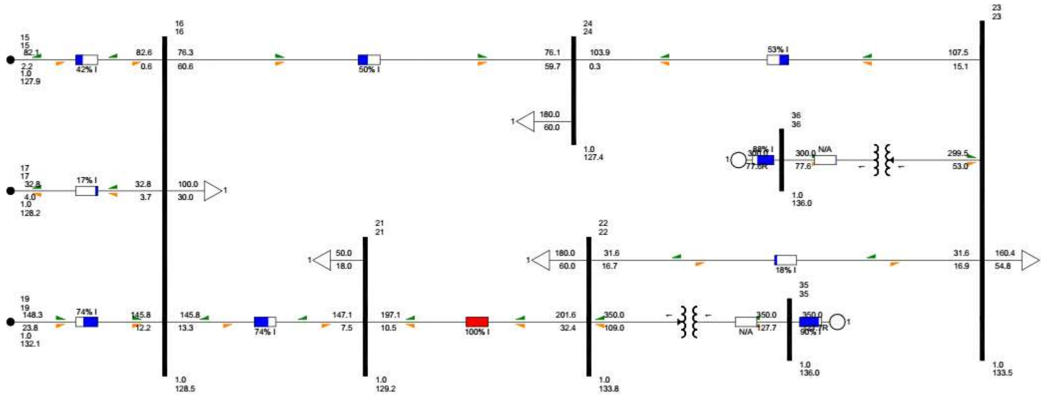
The above results show the considerable improvement in bus voltage in the system after installation of SVC.

4.2.3 Analysis on IEEE 39 bus System with Series Compensation:

The concept of Series Compensation was applied in 39 Bus IEEE System. We have already learnt in the literature review that Series compensation alters the reactance of the line and hence the desired power flow can be achieved. The benefit of the series compensation in controlling the flow of power in the parallel paths has been demonstrated in the example.

The Series compensation effect is more noticeable in long lines, hence slight modification in IEEE-39 bus test case were made and lengths of the links 21-22 and 23-24 have been doubled. The SLD of the area of interest is shown below:

IEEE 39 Bus System Without Series Compensation



Now we can observe that power generated at buses 35 & 36 have two alternate paths. One option is to flow through 23 to 22 to 21 to 16 and then other one is to flow through 22 to 23 to 24 to 16. The load sharing is to be done as per the current division rule in the parallel paths. However, due to different lengths and hence different impedances, the power mostly flows through the path which offer least hindrance to flow of current which is 23-22-21-16 which results in 100% loading of line 21-22. Whereas the other link remain lightly loaded at 53% only.

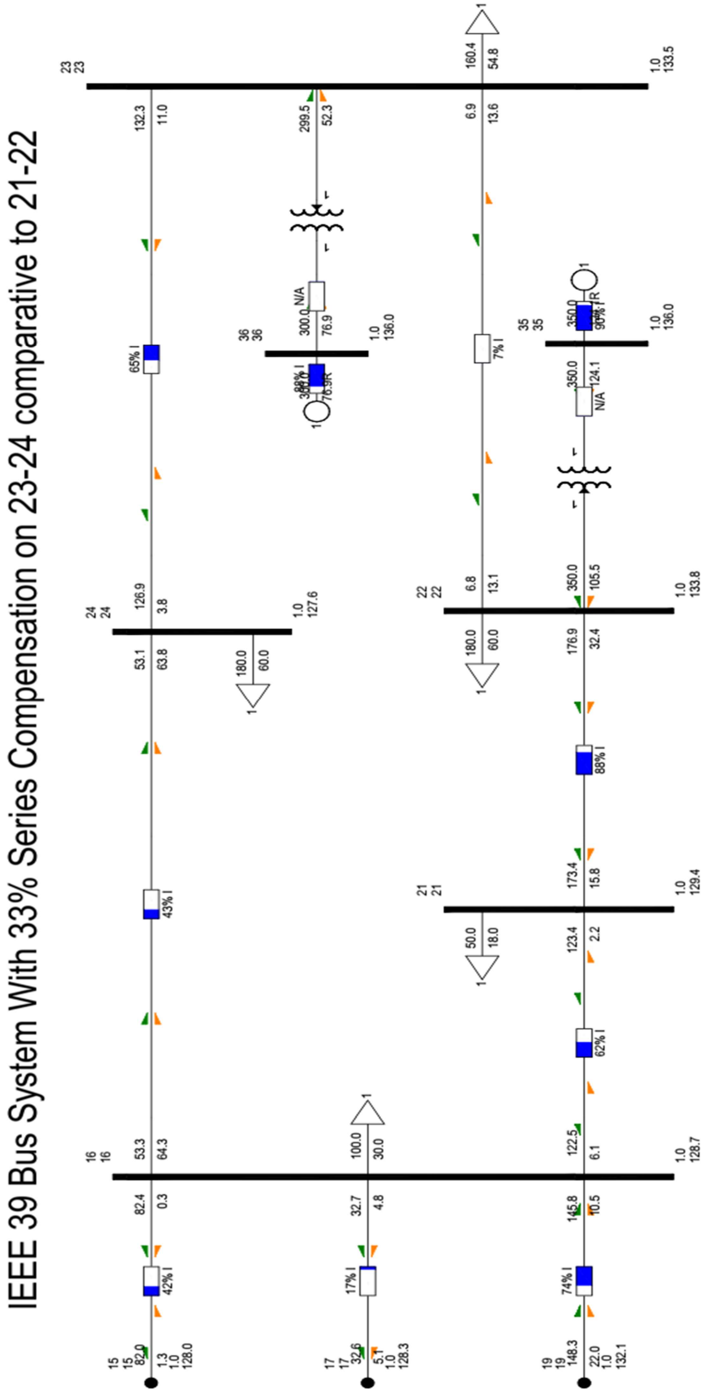
The purpose of Series Compensation in this case is to force the power to flow through the other path to reduce loading of first link. The power transfer function is given as:

$$P_R = \frac{V_R V_S}{X_L - X_C} \sin\delta = \frac{V_R V_S}{X_L(1-K)} \sin\delta$$

The value of K is set as 33%, 50% and 66% and the results are studied.

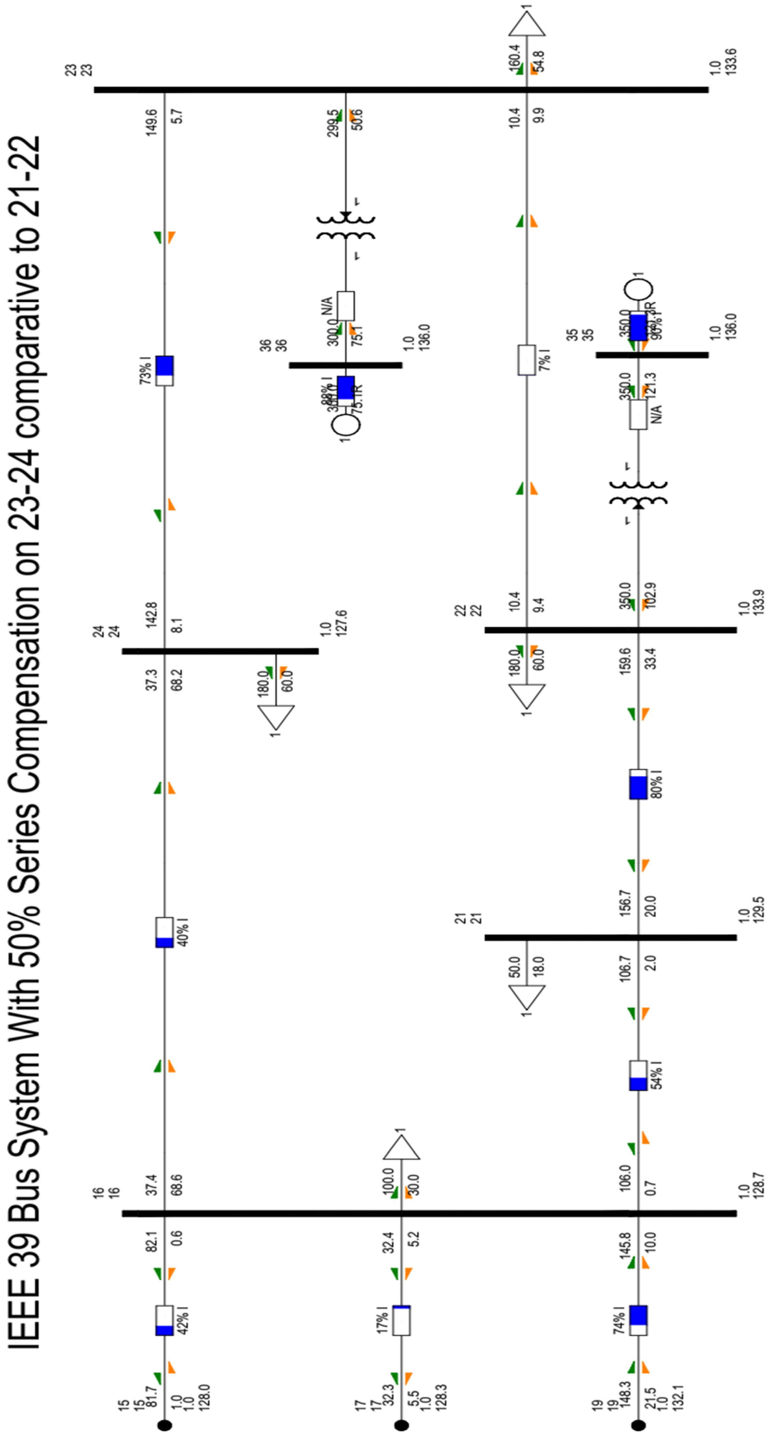
4.2.3.1 With Series Compensation (K=33%):

The reactance of the line was reduced by a factor of 33% for the link 23-24 and hence power flow increase was observed. The same is shown in following Single Line Diagram:



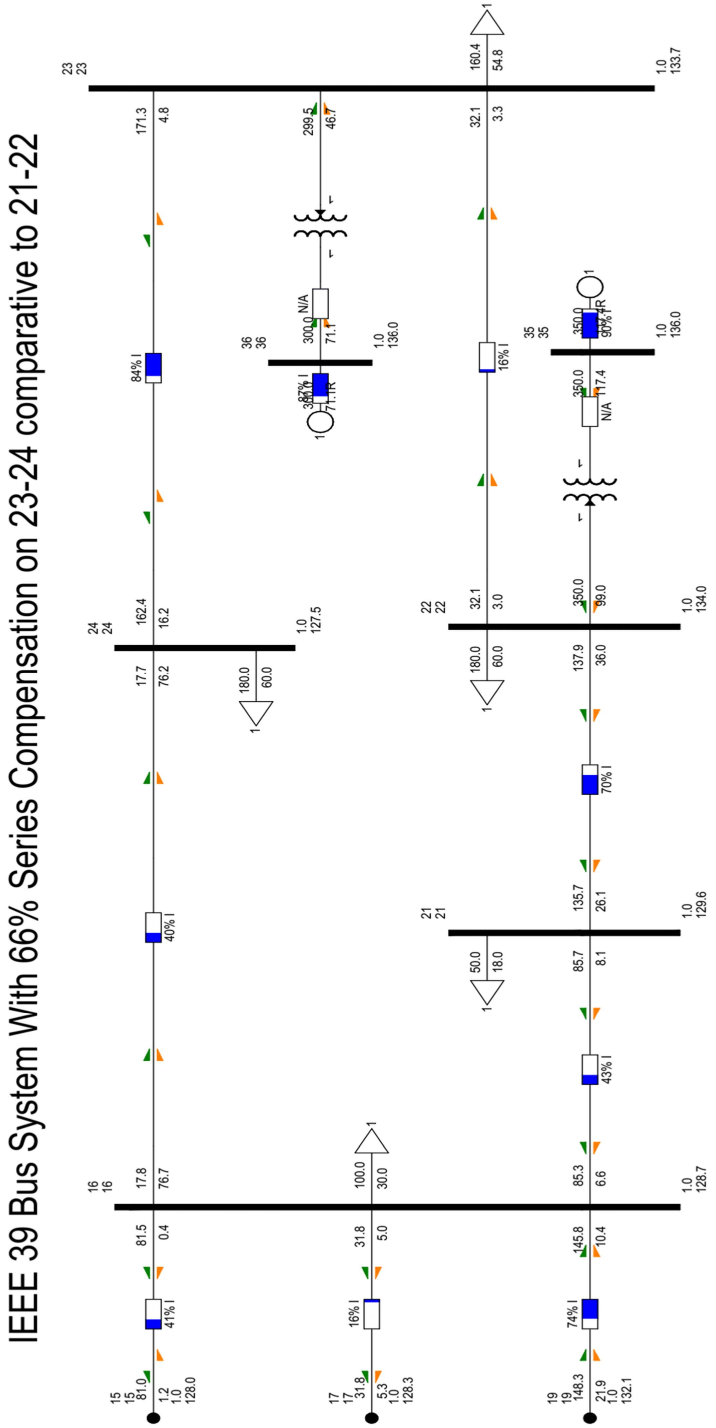
4.2.3.2 With Series Compensation (K=50%):

The reactance of the line was reduced by a factor of 50% for the link 23-24 and hence power flow increase was observed. The same is shown in following Single Line Diagram:



4.2.3.3 With Series Compensation (K=66%):

The reactance of the line was reduced by a factor of 66% for the link 23-24 and hence power flow increase was observed. The same is shown in following Single Line Diagram:



The Comparison of Line Loadings and MW Flow, MVAR Losses (absorption) by the transmission lines is shown below:

Table 4.7: Comparison of Parameters Before/After Series Compensation

	Without SVC	**With K=33%**	**With K=50%**	**With K=66%**
Line Loading on 23-24	53%	65%	73%	84%
MVAR Absorbed by Line	15.1+0.3 = 15.4	11.0+3.8 = 14.8	5.7+8.1 = 13.8	16.2-4.8 = 11.4
Line Loading on 21-22	100%	88%	80%	70%

From the above results, it can be seen that by reducing the net reactance of line more real power flows through the transmission line and MVAR flow absorbed by the transmission line are reduced. Hence, the series compensation is effective in enhancing the system capability by diverting the power flow through the parallel paths which are lightly loaded.

Hence, Series Compensation is specifically helpful in improving the power flow in the transmission line and using the existing infrastructure up to the maximum possible extent.

4.3 Simulations on IEEE-118 Bus System:

In IEEE-118 bus system, performance parameters are calculated through the contingency analysis in PSSE. Then compensation is applied on the selected area and then the results are compared.

4.3.1 Contingency Analysis on Normal IEEE 118 bus System:

Based on outage of each transmission line, contingency cases were built based on outages of transmission lines. The observations were recorded as no. of overloaded lines and no. of voltage deviation buses. The performance parameter was calculated for the system using contingency analysis. The detailed contingency analysis.

Appendix III shows the results of complete process. However, some top contingencies are shown below:

Table 4.8: Main Contingency Analysis on IEEE-118 Bus System

Label	Flow Violation #	Flow Violation Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 37-38(1)	2	121.25	16	0.7957	18
SINGLE 5-8(1)	1	133.26	24	0.8613	16
SINGLE 42-49(1)	2	104.52	9	0.8023	11
SINGLE 89-90(1)	1	148.74	8	0.7185	9
SINGLE 17-30(1)	0	0	8	0.9259	8
SINGLE 22-23(1)	0	0	7	0.9276	7
SINGLE 26-30(1)	3	113.83	4	0.9266	7
SINGLE 17-18(1)	0	0	6	0.9272	6
SINGLE 21-22(1)	0	0	6	0.928	6
SINGLE 49-51(1)	0	0	6	0.9288	6
				Total of all contingencies	**818**

Based on highest values of performance parameters and contingency cases with harsh results, region with buses 37, 38, 42, 49, etc. is most volatile and tripping in the area result in overloading and low voltages. The system results in 818 no. overloading sand voltage violations when contingency analysis was performed.

Now from the analysis, we conclude that we should provide VAR support in the above stated area.

4.3.2 Analysis on IEEE 118 bus System with SVC at Bus 37:

A Static VAR Compensator with Max Limit of 300MVAR is installed on Bus no. 37 and then contingency analysis is performed to study the improvements. Appendix III shows the results of complete process. However, some top contingencies are shown below:

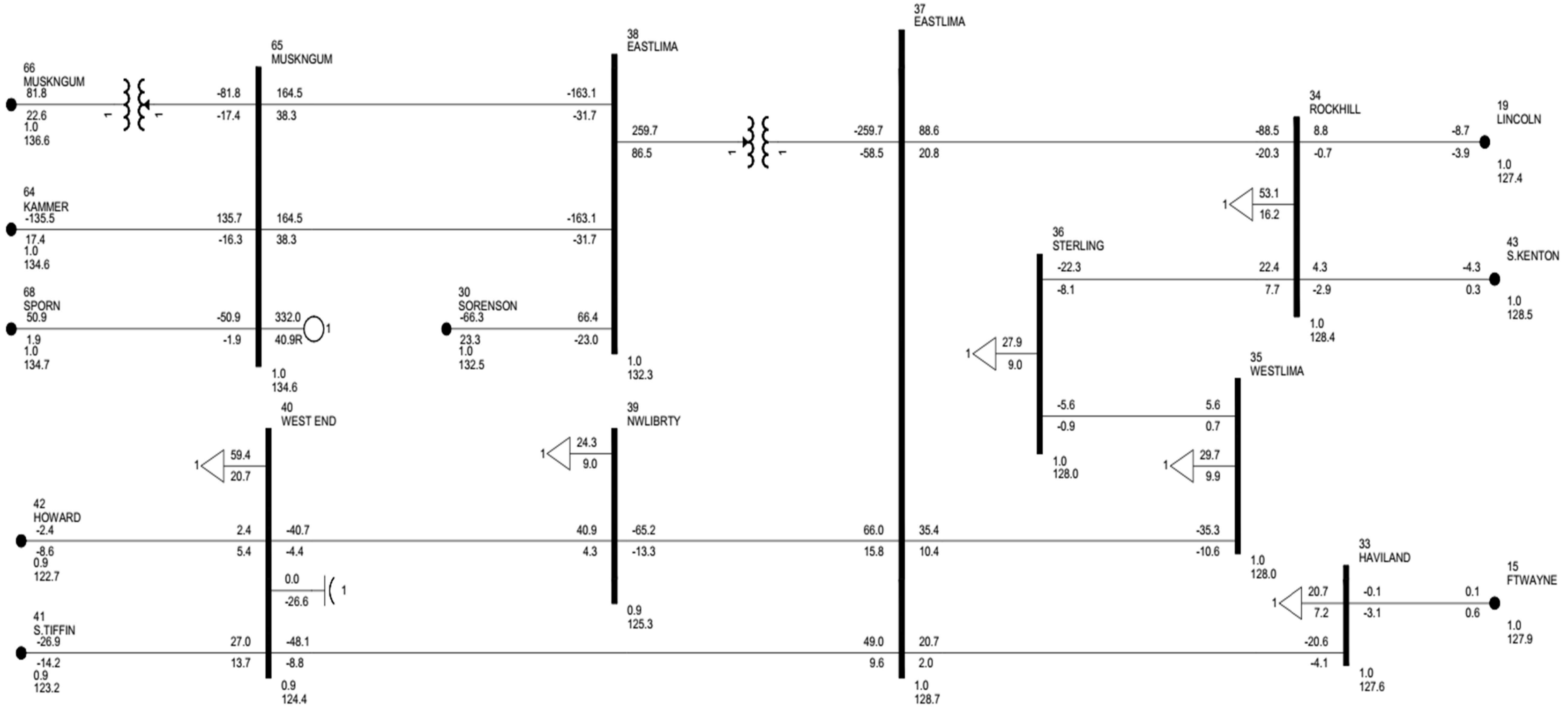
Table 4.9: Main Contingency Analysis on IEEE-118 Bus System after SVC

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 5-8(1)	1	129.09	14	0.896	15
SINGLE 37-39(1)	0	0	4	0.9268	4
SINGLE 42-49(1)	2	100.48	2	0.9235	4
SINGLE 89-90(1)	1	148.75	3	0.7185	4
SINGLE 26-30(1)	3	113.67	0	0	3
SINGLE 37-38(1)	2	120.27	0	0	2
SINGLE 40-41(1)	0	0	2	0.9198	2
SINGLE 49-51(1)	0	0	2	0.9497	2
SINGLE 75-118(1)	0	0	2	0.9197	2
SINGLE 76-77(1)	0	0	2	0.9282	2
				Total of all contingencies	**69**

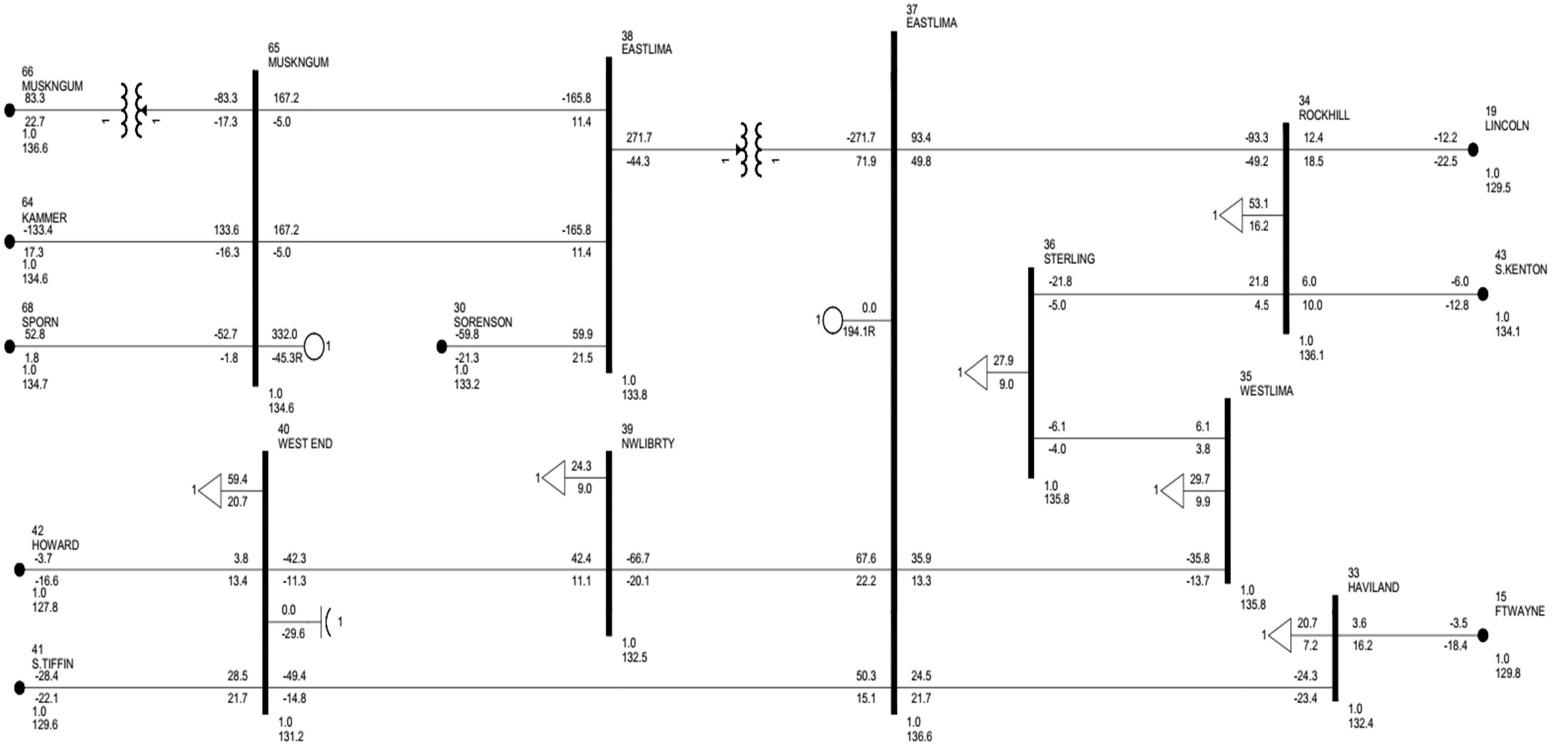
From the above results, it can be observed that the system has resulted in less voltage and flow violations after the installation of SVC and the same have been reduced to 69 against the original value of 818. Hence, the system has improved considerably.

The Single Line diagrams of the system developed in PSSE with the load flow values are shown:

IEEE-118 Bus SLD (Selected Area) Without FACTS Device



IEEE-118 Bus SLD (Selected Area) With SVC at Bus 37



Now we compare the improvement in voltages at some nearby buses before and after installation of SVC in normal condition i.e., without contingency.

Table 4.10: Comparison of Bus Voltages Before/After Installation of SVC on IEEE-118

Bus No.	Voltage before installation of SVC	Voltage after installation of SVC	Improvement
15	127.9 kV	129.8 kV	1.9 kV
19	127.4 kV	129.5 kV	2.1 kV
30	132.5 kV	133.2 kV	0.7 kV
33	127.6 kV	132.4 kV	4.8 kV
34	128.4 kV	136.1 kV	7.7 kV
35	128.0 kV	135.8 kV	7.8 kV
36	128.0 kV	135.8 kV	7.8 kV
37	128.7 kV	136.6 kV	7.9 kV
38	132.3 kV	133.8 kV	1.5 kV
39	125.3 kV	132.5 kV	7.2 kV
40	124.4 kV	131.2 kV	6.8 kV
41	123.2 kV	129.6 kV	6.4 kV
42	122.7 kV	127.8 kV	5.1 kV
43	128.5 kV	134.1 kV	5.6 kV
64	134.6 kV	134.6 kV	-
65	134.6 kV	134.6 kV	-
66	136.6 kV	136.6 kV	-
68	134.7 kV	134.7 kV	-

The above results show the considerable improvement in bus voltage in the system after installation of SVC.

4.3.3 Dynamic/Fault Analysis on Normal IEEE 118 bus System:

Various cases with bus fault on different buses were studied in normal scenario. The dynamic data of generators, exciters & rotors was taken from NTDC base cases [37]. This data is based on the actual models of generators (salient and non-salient poles).

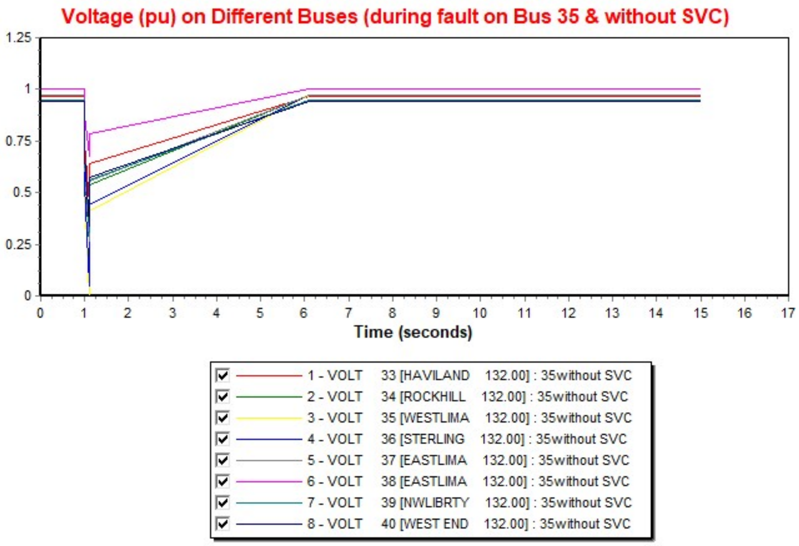
The dynamic simulations were run as per following steps:

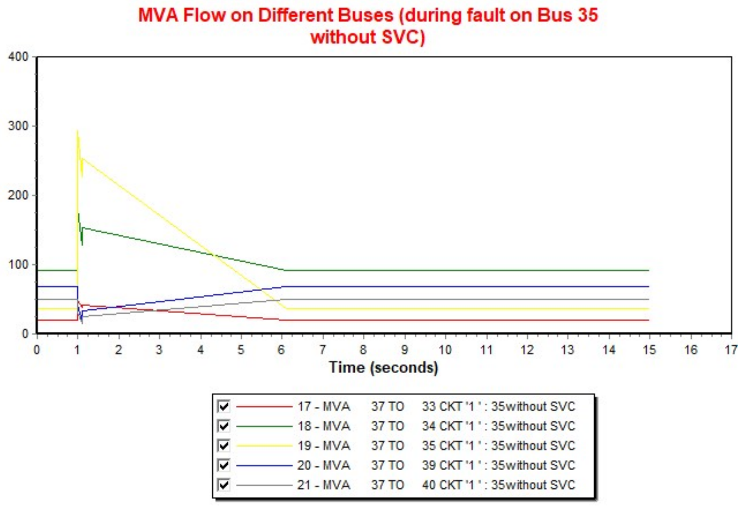
- System was initialized on dynamic parameters of generators.
- Simulation was run for 1 second.
- Fault on bus was introduced at t=1sec.
- Fault was cleared at t=1.1sec with/without outage of transmission line.
- Simulation was run till t=15sec to study Load flow on nearby transmission lines.

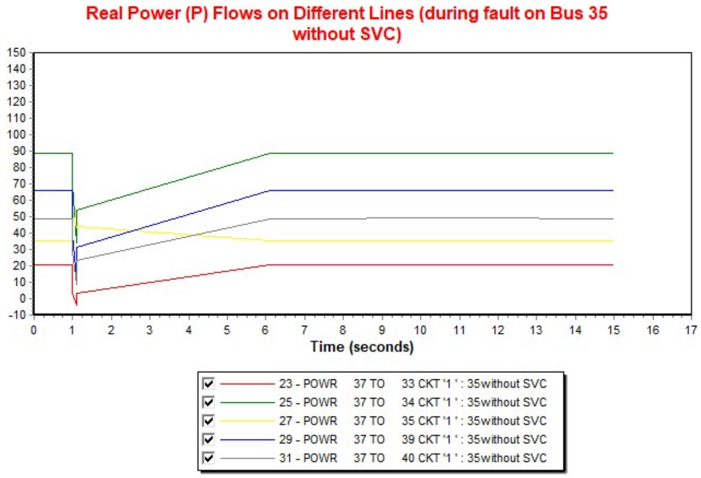
The case scenarios are discussed as under:

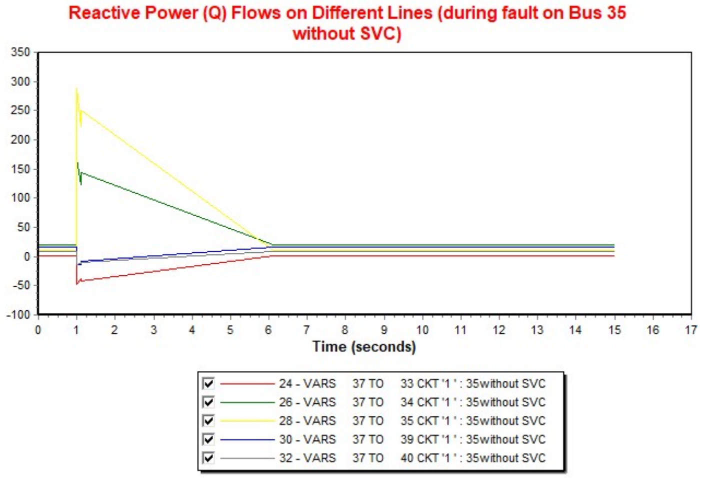
4.3.3.1 Fault on Bus 35 without line tripping & without FACTS Device:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown.



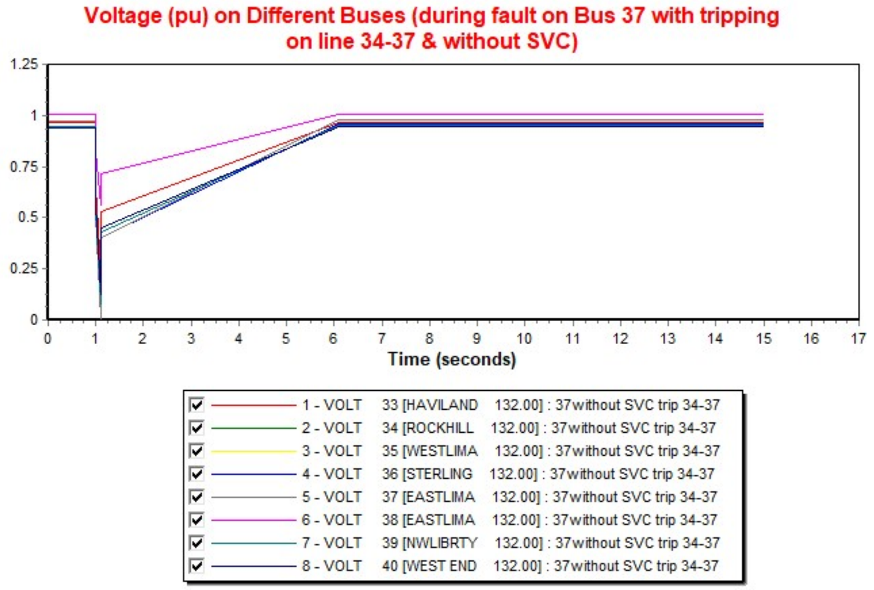

MVA Flow on Different Buses (during fault on Bus 35 without SVC)
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Time (seconds)
☑ 17 - MVA 37 TO 33 CKT '1 ' : 35without SVC
☑ 18 - MVA 37 TO 34 CKT '1 ' : 35without SVC
☑ 19 - MVA 37 TO 35 CKT '1 ' : 35without SVC
☑ 20 - MVA 37 TO 39 CKT '1 ' : 35without SVC
☑ 21 - MVA 37 TO 40 CKT '1 ' : 35without SVC

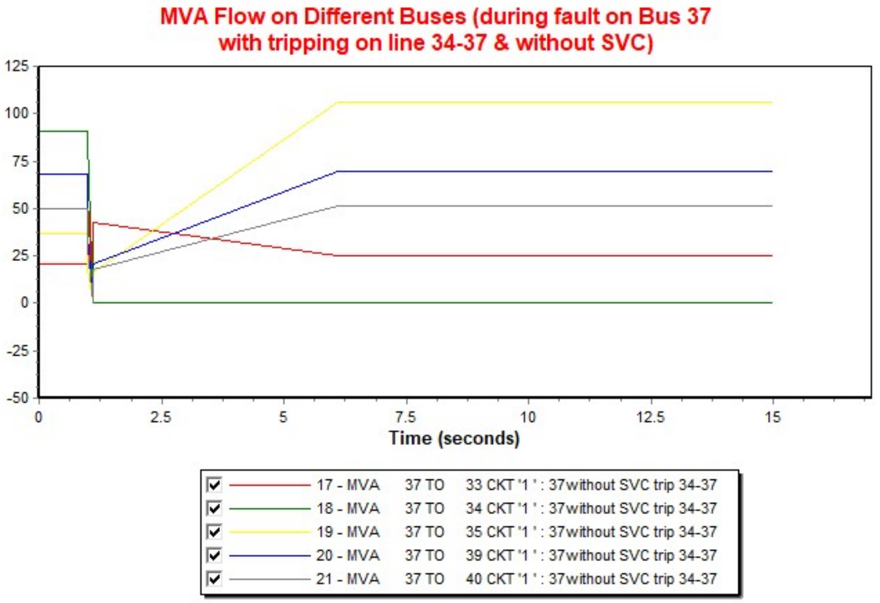

Real Power (P) Flows on Different Lines (during fault on Bus 35 without SVC)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Time (seconds)
☑ 23 - POWR 37 TO 33 CKT '1 ' : 35without SVC
☑ 25 - POWR 37 TO 34 CKT '1 ' : 35without SVC
☑ 27 - POWR 37 TO 35 CKT '1 ' : 35without SVC
☑ 29 - POWR 37 TO 39 CKT '1 ' : 35without SVC
☑ 31 - POWR 37 TO 40 CKT '1 ' : 35without SVC

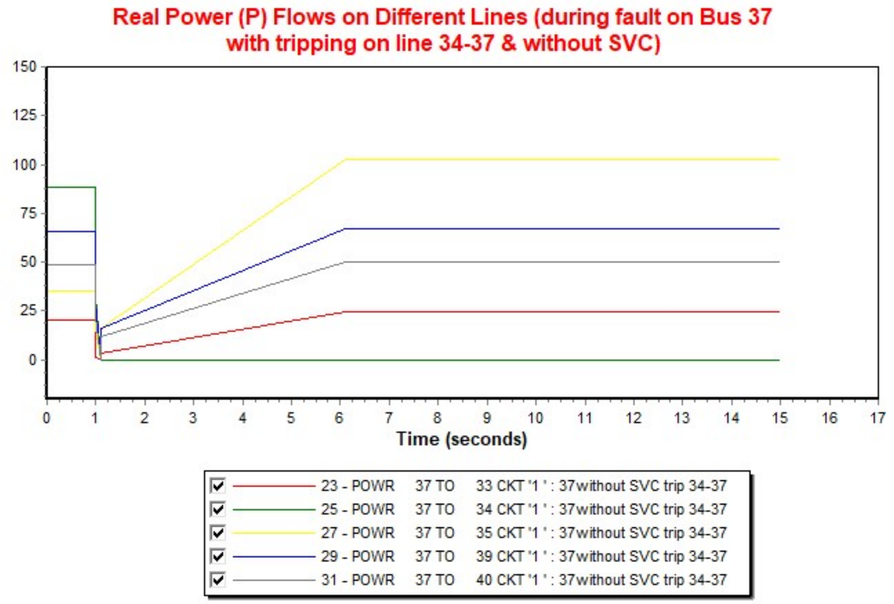

Reactive Power (Q) Flows on Different Lines (during fault on Bus 35 without SVC)
350
300
250
200
150
100
50
0
-50
-100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Time (seconds)
☑ 24 - VARS 37 TO 33 CKT '1 ' : 35without SVC
☑ 26 - VARS 37 TO 34 CKT '1 ' : 35without SVC
☑ 28 - VARS 37 TO 35 CKT '1 ' : 35without SVC
☑ 30 - VARS 37 TO 39 CKT '1 ' : 35without SVC
☑ 32 - VARS 37 TO 40 CKT '1 ' : 35without SVC

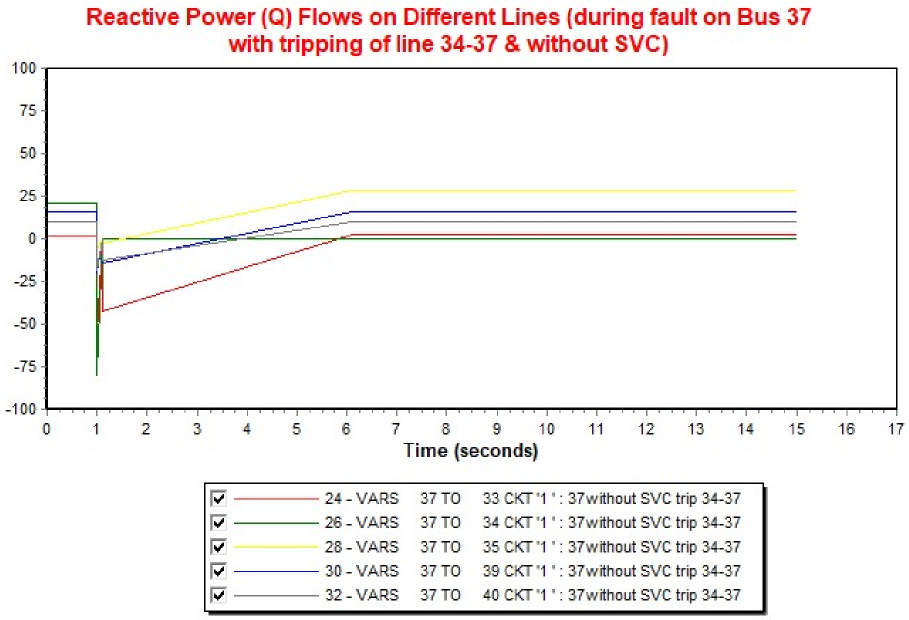
4.3.3.2 Fault on Bus 37 with tripping of line 34-37 & without FACTS Device:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown.



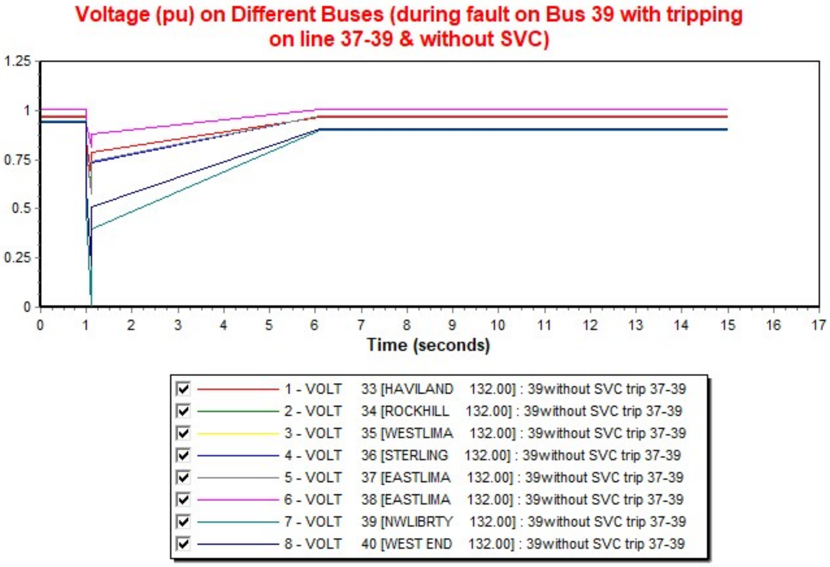


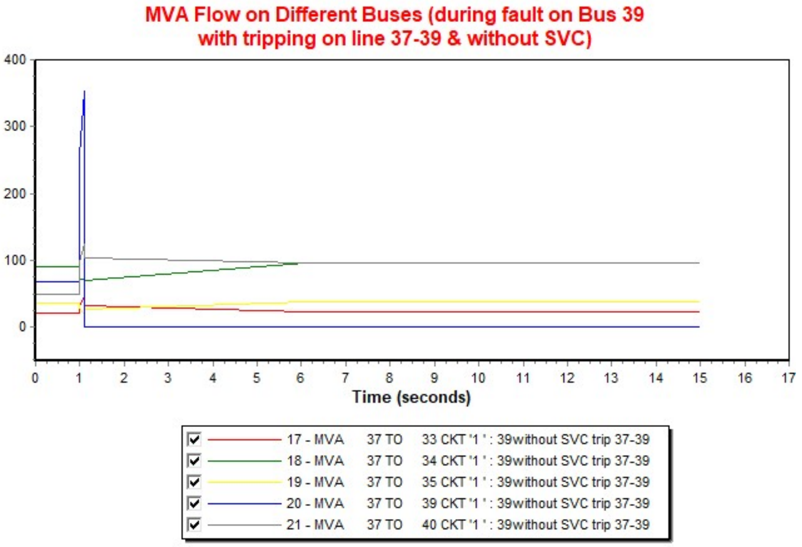

Real Power (P) Flows on Different Lines (during fault on Bus 37 with tripping on line 34-37 & without SVC)

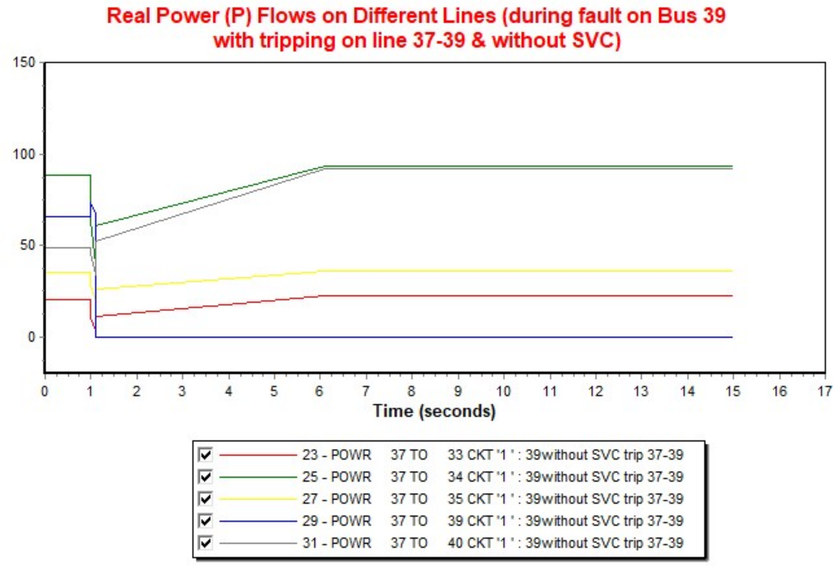

Reactive Power (Q) Flows on Different Lines (during fault on Bus 37 with tripping of line 34-37 & without SVC)

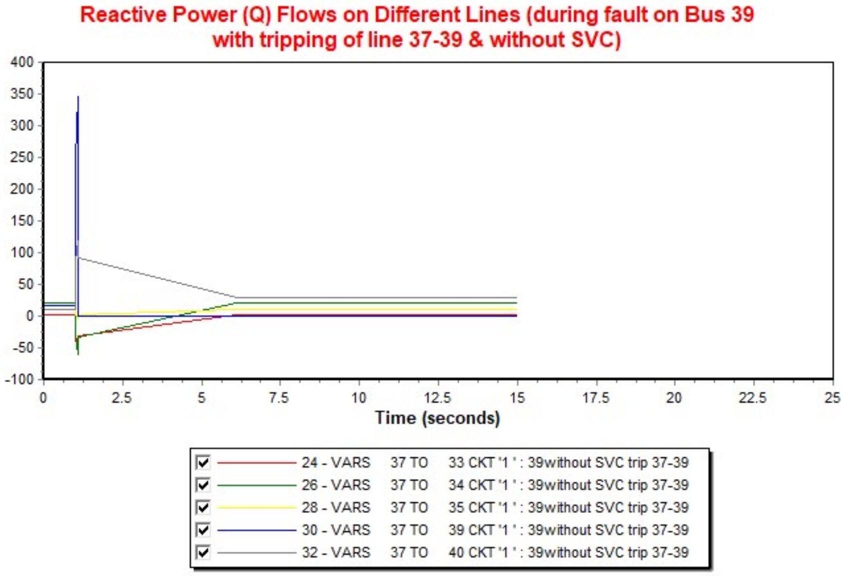
4.3.3.3 Fault on Bus 39 with line tripping of 37-39 & without FACTS Device:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown.


Voltage (pu) on Different Buses (during fault on Bus 39 with tripping on line 37-39 & without SVC)

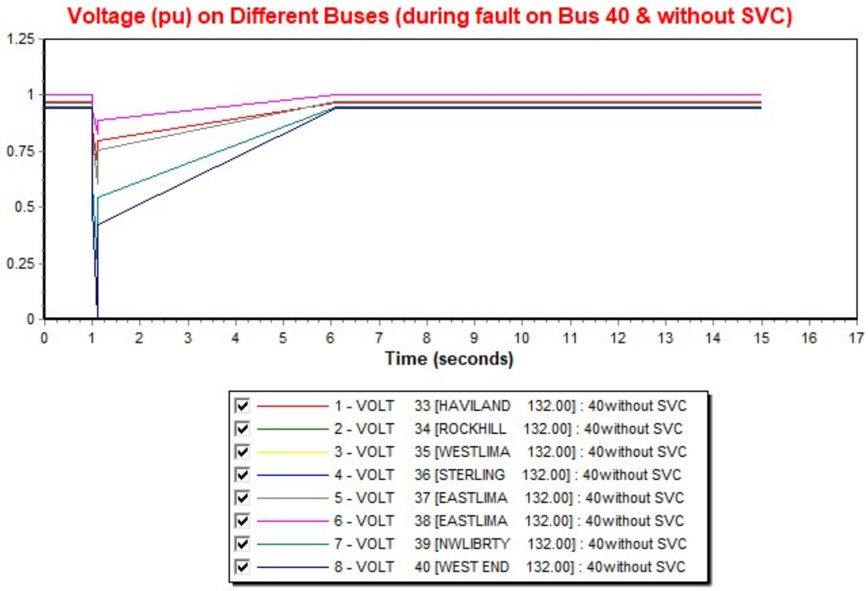

MVA Flow on Different Buses (during fault on Bus 39 with tripping on line 37-39 & without SVC)

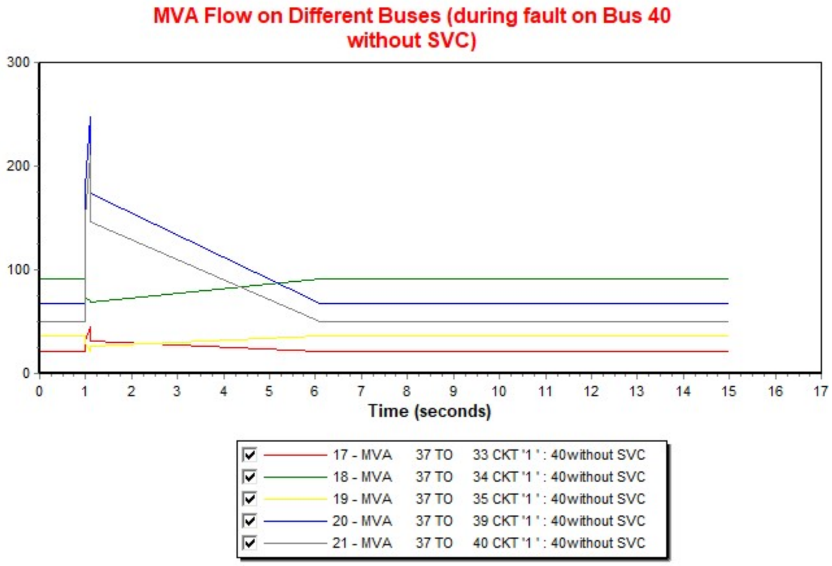

Real Power (P) Flows on Different Lines (during fault on Bus 39
with tripping on line 37-39 & without SVC)
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Time (seconds)
☑ 23 - POWR 37 TO 33 CKT '1 ' : 39without SVC trip 37-39
☑ 25 - POWR 37 TO 34 CKT '1 ' : 39without SVC trip 37-39
☑ 27 - POWR 37 TO 35 CKT '1 ' : 39without SVC trip 37-39
☑ 29 - POWR 37 TO 39 CKT '1 ' : 39without SVC trip 37-39
☑ 31 - POWR 37 TO 40 CKT '1 ' : 39without SVC trip 37-39

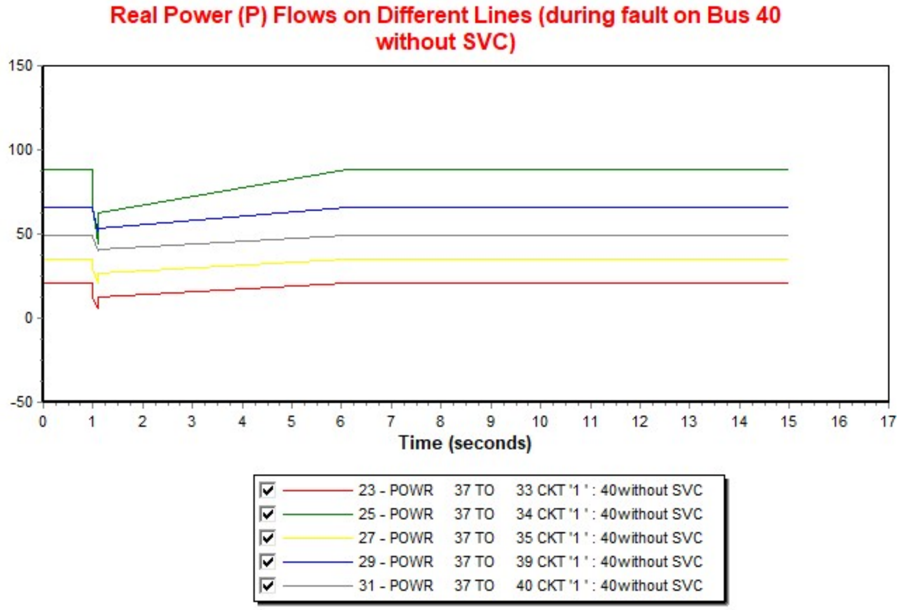

Reactive Power (Q) Flows on Different Lines (during fault on Bus 39
with tripping of line 37-39 & without SVC)
400
350
300
250
200
150
100
50
0
-50
-100
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
Time (seconds)
☑ 24 - VARS 37 TO 33 CKT '1 ' : 39without SVC trip 37-39
☑ 26 - VARS 37 TO 34 CKT '1 ' : 39without SVC trip 37-39
☑ 28 - VARS 37 TO 35 CKT '1 ' : 39without SVC trip 37-39
☑ 30 - VARS 37 TO 39 CKT '1 ' : 39without SVC trip 37-39
☑ 32 - VARS 37 TO 40 CKT '1 ' : 39without SVC trip 37-39

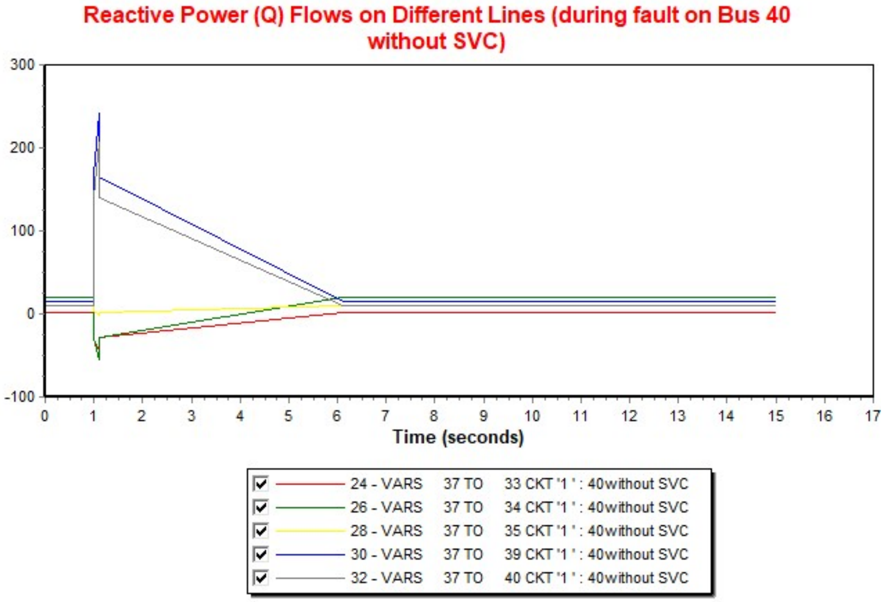
4.3.3.4 Fault on Bus 40 without tripping & without FACTS Device:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown.






Real Power (P) Flows on Different Lines (during fault on Bus 40 without SVC)
150
100
50
0
-50
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Time (seconds)
☑ 23 - POWR 37 TO 33 CKT '1 ' : 40without SVC
☑ 25 - POWR 37 TO 34 CKT '1 ' : 40without SVC
☑ 27 - POWR 37 TO 35 CKT '1 ' : 40without SVC
☑ 29 - POWR 37 TO 39 CKT '1 ' : 40without SVC
☑ 31 - POWR 37 TO 40 CKT '1 ' : 40without SVC


Reactive Power (Q) Flows on Different Lines (during fault on Bus 40 without SVC)
300
200
100
0
-100
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Time (seconds)
☑ 24 - VARS 37 TO 33 CKT '1 ' : 40without SVC
☑ 26 - VARS 37 TO 34 CKT '1 ' : 40without SVC
☑ 28 - VARS 37 TO 35 CKT '1 ' : 40without SVC
☑ 30 - VARS 37 TO 39 CKT '1 ' : 40without SVC
☑ 32 - VARS 37 TO 40 CKT '1 ' : 40without SVC

4.3.4 Dynamic Analysis on IEEE 118 bus System with SVC at Bus 37:

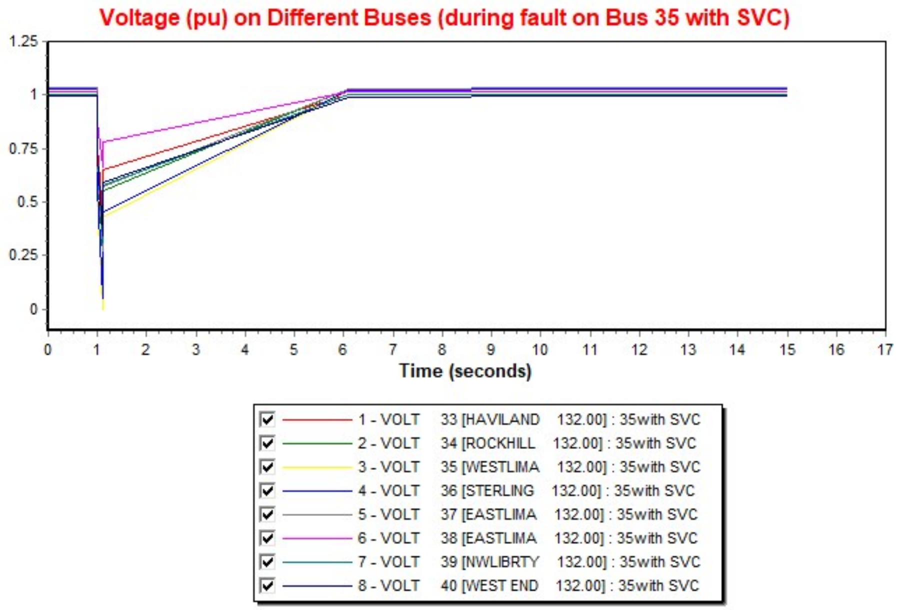
Various cases with bus fault on different buses were studied after installation of SVC in the system. The dynamic data of generators, exciters, SVC & rotors was taken from NTDC base cases [37]. This data is based on the actual models of generators (salient and non-salient poles).

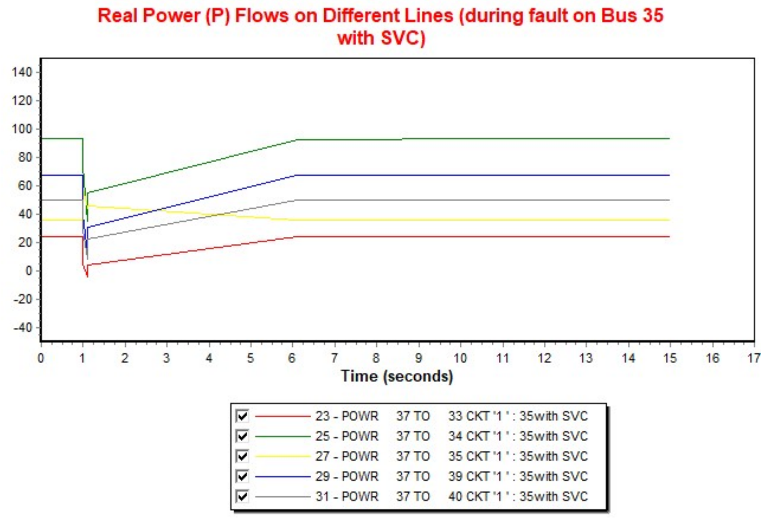
- The dynamic simulations were run as per following steps:
- System was initialized on dynamic parameters of generators.
- Simulation was run for 1 second.
- Fault on bus was introduced at t=1sec.
- Fault was cleared at t=1.1sec with/without outage of transmission line.
- Simulation was run till t=15sec to study Load flow on nearby transmission lines.

The case scenarios are discussed as under:

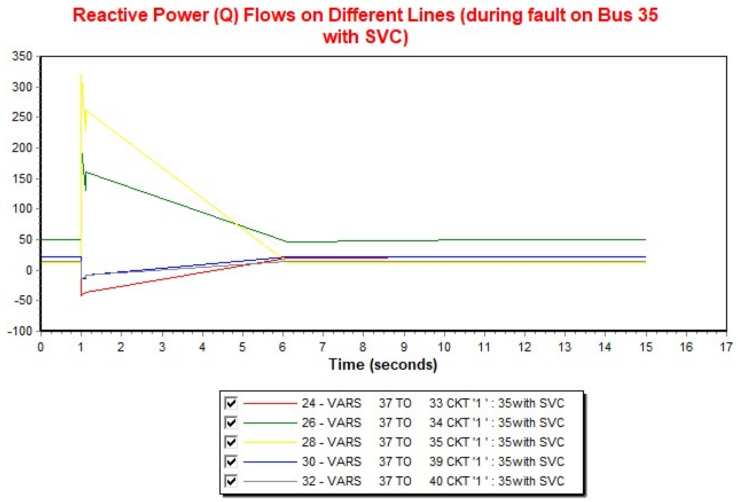
4.3.4.1 Fault on Bus 35 without line tripping & with SVC at Bus 37:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown:

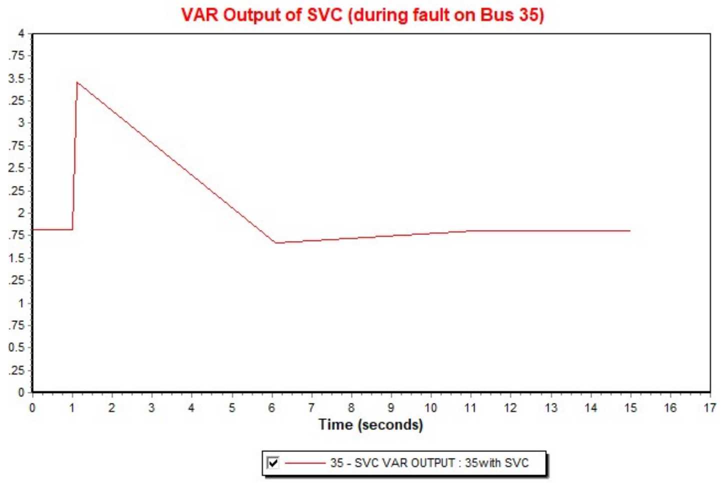




Real Power (P) Flows on Different Lines (during fault on Bus 35 with SVC)



Reactive Power (Q) Flows on Different Lines (during fault on Bus 35 with SVC)

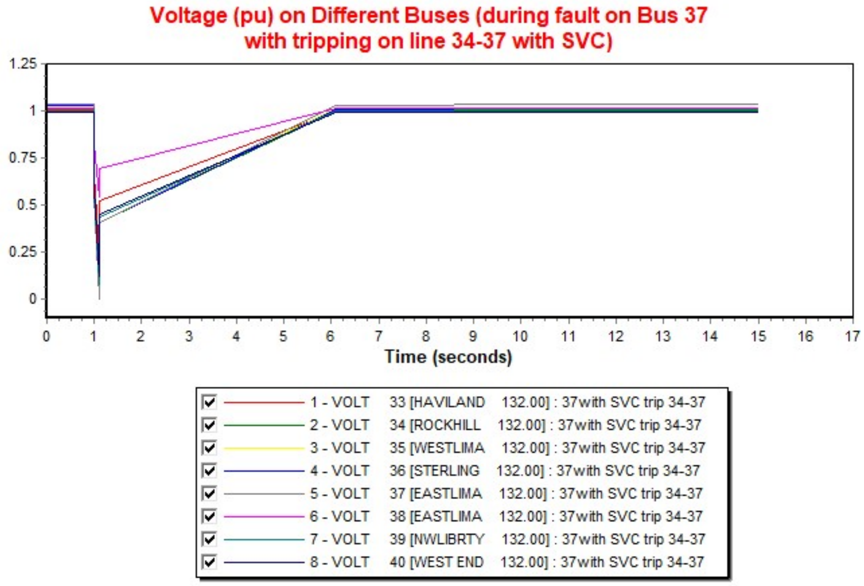


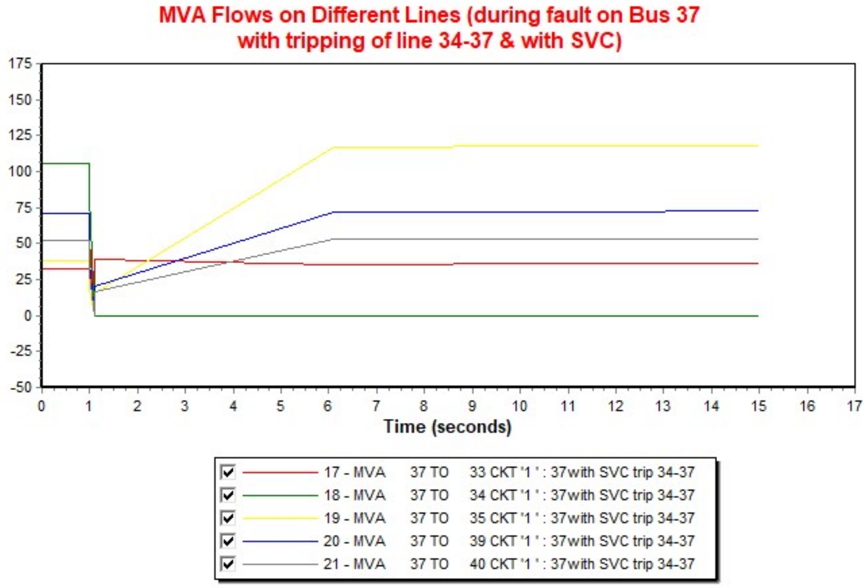
VAR Output of SVC (during fault on Bus 35)

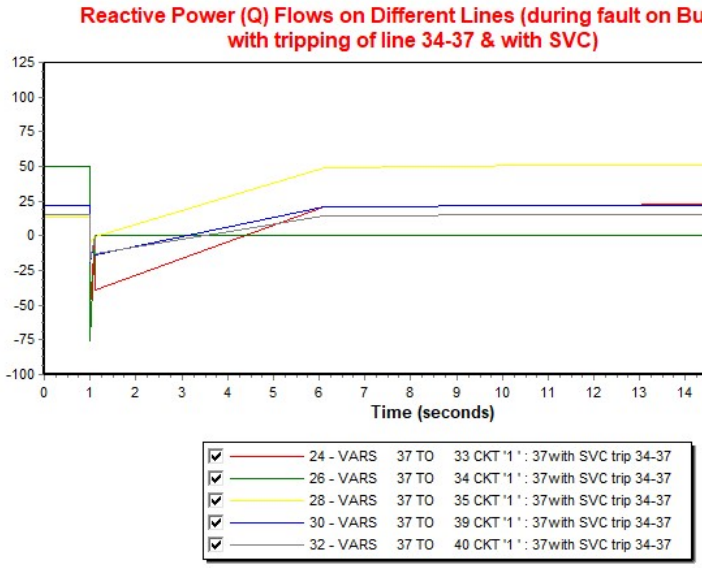
The results depict that system normalizes to its pre-fault position in the steady state after fault introduction and clearing. The SVC provide reactive power support during the fault up to the maximum limit and adjust its output accordingly.

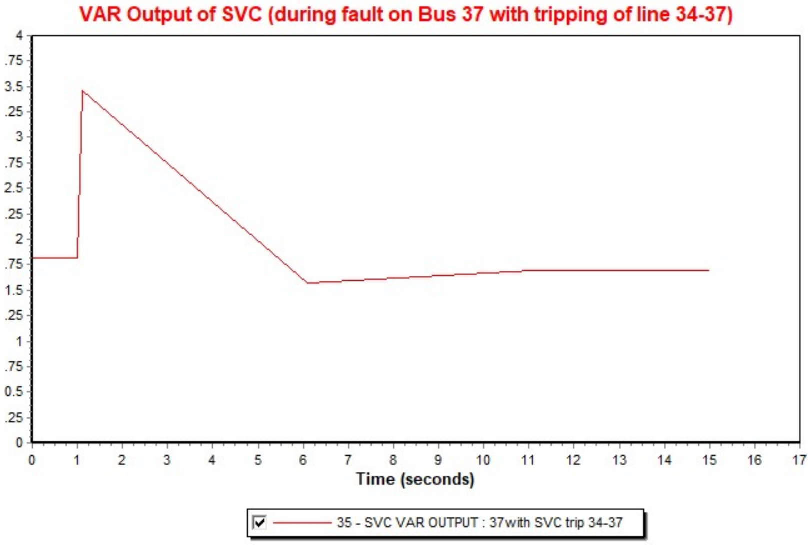
4.3.4.2 Fault on Bus 37 with tripping of line 34-37 & with SVC at Bus 37:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown:





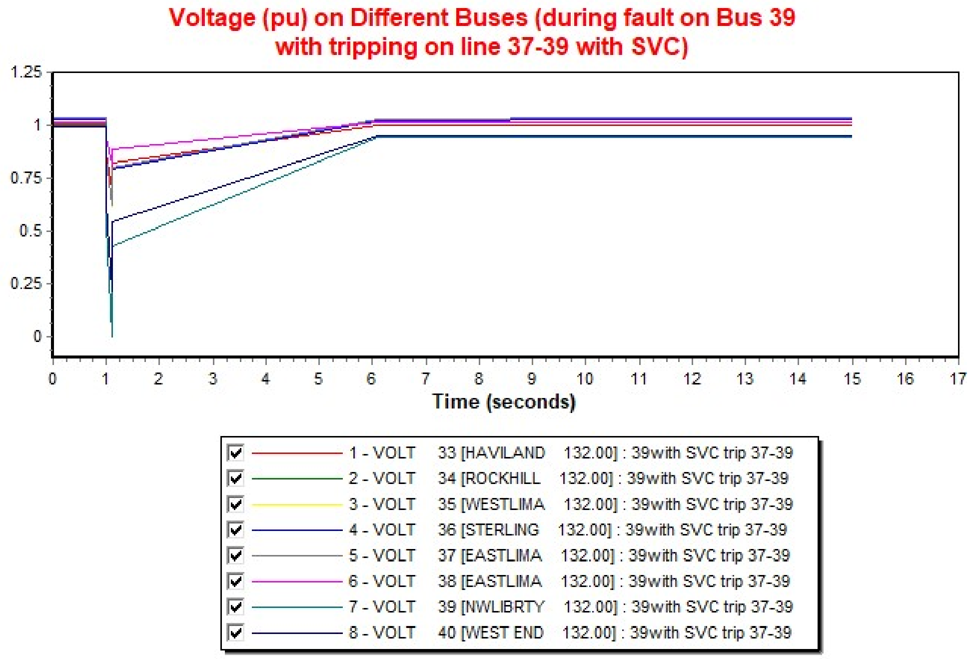




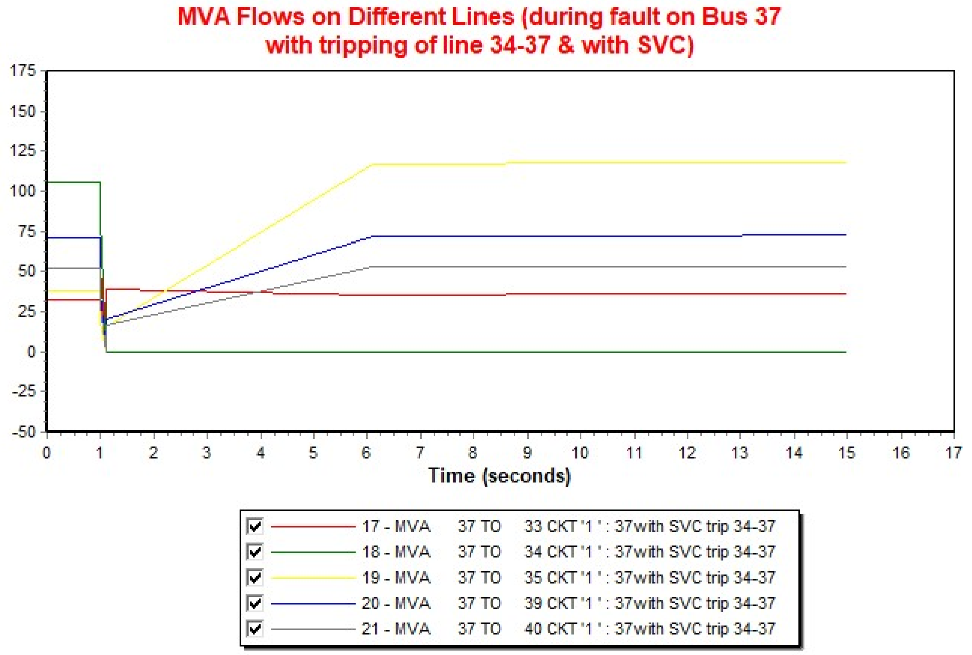
The results depict that system normalizes to its pre-fault position in the steady state after fault introduction and clearing. The SVC provide reactive power support during the fault up to the maximum limit and adjust its output accordingly. The real and reactive power flows change on the lines due to tripping/outage of a single circuit.

4.3.4.3 Fault on Bus 39 with line tripping at 37-39 & with SVC at Bus 37:

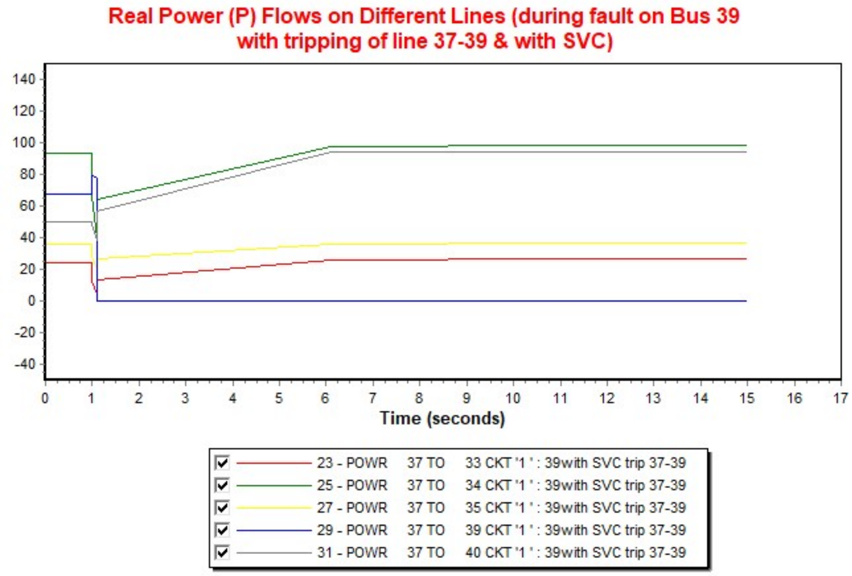
The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown:

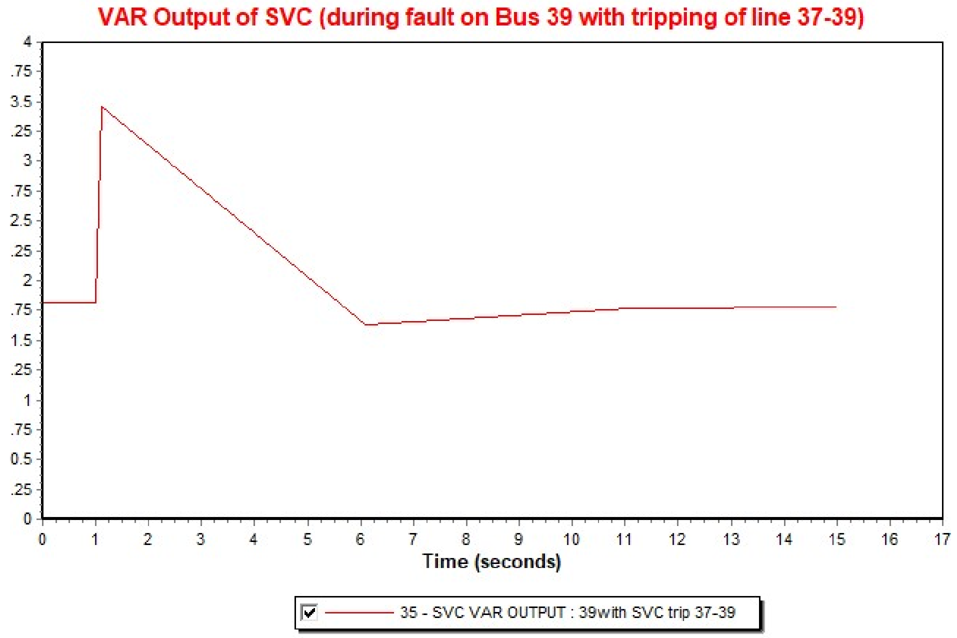


Voltage (pu) on Different Buses (during fault on Bus 39 with tripping on line 37-39 with SVC)



MVA Flows on Different Lines (during fault on Bus 37 with tripping of line 34-37 & with SVC)

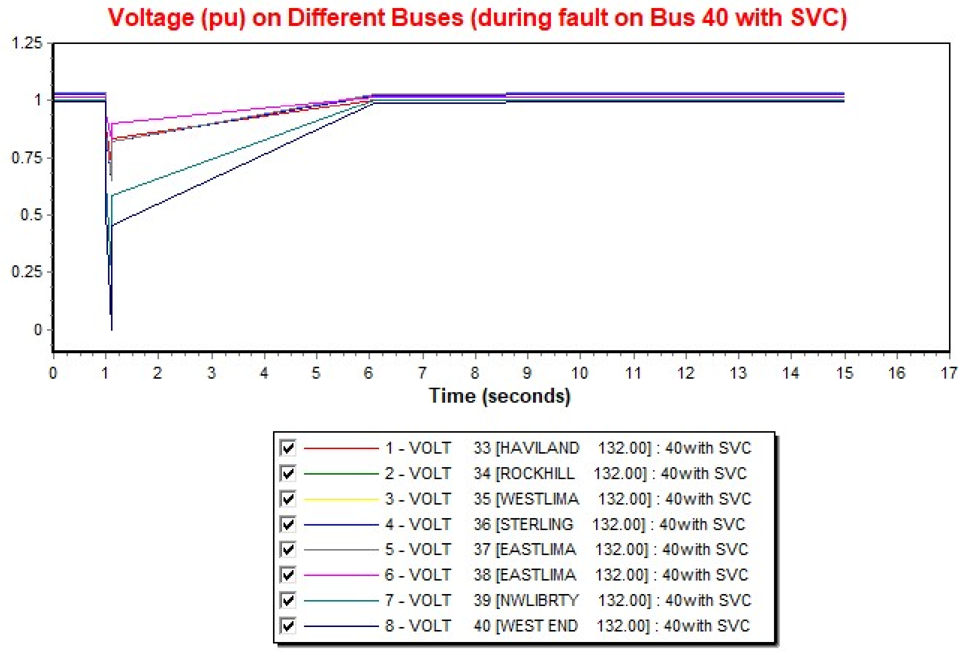

Real Power (P) Flows on Different Lines (during fault on Bus 39 with tripping of line 37-39 & with SVC)

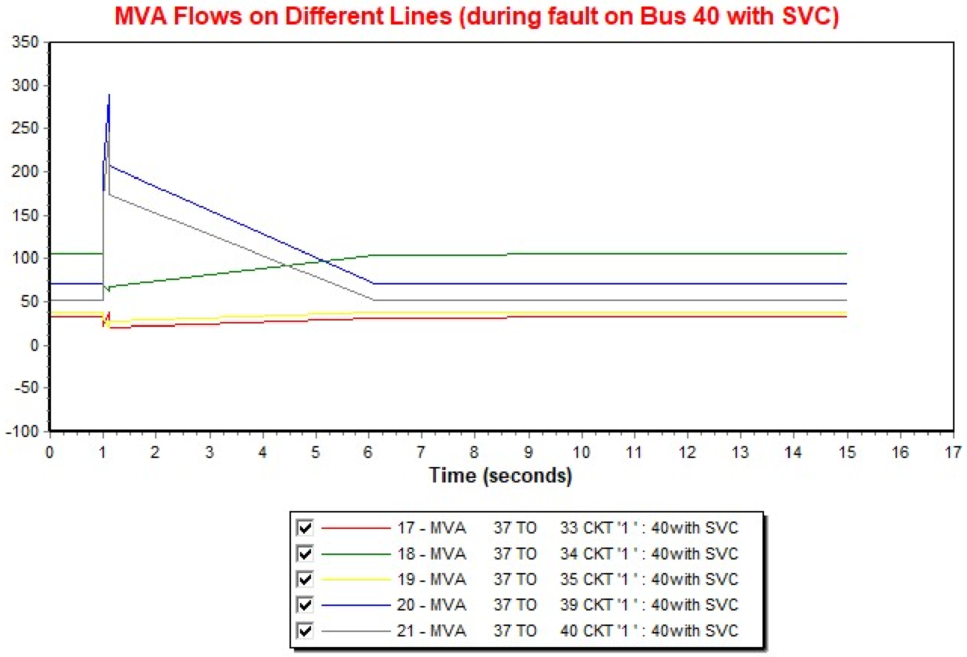

VAR Output of SVC (during fault on Bus 39 with tripping of line 37-39)

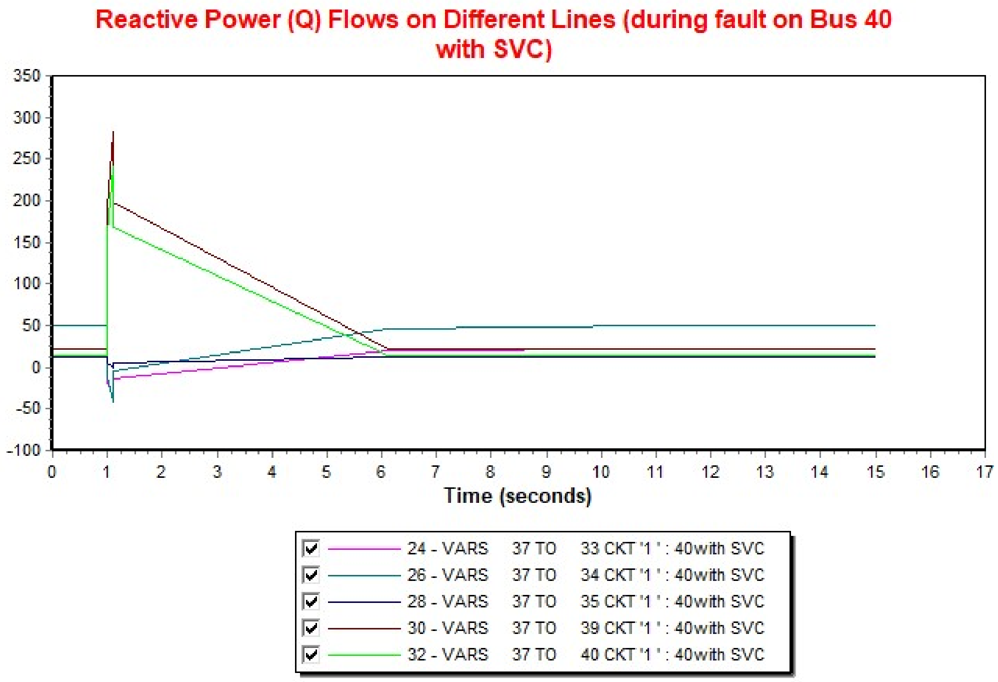
The results depict that system normalizes to its pre-fault position in the steady state after fault introduction and clearing. The SVC provide reactive power support during the fault up to the maximum limit and adjust its output accordingly. The real and reactive power flows change on the lines due to tripping/outage of a single circuit.

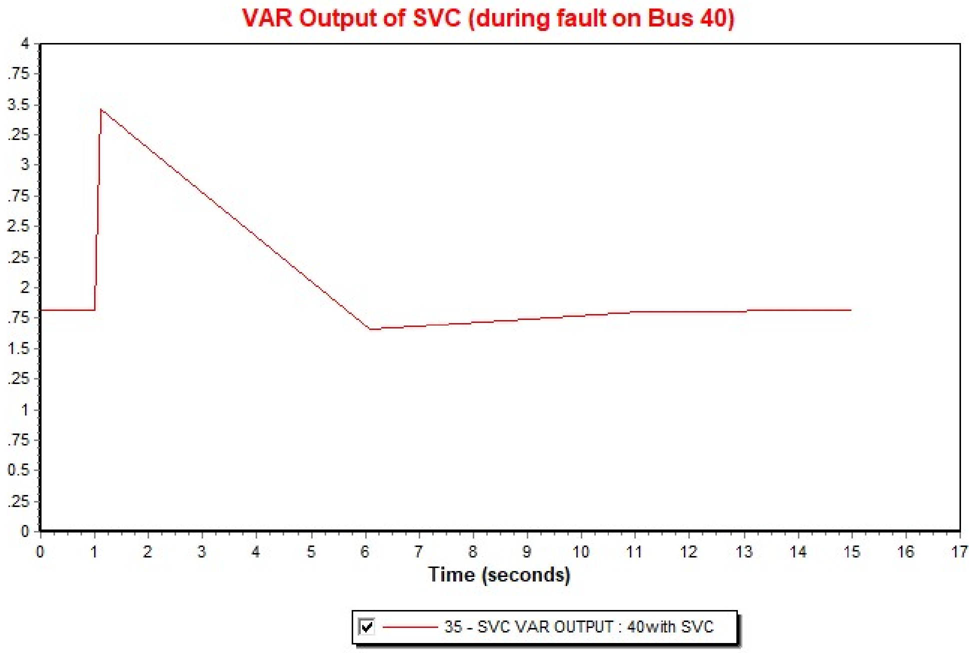
4.3.4.4 Fault on Bus 40 without tripping of line & with SVC at Bus 37:

The fault was introduced at t=1sec and cleared at 1.1sec. The results were plotted which show response of system after fault clearing, which are shown









The results depict that system normalizes to its pre-fault position in the steady state after fault introduction and clearing. The SVC provide reactive power support during the fault up to the maximum limit and adjust its output accordingly.

4.4 Simulations on Real Time System of Pakistan:

In the real time system of Pakistan weak areas are identified. In the PESCO network near DI Khan, extreme low voltage issues have been observed and SVC is proposed in the area. Even after the commissioning of 220kV Grid Station DI Khan in February, 2019, the area still faces low voltage problems.

The SVC is proposed at 132kV level (secondary transmission) as the requirement of reactive power is mostly in the distribution network due to presence of inductive loads and hence compensation shall be provided near to the distribution.

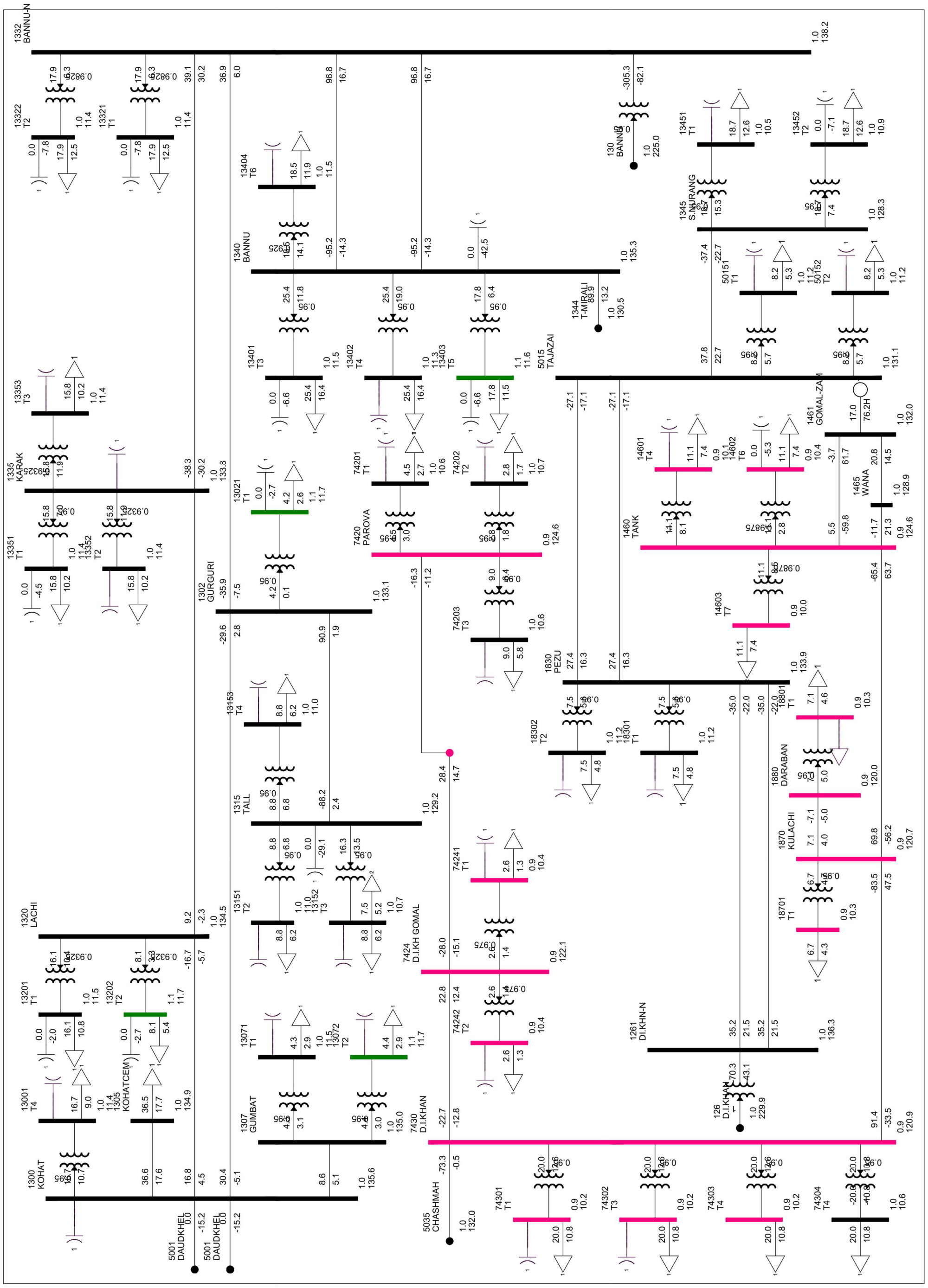
The Voltage improvement in the system with and without installation of SVC is shown below:

Table 4.11: Comparison of Bus Voltages Before/After Installation of SVC in Real Time Network of Pakistan

Bus No.	Base kV	Voltage before installation of SVC	Voltage after installation of SVC	Improvement	% age Improvement
7420	132 kV	124.6 kV	132.0 kV	7.4 kV	5.93 %
7424	132 kV	122.1 kV	131.9 kV	9.8 kV	8.03 %
7430	132 kV	120.9 kV	132.0 kV	11.1 kV	9.18 %
1460	132 kV	124.6 kV	127.8 kV	3.2 kV	2.57 %
1880	132 kV	120.0 kV	127.0 kV	7.0 kV	5.83 %
1870	132 kV	120.7 kV	127.6 kV	7.1 kV	5.88 %
74201	11 kV	10.6 kV	11.3 kV	0.7 kV	6.60 %
74202	11 kV	10.7 kV	11.4 kV	0.7 kV	6.54 %
74203	11 kV	10.6 kV	11.3 kV	0.7 kV	6.60 %
74241	11 kV	10.4 kV	11.2 kV	0.8 kV	7.69 %
74242	11 kV	10.4 kV	11.2 kV	0.8 kV	7.69 %
74301	11 kV	10.2 kV	11.2 kV	1.0 kV	9.80 %
74302	11 kV	10.2 kV	11.2 kV	1.0 kV	9.80 %
74303	11 kV	10.2 kV	11.2 kV	1.0 kV	9.80 %
74304	11 kV	10.6 kV	11.6 kV	1.0 kV	9.43 %
14601	11 kV	10.1 kV	10.4 kV	0.3 kV	2.97 %
14602	11 kV	10.4 kV	10.7 kV	0.3 kV	2.88 %
14603	11 kV	10.0 kV	10.3 kV	0.3 kV	3.00 %
18801	11 kV	10.3 kV	10.9 kV	0.6 kV	5.83 %
18701	11 kV	10.3 kV	11.0 kV	0.7 kV	6.79 %

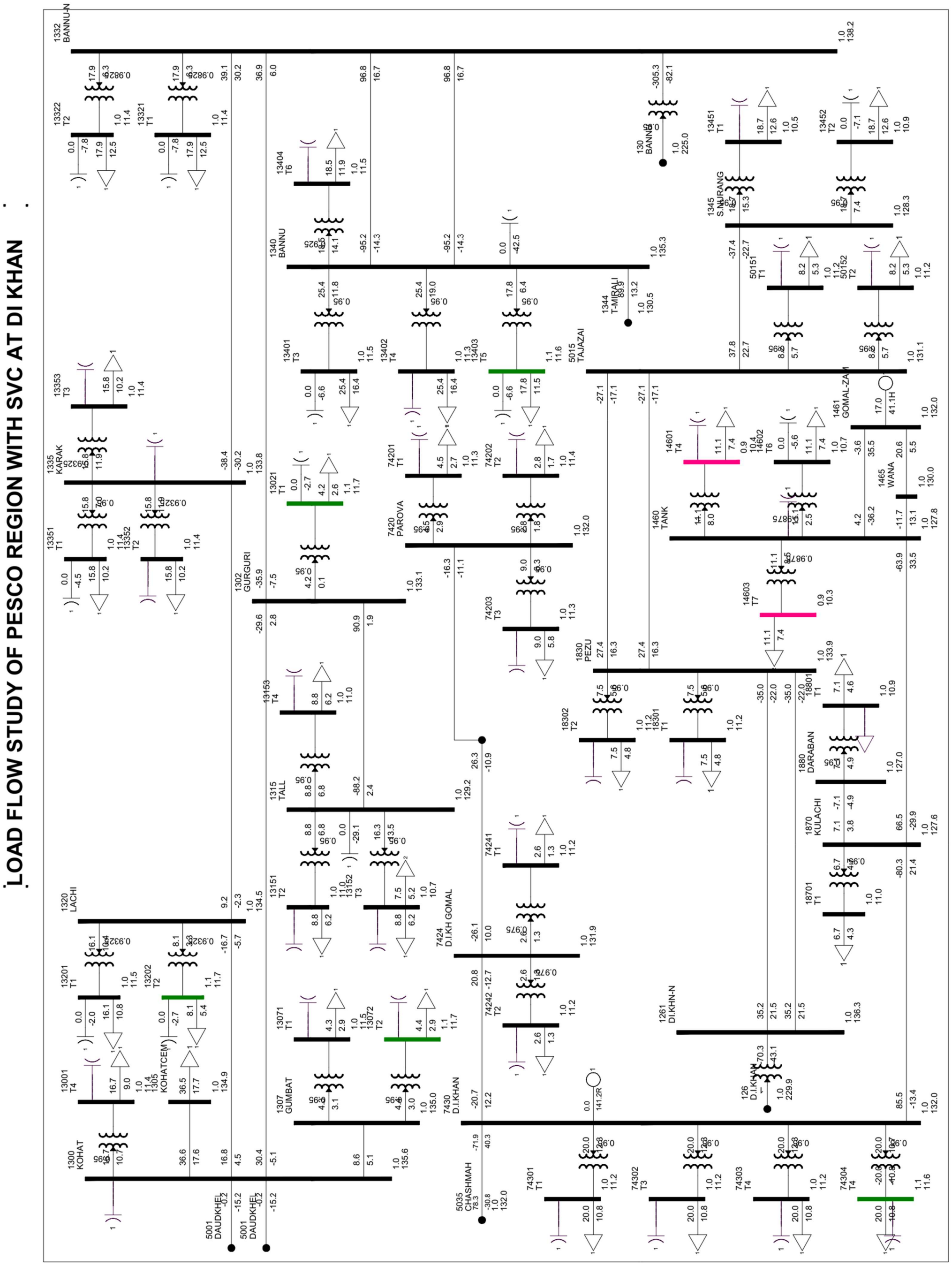
The above results show the considerable improvement in bus voltage in the system after installation of SVC.

The Single Line Diagram of the System without/before installation of SVC is shown below:



LOAD FLOW STUDY OF PESCO REGION WITHOUT SVC

The Single Line Diagram of the System with/after installation of 200MVAR SVC is shown below:



The System showed considerable improvement after installation of SVC on DI Khan and Voltage improvements were confirmed. The installation of SVC also results in low losses as the VAR support is provided at the local level.

CHAPTER 5

DISCUSSION & CONCLUSION

In this research work, the effect of installation of SVC and Series Compensation has been studied. The SVC were installed at suitable locations pointed out using Performance Parameter and the improvements were recorded. The simulations were done both on IEEE networks and Real Time network of Pakistan and hence a local contribution was also included in the thesis.

The above stated techniques have been utilized to provide compensation to the weak branches of the system identified through Performance Parameter. Installation of SVC resulted in improvement of the power system and minimized the voltage deviations from nominal values and overloading of transmission lines whereas the Series Compensation of Transmission Line primarily improves the flow of Power through the Transmission Line.

The work was done in two parts: In the first part contingencies analysis was performed using Newton Raphson method and performance parameter was calculated based on number of overloaded transmission line and Number of buses with voltage violations. Based on the performance parameter, weakest area was identified and then compensation was installed on the system in the form of Static VAR Compensator (SVC) in IEEE-14, 39 & 118 Bus System and Real time network of Pakistan. Moreover, Series Compensation was applied on IEEE-39 Bus System.

5.1 Comments on Results:

The results were acquired for both before and after installation of Compensation mechanism. The results showed that power flow, voltages and reliability of power system is greatly improved after installation of FACTS Devices. SVC and Series Compensation yielded different results which are listed below:

- The installation of SVC resulted in VAR support in the system and notable improvement in Voltage Profile was observed.
- The Reactive Power required was provided locally instead of taking it from the transmission network which previously caused overloading of lines.
- The VAR output of the SVC was dependent on the requirement of the system and it automatically adjust its output to meet the reactive power demand and hence it is very advantageous as compared to the traditionally used Fixed Shunt Capacitors.
- The installation of Series Compensation resulted in modified reactance of transmission line due to which power flow was increased through the line.
- The Series Compensation is specifically helpful in maneuvering the power flow towards lightly loaded lines in the parallel/ring system.
- Series Compensation can control power flow in such a way that loading on one line was minimized and power flow was diverted to other lightly loaded line.

5.2 Future Work:

Following future work is proposed:

- The dynamic analysis show that the system is stable after the introduction of fault and clearing it with/without tripping of transmission line, however, fine tuning of parameters can be studied to dampen the oscillations/surge in system parameters and steady state settling time can be minimized.
- Coordinated response of multiple FACTS devices installed in the system can be studied.
- The uncertain generations i.e., Wind & Solar can be included and impact of different generation levels can be studied.

REFERENCES

[1] Hines, P., Apt, J., & Talukdar, S. (2009). Large blackouts in North America: Historical trends and policy implications. *Energy Policy*, *37*(12), 5249-5259.

[2] Amraee, T., & Saberi, H. (2017). Controlled islanding using transmission switching and load shedding for enhancing power grid resilience. *International Journal of Electrical Power & Energy Systems*, *91*, 135-143.

[3] Soroudi, A. (2021). Controllable transmission networks under demand uncertainty with modular FACTS. *International Journal of Electrical Power & Energy Systems*, *130*, 106978.

[4] Museler, W. J. (2004). President and CEO of the New York Independent System Operator (NYISO), presentation May 22, 2003, New York City. *Accessed April*.

[5] Divan, D., Brumsickle, W., Schneider, R., Kranz, B., Gascoigne, R., Bradshaw, D., ... & Grant, I. (2004, October). A distributed static series compensator system for realizing active power flow control on existing power lines. In *IEEE PES Power Systems Conference and Exposition, 2004.* (pp. 654-661). IEEE.

[6] Gogoi, K., & Chatterjee, S. (2021). PSSE-Based Dynamic Simulation of Western Regional Grid of India. *Electrica*, *21*(3), 408-420.

[7] Gogoi, K., & Chatterjee, S. (2020). Dynamic Simulation of Eastern Regional Grid of India using Power System Simulator for Engineering PSS® E. *International Journal of Emerging Electric Power Systems*, *21*(3).

[8] H. Saadat, Power System Analysis, 13th ed. Tata McGraw Hill Publications, pp. 200–202, 450–460.

[9] P. Kundur., Power System Stability and Control, McGraw-Hill, 1994

[10] Sahu, S. K., Reddy, S. S., & Kumar, S. J. (2012). New voltage stability index for voltage stability analysis in power system. *Int. J. Elec. Electron. Eng. Res*, *2*(4), 13-20.

[11] Samuel, I. A., Katende, J., Awosope, C. O. A., Awelewa, A. A., Adekitan, A. I., & Agbetuyi, F. A. (2019). Power system voltage collapse prediction using a new line stability index (NLSI-1): A case study of the 330-kV Nigerian National Grid. *International Journal of Electrical and Computer Engineering*, *9*(6), 5125.

[12] Gupta, A., & Sharma, P. R. (2013). Static and transient voltage stability assessment of power system by proper placement of UPFC with POD controller. *WSEAS Transactions on Power System, ISSN*, 197-206.

[13] Veleba, J. (2013). Performance of Steady-State Voltage Stability Analysis in MATLAB Environment. *Transactions on Electrical Engineering*, *2*(3), 82-88.

[14] Adebayo, I. G., Jimoh, A. A., & Yusuff, A. A. (2015, November). Detection of weak bus through Fast Voltage Stability index and inherent structural characteristics of

power system. In *2015 4th International Conference on Electric Power and Energy Conversion Systems (EPECS)* (pp. 1-5). IEEE.

[15] Reddy, K. V. R., & Lalitha, M. P. (2014). Identification of instability and its Enhancement through optimal placement of FACTS using L-index method. *Journal of theoretical and applied information technology*, *60*(3), 616-622.

[16] Reddy, K. V. R., Lalitha, M. P., & Chennaiah, P. B. (2014). Improvement of Voltage Profile through the Optimal Placement of FACTS Using L-Index Method. *International Journal of Electrical and Computer Engineering*, *4*(2), 207.

[17] Huang, H., Kong, Y., & Zhang, J. (2008). The analysis on the L-index based optimal power flow considering voltage stability constraints. *WSEAS Trans. Syst*, *7*(11), 1300-1309.

[18] Hedman, K. W., Oren, S. S., & O'Neill, R. P. (2011, July). A review of transmission switching and network topology optimization. In *2011 IEEE power and energy society general meeting* (pp. 1-7). IEEE.

[19] Pourbabak, H., Nudell, T. R., & Su, W. (2019, August). An efficient algorithm for dispatch of modular facts devices in transmission planning. In *2019 IEEE Power & Energy Society General Meeting (PESGM)* (pp. 1-5). IEEE.

[20] Dawn, S., Tiwari, P. K., & Goswami, A. K. (2019). An approach for long term economic operations of competitive power market by optimal combined scheduling of wind turbines and FACTS controllers. *Energy*, *181*, 709-723.

[21] Heffernan, A., & Courtney, J. (2019, September). Series Compensation to Increase Power Flow: A Case Study on the Irish Transmission System. In *2019 54th International Universities Power Engineering Conference (UPEC)* (pp. 1-5). IEEE.

[22] Hingorani, N. G. (1993). Flexible AC transmission. *IEEE spectrum*, *30*(4), 40-45.

[23] Georgilakis, P. S., & Vernados, P. G. (2011). Flexible AC transmission system controllers: An evaluation. In *Materials Science Forum* (Vol. 670, pp. 399-406). Trans Tech Publications Ltd.

[24] SAMSON, O. C., & AJ, A. (2021). Voltage Profile Enhancement in The Nigeria 330kv Line Using Statcom.

[25] Acha, E., Fuerte-Esquivel, C. R., Ambriz-Perez, H., & Angeles-Camacho, C. (2004). *FACTS: modelling and simulation in power networks*. John Wiley & Sons.

[26] Divan, D. M., Schneider, R., & Brumsickle, W. E. (2006). *U.S. Patent No. 7,105,952*. Washington, DC: U.S. Patent and Trademark Office.

[27] Iakubovskii, D., Krupenev, D., Komendantova, N., & Boyarkin, D. (2021). A model for power shortage minimization in electric power systems given constraints on controlled sections. *Energy Reports*, *7*, 4577-4586.

[28] Amraee, T., & Saberi, H. (2017). Controlled islanding using transmission switching and load shedding for enhancing power grid resilience. *International Journal of Electrical Power & Energy Systems*, *91*, 135-143.

[29] do Nascimento, S., & Gouvêa Jr, M. M. (2017). Voltage stability enhancement in power systems with automatic facts device allocation. *Energy Procedia*, *107*, 60-67.

[30] Kulkarni, P. P., & Ghawghawe, N. D. (2015, October). Optimal placement and parameter setting of TCSC in power transmission system to increase the power transfer capability. In *2015 International Conference on Energy Systems and Applications* (pp. 735-739). IEEE.

[31] Vadivelu, K. R., & Marutheswar, G. V. (2014). Maximum loadability estimation for weak bus identification using Fast Voltage Stability Index in a power transmission system by real time approach. *IJEETC, ISSN*, 2319-2518.

[32] Yu, Q. (2014, August). Applications of flexible AC transmissions system (FACTS) technology in SmartGrid and its EMC impact. In *2014 IEEE International Symposium on Electromagnetic Compatibility (EMC)* (pp. 392-397). IEEE.

[33] Kiran Daware. *Variable Loads On Power System* https://www.electricaleasy.com/2016/01/variable-loads-on-power-system.html

[34] Illinois Information Trust Institute. *New England IEEE 14-Bus System* https://icseg.iti.illinois.edu/ieee-14-bus-system/

[35] Illinois Information Trust Institute. *New England IEEE 39-Bus System* http://icseg.iti.illinois.edu/ieee-39-bus-system/

[36] Illinois Information Trust Institute. *New England IEEE 118-Bus System* https://icseg.iti.illinois.edu/ieee-118-bus-system/

[37] National Transmission & Despatch Company. https://ntdc.gov.pk/

[38] University of Washington. *Power Systems Test Case Archive* http://www.ee.washington.edu/research/pstca/pf14/pg_tca14bus.htm

[39] Illinois Information Trust Institute. *New England IEEE 39-Bus System* "https://icseg.iti.illinois.edu/ieee-39-bus-system-2"

[40] Illinois Information Trust Institute. *New England IEEE 118-Bus System* "https://icseg.iti.illinois.edu/ieee-118-bus-system"

[41] Adebayo, I. G., & Sun, Y. (2019, June). Voltage stability based on a novel critical bus identification index. In *2019 14th IEEE Conference on Industrial Electronics and Applications (ICIEA)* (pp. 1777-1782). IEEE.

[42] Lin, J., Magnago, F., & Alemany, J. M. (2018). Optimization methods applied to power systems: current practices and challenges. In *Classical and recent aspects of power system optimization* (pp. 1-18). Academic Press.

[43] Chen, G., Liu, L., Song, P., & Du, Y. (2014). Chaotic improved PSO-based multi-objective optimization for minimization of power losses and L index in power systems. *Energy Conversion and Management*, *86*, 548-560.

[44] Lipu, M. S. H., & Karim, T. F. (2013). Effectiveness of FACTS controllers and HVDC transmissions for improving power system stability and increasing power transmission capability. *International Journal of Energy and Power Engineering*, *2*(4), 154-163.

[45] Sode-Yome, A., Mithulananthan, N., & Lee, K. Y. (2012). Reactive power loss sensitivity approach in placing FACTS devices and UPFC. *IFAC Proceedings Volumes*, *45*(21), 416-421.

[46] Gouveia, E. M., & Matos, M. A. (2009). Symmetric ac fuzzy power flow model. *European Journal of Operational Research*, *197*(3), 1012-1018.

[47] Alexandrov, G. N., & Dardeer, M. M. (2008, March). Long distance transmission line with controlled shunt reactors (CSRT). In *2008 12th International Middle-East Power System Conference* (pp. 294-299). IEEE.

[48] Padmavathi, S. V., Sahu, S. K., & Jayalaxmi, A. (2013, December). Modeling and simulation of static var compensator to enhance the power system security. In *2013 IEEE Asia Pacific Conference on Postgraduate Research in Microelectronics and Electronics (PrimeAsia)* (pp. 52-55). IEEE.

[49] Cai L., *Robust Co-ordinated Control of FACTS Devices in Large Power Systems* a PhD thesis, University of Duisburg, Germany, published by Logos Verlag Berlin, 2004.

[50] Acha E., Ambriz-Perez H., Fuerte-Esquivel, *Advanced SVC Models for Newton Raphson Load Flow and Newton Optimal Power Flow Studies*, IEEE Transactions on Power Systems, 15(1), p.129-136, 2000.

[51] Nwohu, M. N. (2009). Voltage stability improvement using static VAR compensator in power systems. *Leonardo Journal of Sciences*, *14*, 167-172.

[52] CIGRE WG 38-01, " Static Var Compensators", CIGRE, Paris, 1986.

[53] "Application of Static Var Systems for System Dynamic Performance," IEEE *87ThOl87-5-PWR,* 1981.

[54] Hingorani N. G., Gyugyi L., *Understanding FACTS concepts and Technology of flexible AC transmission systems*, New York. IEEE Press, 2000

[55] Manitoba H. V. D. C. Research centre Inc., PSCAD/EMTDC manual version 3.0, 244 Cree Crescent, Winnipeg, Manitoba, Canada R3J 3W1.

[56] Miller, J., Brunet-Watson, M., & Leighfield, J. (2014). *Review of series compensation for transmission lines*. *PSC North America*, 09.

[57] ABB. (2010). "*Series Compensation – Boosting transmission capacity*". A02- 0135E, 2010-12

[58] Altuve, Mooney and Alexander. (2008). "*Advances in Series-Compensated Transmission Lines*". TP6340-01, Schweitzer Engineering Laboratories, Inc.

[59] Anderson and Farmer. (1996). "*Series Compensation of Power Systems*". Encinitas, CA: PBLSH, Inc.

Appendix-I

IEEE-14 bus Branch Data:

The parameters of 132kV Lynx Conductor are used for setting R, X and B values of transmission lines with MVA capacity of 112 MVA.

The branch data used is as follows:

Branch Data for IEEE 14 Bus System

From Bus	To Bus	Line R (pu)	Line X (pu)	Charging B (pu)	Rating	Length
1	2	0.01102	0.02327	0.00489	112	10
1	2	0.01102	0.02327	0.00489	112	10
1	5	0.02755	0.058175	0.012225	112	25
2	3	0.024244	0.051194	0.010758	112	22
2	4	0.029754	0.062829	0.013203	112	27
2	5	0.029754	0.062829	0.013203	112	27
3	4	0.035264	0.074464	0.015648	112	32
4	5	0.006612	0.013962	0.002934	112	6
6	11	0.048488	0.102388	0.021516	112	44
6	12	0.063916	0.134966	0.028362	112	58
6	13	0.034162	0.072137	0.015159	112	31
7	8	0.01102	0.02327	0.00489	112	10
7	9	0.01102	0.02327	0.00489	112	10
9	10	0.01653	0.034905	0.007335	112	15
9	14	0.06612	0.13962	0.02934	112	60
10	11	0.041876	0.088426	0.018582	112	38
12	13	0.1102	0.2327	0.0489	112	100
13	14	0.08816	0.18616	0.03912	112	80

Contingency Analysis on IEEE-14 without SVC:

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 1-5(1)	2	128.82	9	0.926	11
SINGLE 2-3(1)	1	113.09	8	0.9159	9
SINGLE 4-7(1)	0	0	9	0.9191	9
SINGLE 5-6(1)	0	0	9	0.8653	9
SINGLE 7-9(1)	0	0	7	0.9166	7
SINGLE 2-4(1)	1	109.53	5	0.9393	6
SINGLE 1-2(1)	2	149.57	1	0.9497	3
SINGLE 2-5(1)	1	110.24	2	0.9446	3
SINGLE 9-14(1)	0	0	3	0.9178	3
SINGLE 6-13(1)	0	0	2	0.9379	2
SINGLE 9-10(1)	0	0	2	0.9333	2
SINGLE 4-9(1)	0	0	1	0.9479	1
SINGLE 6-12(1)	0	0	1	0.9471	1
SINGLE 12-13(1)	0	0	1	0.9497	1
SINGLE 13-14(1)	0	0	1	0.9443	1
SINGLE 3-4(1)	0	0	0	0	0
SINGLE 4-5(1)	0	0	0	0	0
SINGLE 6-11(1)	0	0	0	0	0
SINGLE 7-8(1)	0	0	0	0	0
SINGLE 10-11(1)	0	0	0	0	0

Contingency Analysis on IEEE-14 with SVC at Bus 4:

Label	**Flow Violations #**	**Flow Violations Largest %**	**Low Range Violations #**	**Low Range Violations Largest**	**Performance Parameter**
SINGLE 4-7(1)	0	0	7	0.9312	7
SINGLE 5-6(1)	0	0	7	0.8927	7
SINGLE 7-9(1)	0	0	6	0.9288	6
SINGLE 1-2(1)	2	146.89	0	0	2
SINGLE 1-5(1)	2	124.59	0	0	2
SINGLE 2-3(1)	1	105.99	1	0.9487	2
SINGLE 2-4(1)	1	103.51	0	0	1
SINGLE 2-5(1)	1	104.27	0	0	1
SINGLE 6-13(1)	0	0	1	0.9492	1
SINGLE 9-10(1)	0	0	1	0.9427	1
SINGLE 9-14(1)	0	0	1	0.9284	1
SINGLE 3-4(1)	0	0	0	0	0
SINGLE 4-5(1)	0	0	0	0	0
SINGLE 4-9(1)	0	0	0	0	0
SINGLE 6-11(1)	0	0	0	0	0
SINGLE 6-12(1)	0	0	0	0	0
SINGLE 7-8(1)	0	0	0	0	0
SINGLE 10-11(1)	0	0	0	0	0
SINGLE 12-13(1)	0	0	0	0	0
SINGLE 13-14(1)	0	0	0	0	0

Appendix-II

IEEE-39 bus Branch Data:

The parameters of 132kV Rail Conductor are used for setting R, X and B values of transmission lines with MVA capacity of 202 MVA.

From Bus	To Bus	Id	Line R (pu)	Line X (pu)	Charging B (pu)	Rate A	Length
1	2	1	0.024339	0.125172	0.029868	202	57
1	39	1	0.006832	0.035136	0.008384	202	16
2	3	1	0.008967	0.046116	0.011004	202	21
2	25	1	0.049105	0.25254	0.06026	202	115
3	4	1	0.008967	0.046116	0.011004	202	21
3	18	1	0.008967	0.046116	0.011004	202	21
4	5	1	0.007686	0.039528	0.009432	202	18
4	14	1	0.005551	0.028548	0.006812	202	13
5	6	1	0.005551	0.028548	0.006812	202	13
5	8	1	0.001281	0.006588	0.001572	202	3
6	7	1	0.005551	0.028548	0.006812	202	13
6	11	1	0.00427	0.02196	0.00524	202	10
7	8	1	0.004697	0.024156	0.005764	202	11
8	9	1	0.002989	0.015372	0.003668	202	7
9	39	1	0.016226	0.083448	0.019912	202	38
10	11	1	0.006832	0.035136	0.008384	202	16
10	13	1	0.002989	0.015372	0.003668	202	7
13	14	1	0.002989	0.015372	0.003668	202	7
14	15	1	0.012383	0.063684	0.015196	202	29
15	16	1	0.006405	0.03294	0.00786	202	15
16	17	1	0.004697	0.024156	0.005764	202	11
16	19	1	0.011102	0.057096	0.013624	202	26
16	21	1	0.005551	0.028548	0.006812	202	13
16	24	1	0.002135	0.01098	0.00262	202	5
17	18	1	0.004697	0.024156	0.005764	202	11
17	27	1	0.008967	0.046116	0.011004	202	21
21	22	1	0.005551	0.028548	0.006812	202	13
22	23	1	0.00427	0.02196	0.00524	202	10
23	24	1	0.015372	0.079056	0.018864	202	36
25	26	1	0.022204	0.114192	0.027248	202	52
26	27	1	0.009821	0.050508	0.012052	202	23
26	28	1	0.030317	0.155916	0.037204	202	71
26	29	1	0.039711	0.204228	0.048732	202	93
28	29	1	0.009821	0.050508	0.012052	202	23

Contingency Analysis on IEEE-39 without SVC:

Label	**Flow Violations #**	**Flow Violations Largest %**	**Low Range Violations #**	**Low Range Violations Largest**	**Performance Parameter**
SINGLE 2-3(1)	5	129.05	9	0.9003	14
SINGLE 22-35(1)	6	139.18	8	0.9302	14
SINGLE 20-34(1)	8	139	3	0.9487	11
SINGLE 21-22(1)	1	156.13	7	0.9282	8
SINGLE 2-25(1)	4	149.12	3	0.9253	7
SINGLE 2-30(1)	1	110.19	6	0.9219	7
SINGLE 10-32(1)	1	105	6	0.9381	7
SINGLE 9-39(1)	3	153.17	3	0.943	6
SINGLE 23-36(1)	6	130.44	0	0	6
SINGLE 25-37(1)	4	133.16	2	0.8878	6
SINGLE 13-14(1)	3	106.94	2	0.9485	5
SINGLE 28-29(1)	1	165.67	4	0.8549	5
SINGLE 5-8(1)	1	138.29	3	0.9321	4
SINGLE 16-21(1)	1	130.89	3	0.9424	4
SINGLE 19-33(1)	4	123.4	0	0	4
SINGLE 26-29(1)	2	163.95	2	0.9045	4
SINGLE 4-14(1)	2	102.2	1	0.946	3
SINGLE 6-7(1)	2	144.33	1	0.9307	3
SINGLE 6-11(1)	3	119.31	0	0	3
SINGLE 8-9(1)	3	132.71	0	0	3
SINGLE 23-24(1)	2	158.67	1	0.9415	3
SINGLE 25-26(1)	2	130.41	1	0.9335	3
SINGLE 26-27(1)	2	150.45	1	0.9264	3
SINGLE 26-28(1)	1	147.04	2	0.9093	3
SINGLE 10-13(1)	2	159.17	0	0	2
SINGLE 16-19(1)	2	109.47	0	0	2
SINGLE 16-24(1)	1	103.16	1	0.9074	2
SINGLE 17-18(1)	2	115.78	0	0	2
SINGLE 17-27(1)	2	141.2	0	0	2
SINGLE 3-18(1)	1	103.18	0	0	1
SINGLE 5-6(1)	1	107.86	0	0	1
SINGLE 10-11(1)	1	161.16	0	0	1
SINGLE 15-16(1)	1	105.31	0	0	1
BASE CASE	0	0	0	0	0
SINGLE 1-2(1)	0	0	0	0	0
SINGLE 1-39(1)	0	0	0	0	0
SINGLE 3-4(1)	0	0	0	0	0

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 4-5(1)	0	0	0	0	0
SINGLE 6-31(1)	0	0	0	0	0
SINGLE 7-8(1)	0	0	0	0	0
SINGLE 11-12(1)	0	0	0	0	0
SINGLE 12-13(1)	0	0	0	0	0
SINGLE 14-15(1)	0	0	0	0	0
SINGLE 16-17(1)	0	0	0	0	0
SINGLE 19-20(1)	0	0	0	0	0
SINGLE 22-23(1)	0	0	0	0	0

Contingency Analysis on IEEE-39 with SVC at Bus 3:

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 22-35(1)	5	136.37	3	0.9439	8
SINGLE 20-34(1)	6	136.83	0	0	6
SINGLE 25-37(1)	4	131.31	2	0.903	6
SINGLE 2-25(1)	4	151.55	1	0.9348	5
SINGLE 28-29(1)	2	164.58	3	0.8682	5
SINGLE 2-3(1)	4	129.35	0	0	4
SINGLE 23-36(1)	4	128.48	0	0	4
SINGLE 5-8(1)	1	139.09	2	0.9354	3
SINGLE 6-7(1)	2	146.46	1	0.9415	3
SINGLE 6-11(1)	3	117.53	0	0	3
SINGLE 8-9(1)	3	126.11	0	0	3
SINGLE 9-39(1)	3	146.99	0	0	3
SINGLE 16-24(1)	2	103.13	1	0.9084	3
SINGLE 19-33(1)	3	121.52	0	0	3
SINGLE 21-22(1)	1	154.78	2	0.9435	3
SINGLE 25-26(1)	2	126.45	1	0.9463	3
SINGLE 26-27(1)	2	151.45	1	0.9271	3
SINGLE 26-29(1)	2	163.07	1	0.916	3
SINGLE 13-14(1)	2	106.74	0	0	2
SINGLE 16-19(1)	2	107.18	0	0	2
SINGLE 17-18(1)	2	110.73	0	0	2
SINGLE 17-27(1)	2	138.51	0	0	2
SINGLE 23-24(1)	2	156.5	0	0	2

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 26-28(1)	1	146.09	1	0.9207	2
SINGLE 2-30(1)	1	105.39	0	0	1
SINGLE 4-14(1)	1	101.3	0	0	1
SINGLE 5-6(1)	1	105.21	0	0	1
SINGLE 10-11(1)	1	159.45	0	0	1
SINGLE 10-13(1)	1	158.67	0	0	1
SINGLE 15-16(1)	1	111.37	0	0	1
SINGLE 16-17(1)	1	103.82	0	0	1
SINGLE 16-21(1)	1	129.67	0	0	1
BASE CASE	0	0	0	0	0
SINGLE 1-2(1)	0	0	0	0	0
SINGLE 1-39(1)	0	0	0	0	0
SINGLE 3-4(1)	0	0	0	0	0
SINGLE 3-18(1)	0	0	0	0	0
SINGLE 4-5(1)	0	0	0	0	0
SINGLE 6-31(1)	0	0	0	0	0
SINGLE 7-8(1)	0	0	0	0	0
SINGLE 10-32(1)	0	0	0	0	0
SINGLE 11-12(1)	0	0	0	0	0
SINGLE 12-13(1)	0	0	0	0	0
SINGLE 14-15(1)	0	0	0	0	0
SINGLE 19-20(1)	0	0	0	0	0
SINGLE 22-23(1)	0	0	0	0	0

Appendix-III

IEEE-118 bus Branch Data:

The parameters of 132kV Rail Conductor are used for setting R, X and B values of transmission lines with MVA capacity of 202 MVA.

From Bus	To Bus	Id	Line R (pu)	Line X (pu)	Charging B (pu)	Rate A	Length
1	2	1	0.01708	0.08784	0.02096	202	40
1	3	1	0.007259	0.037332	0.008908	202	17
2	12	1	0.010248	0.052704	0.012576	202	24
3	5	1	0.01281	0.06588	0.01572	202	30
3	12	1	0.026901	0.138348	0.033012	202	63
4	5	1	0.000854	0.004392	0.001048	202	2
4	11	1	0.011529	0.059292	0.014148	202	27
5	6	1	0.006405	0.03294	0.00786	202	15
5	11	1	0.011102	0.057096	0.013624	202	26
6	7	1	0.002562	0.013176	0.003144	202	6
7	12	1	0.004697	0.024156	0.005764	202	11
8	9	1	0.001281	0.006588	0.001572	202	3
8	30	1	0.002562	0.013176	0.003144	202	6
9	10	1	0.001281	0.006588	0.001572	202	3
11	12	1	0.003416	0.017568	0.004192	202	8
11	13	1	0.012383	0.063684	0.015196	202	29
12	14	1	0.011956	0.061488	0.014672	202	28
12	16	1	0.011956	0.061488	0.014672	202	28
12	117	1	0.018361	0.094428	0.022532	202	43
13	15	1	0.041419	0.213012	0.050828	202	97
14	15	1	0.032879	0.169092	0.040348	202	77
15	17	1	0.007259	0.037332	0.008908	202	17
15	19	1	0.006832	0.035136	0.008384	202	16
15	33	1	0.02135	0.1098	0.0262	202	50
16	17	1	0.025193	0.129564	0.030916	202	59
17	18	1	0.006832	0.035136	0.008384	202	16
17	31	1	0.026474	0.136152	0.032488	202	62
17	113	1	0.005124	0.026352	0.006288	202	12
18	19	1	0.006405	0.03294	0.00786	202	15
19	20	1	0.014091	0.072468	0.017292	202	33
19	34	1	0.041846	0.215208	0.051352	202	98
20	21	1	0.010248	0.052704	0.012576	202	24
21	22	1	0.011529	0.059292	0.014148	202	27
22	23	1	0.019215	0.09882	0.02358	202	45
23	24	1	0.007686	0.039528	0.009432	202	18

From Bus	To Bus	Id	Line R (pu)	Line X (pu)	Charging B (pu)	Rate A	Length
23	25	1	0.00854	0.04392	0.01048	202	20
23	32	1	0.017507	0.090036	0.021484	202	41
24	70	1	0.001281	0.006588	0.001572	202	3
24	72	1	0.027328	0.140544	0.033536	202	64
25	27	1	0.017934	0.092232	0.022008	202	42
26	30	1	0.00427	0.02196	0.00524	202	10
27	28	1	0.010675	0.0549	0.0131	202	25
27	32	1	0.01281	0.06588	0.01572	202	30
27	115	1	0.009394	0.048312	0.011528	202	22
28	29	1	0.013237	0.068076	0.016244	202	31
29	31	1	0.005978	0.030744	0.007336	202	14
30	38	1	0.002562	0.013176	0.003144	202	6
31	32	1	0.016226	0.083448	0.019912	202	38
32	113	1	0.03416	0.17568	0.04192	202	80
32	114	1	0.007686	0.039528	0.009432	202	18
33	37	1	0.023058	0.118584	0.028296	202	54
34	36	1	0.004697	0.024156	0.005764	202	11
34	37	1	0.001281	0.006588	0.001572	202	3
34	43	1	0.023058	0.118584	0.028296	202	54
35	36	1	0.001281	0.006588	0.001572	202	3
35	37	1	0.005978	0.030744	0.007336	202	14
37	39	1	0.017934	0.092232	0.022008	202	42
37	40	1	0.032879	0.169092	0.040348	202	77
38	65	1	0.005124	0.026352	0.006288	202	12
39	40	1	0.010248	0.052704	0.012576	202	24
40	41	1	0.008113	0.041724	0.009956	202	19
40	42	1	0.030744	0.158112	0.037728	202	72
41	42	1	0.022631	0.116388	0.027772	202	53
42	49	1	0.039711	0.204228	0.048732	202	93
43	44	1	0.033733	0.173484	0.041396	202	79
44	45	1	0.012383	0.063684	0.015196	202	29
45	46	1	0.022204	0.114192	0.027248	202	52
45	49	1	0.03843	0.19764	0.04716	202	90
46	47	1	0.02135	0.1098	0.0262	202	50
46	48	1	0.033733	0.173484	0.041396	202	79
47	49	1	0.010675	0.0549	0.0131	202	25
47	69	1	0.04697	0.24156	0.05764	202	110
48	49	1	0.010248	0.052704	0.012576	202	24
49	50	1	0.014945	0.07686	0.01834	202	35
49	51	1	0.026901	0.138348	0.033012	202	63

From Bus	To Bus	Id	Line R (pu)	Line X (pu)	Charging B (pu)	Rate A	Length
49	54	1	0.048251	0.248148	0.059212	202	113
49	66	1	0.010248	0.052704	0.012576	202	24
49	69	1	0.054656	0.281088	0.067072	202	128
50	57	1	0.026474	0.136152	0.032488	202	62
51	52	1	0.011102	0.057096	0.013624	202	26
51	58	1	0.014091	0.072468	0.017292	202	33
52	53	1	0.022631	0.116388	0.027772	202	53
53	54	1	0.014518	0.074664	0.017816	202	34
54	55	1	0.009394	0.048312	0.011528	202	22
54	56	1	0.001708	0.008784	0.002096	202	4
54	59	1	0.028182	0.144936	0.034584	202	66
55	56	1	0.002989	0.015372	0.003668	202	7
55	59	1	0.026474	0.136152	0.032488	202	62
56	57	1	0.019215	0.09882	0.02358	202	45
56	58	1	0.019215	0.09882	0.02358	202	45
56	59	1	0.044835	0.23058	0.05502	202	105
59	60	1	0.017934	0.092232	0.022008	202	42
59	61	1	0.017934	0.092232	0.022008	202	42
60	61	1	0.001708	0.008784	0.002096	202	4
60	62	1	0.006832	0.035136	0.008384	202	16
61	62	1	0.00427	0.02196	0.00524	202	10
62	66	1	0.026901	0.13835	0.033012	202	63
62	67	1	0.014091	0.072468	0.017292	202	33
63	64	1	0.000854	0.004392	0.001048	202	2
64	65	1	0.001281	0.006588	0.001572	202	3
65	68	1	0.000854	0.004392	0.001048	202	2
66	67	1	0.01281	0.06588	0.01572	202	30
68	81	1	0.000854	0.004392	0.001048	202	2
68	116	1	0.000427	0.002196	0.000524	202	1
69	70	1	0.016653	0.085644	0.020436	202	39
69	75	1	0.022631	0.116388	0.027772	202	53
69	77	1	0.01708	0.08784	0.02096	202	40
70	71	1	0.005124	0.026352	0.006288	202	12
70	74	1	0.022204	0.114192	0.027248	202	52
70	75	1	0.023912	0.122976	0.029344	202	56
71	72	1	0.024766	0.127368	0.030392	202	58
71	73	1	0.004697	0.024156	0.005764	202	11
74	75	1	0.006832	0.035136	0.008384	202	16
75	77	1	0.033306	0.171288	0.040872	202	78
75	118	1	0.008113	0.041724	0.009956	202	19

From Bus	To Bus	Id	Line R (pu)	Line X (pu)	Charging B (pu)	Rate A	Length
76	77	1	0.024766	0.127368	0.030392	202	58
76	118	1	0.009394	0.048312	0.011528	202	22
77	78	1	0.002135	0.01098	0.00262	202	5
77	80	1	0.016226	0.083448	0.019912	202	38
77	82	1	0.016653	0.085644	0.020436	202	39
78	79	1	0.003416	0.017568	0.004192	202	8
79	80	1	0.00854	0.04392	0.01048	202	20
80	96	1	0.019642	0.101016	0.024104	202	46
80	97	1	0.010248	0.052704	0.012576	202	24
80	98	1	0.013237	0.068076	0.016244	202	31
80	99	1	0.025193	0.129564	0.030916	202	59
82	83	1	0.006405	0.03294	0.00786	202	15
82	96	1	0.008967	0.046116	0.011004	202	21
83	84	1	0.035014	0.180072	0.042968	202	82
83	85	1	0.023912	0.122976	0.029344	202	56
84	85	1	0.01708	0.08784	0.02096	202	40
85	86	1	0.019642	0.101016	0.024104	202	46
85	88	1	0.011102	0.057096	0.013624	202	26
85	89	1	0.013237	0.068076	0.016244	202	31
86	87	1	0.015799	0.081252	0.019388	202	37
88	89	1	0.007686	0.039528	0.009432	202	18
89	90	1	0.013237	0.068076	0.016244	202	31
89	92	1	0.021777	0.111996	0.026724	202	51
90	91	1	0.014091	0.072468	0.017292	202	33
91	92	1	0.02135	0.1098	0.0262	202	50
92	93	1	0.014518	0.074664	0.017816	202	34
92	94	1	0.026901	0.138348	0.033012	202	63
92	100	1	0.035868	0.184464	0.044016	202	84
92	102	1	0.006832	0.035136	0.008384	202	16
93	94	1	0.012383	0.063684	0.015196	202	29
94	95	1	0.007259	0.037332	0.008908	202	17
94	96	1	0.014945	0.07686	0.01834	202	35
94	100	1	0.009821	0.050508	0.012052	202	23
95	96	1	0.009394	0.048312	0.011528	202	22
96	97	1	0.009394	0.048312	0.011528	202	22
98	100	1	0.022204	0.114192	0.027248	202	52
99	100	1	0.010248	0.052704	0.012576	202	24
100	101	1	0.015372	0.079056	0.018864	202	36
100	103	1	0.008967	0.046116	0.011004	202	21
100	104	1	0.025193	0.129564	0.030916	202	59

From Bus	To Bus	Id	Line R (pu)	Line X (pu)	Charging B (pu)	Rate A	Length
100	106	1	0.033733	0.173484	0.041396	202	79
101	102	1	0.013664	0.070272	0.016768	202	32
103	104	1	0.026047	0.133956	0.031964	202	61
103	105	1	0.02989	0.15372	0.03668	202	70
103	110	1	0.021777	0.111996	0.026724	202	51
104	105	1	0.005551	0.028548	0.006812	202	13
105	106	1	0.007686	0.039528	0.009432	202	18
105	107	1	0.029463	0.151524	0.036156	202	69
105	108	1	0.014518	0.074664	0.017816	202	34
106	107	1	0.029463	0.151524	0.036156	202	69
108	109	1	0.005978	0.030744	0.007336	202	14
109	110	1	0.015372	0.079056	0.018864	202	36
110	111	1	0.012383	0.063684	0.015196	202	29
110	112	1	0.014091	0.072468	0.017292	202	33
114	115	1	0.001281	0.006588	0.001572	202	3

Contingency Analysis without SVC:

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 37-38(1)	2	121.25	16	0.7957	18
SINGLE 5-8(1)	1	133.26	24	0.8613	16
SINGLE 42-49(1)	2	104.52	9	0.8023	11
SINGLE 89-90(1)	1	148.74	8	0.7185	9
SINGLE 17-30(1)	0	0	8	0.9259	8
SINGLE 22-23(1)	0	0	7	0.9276	7
SINGLE 26-30(1)	3	113.83	4	0.9266	7
SINGLE 17-18(1)	0	0	6	0.9272	6
SINGLE 21-22(1)	0	0	6	0.928	6
SINGLE 49-51(1)	0	0	6	0.9288	6
SINGLE 69-75(1)	0	0	6	0.929	6
SINGLE 75-118(1)	0	0	6	0.9196	6
SINGLE 76-77(1)	0	0	6	0.9276	6
SINGLE 82-83(1)	2	128.02	4	0.9293	6
SINGLE 110-111(1)	0	0	6	0.9237	6
SINGLE 8-9(1)	1	147.1	4	0.9289	5
SINGLE 8-9(2)	1	147.1	4	0.9289	5
SINGLE 9-10(1)	1	147.72	4	0.9289	5
SINGLE 9-10(2)	1	147.72	4	0.9289	5
SINGLE 11-13(1)	0	0	5	0.9275	5
SINGLE 23-25(1)	1	114.56	4	0.9288	5
SINGLE 25-27(1)	1	106.85	4	0.9286	5
SINGLE 38-65(1)	1	151.59	4	0.9242	5
SINGLE 38-65(2)	1	151.59	4	0.9242	5
SINGLE 47-69(1)	1	102.2	4	0.9298	5
SINGLE 49-50(1)	0	0	5	0.929	5
SINGLE 49-69(1)	1	100.57	4	0.9297	5
SINGLE 51-52(1)	0	0	5	0.9292	5
SINGLE 53-54(1)	0	0	5	0.9294	5
SINGLE 54-59(1)	1	100.28	4	0.9296	5
SINGLE 55-59(1)	1	100.59	4	0.9297	5
SINGLE 59-63(1)	1	100.73	4	0.93	5
SINGLE 62-66(1)	1	101.85	4	0.9291	5
SINGLE 62-67(1)	1	100.34	4	0.9292	5
SINGLE 63-64(1)	1	100.73	4	0.93	5
SINGLE 65-66(1)	1	113.93	4	0.9283	5
SINGLE 66-67(1)	1	103.52	4	0.929	5

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 68-116(1)	1	100.04	4	0.9296	5
SINGLE 74-75(1)	0	0	5	0.9292	5
SINGLE 83-85(1)	1	102.99	4	0.9293	5
SINGLE 85-89(1)	1	100.81	4	0.9293	5
SINGLE 88-89(1)	1	105.23	4	0.9293	5
SINGLE 89-92(1)	1	132.61	4	0.9293	5
SINGLE 90-91(1)	1	100.61	4	0.9293	5
SINGLE 105-107(1)	0	0	5	0.9293	5
SINGLE 1-2(1)	0	0	4	0.9293	4
SINGLE 1-3(1)	0	0	4	0.9294	4
SINGLE 2-12(1)	0	0	4	0.9293	4
SINGLE 3-5(1)	0	0	4	0.9294	4
SINGLE 3-12(1)	0	0	4	0.9293	4
SINGLE 4-5(1)	0	0	4	0.9293	4
SINGLE 4-11(1)	0	0	4	0.9293	4
SINGLE 5-6(1)	0	0	4	0.9294	4
SINGLE 5-11(1)	0	0	4	0.9293	4
SINGLE 6-7(1)	0	0	4	0.9293	4
SINGLE 7-12(1)	0	0	4	0.9293	4
SINGLE 8-30(1)	0	0	4	0.9279	4
SINGLE 11-12(1)	0	0	4	0.9292	4
SINGLE 12-14(1)	0	0	4	0.9286	4
SINGLE 12-16(1)	0	0	4	0.9289	4
SINGLE 12-117(1)	0	0	4	0.9295	4
SINGLE 13-15(1)	0	0	4	0.929	4
SINGLE 14-15(1)	0	0	4	0.9288	4
SINGLE 15-17(1)	0	0	4	0.9272	4
SINGLE 15-19(1)	0	0	4	0.9291	4
SINGLE 15-33(1)	0	0	4	0.9286	4
SINGLE 16-17(1)	0	0	4	0.9293	4
SINGLE 17-31(1)	0	0	4	0.9294	4
SINGLE 17-113(1)	0	0	4	0.9294	4
SINGLE 18-19(1)	0	0	4	0.9288	4
SINGLE 19-20(1)	0	0	4	0.929	4
SINGLE 19-34(1)	0	0	4	0.9294	4
SINGLE 20-21(1)	0	0	4	0.9285	4
SINGLE 23-24(1)	0	0	4	0.9293	4
SINGLE 23-32(1)	0	0	4	0.929	4
SINGLE 24-70(1)	0	0	4	0.9292	4

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 24-72(1)	0	0	4	0.9293	4
SINGLE 25-26(1)	0	0	4	0.9294	4
SINGLE 27-28(1)	0	0	4	0.9293	4
SINGLE 27-32(1)	0	0	4	0.9293	4
SINGLE 27-115(1)	0	0	4	0.9293	4
SINGLE 28-29(1)	0	0	4	0.9293	4
SINGLE 29-31(1)	0	0	4	0.9293	4
SINGLE 30-38(1)	0	0	4	0.9283	4
SINGLE 31-32(1)	0	0	4	0.9293	4
SINGLE 32-113(1)	0	0	4	0.9293	4
SINGLE 32-114(1)	0	0	4	0.9294	4
SINGLE 34-36(1)	0	0	4	0.929	4
SINGLE 34-43(1)	0	0	4	0.929	4
SINGLE 35-36(1)	0	0	4	0.9293	4
SINGLE 35-37(1)	0	0	4	0.9291	4
SINGLE 37-39(1)	0	0	4	0.8854	4
SINGLE 37-40(1)	0	0	4	0.9049	4
SINGLE 40-42(1)	0	0	4	0.9203	4
SINGLE 41-42(1)	0	0	4	0.9248	4
SINGLE 43-44(1)	0	0	4	0.9271	4
SINGLE 44-45(1)	0	0	4	0.9278	4
SINGLE 45-46(1)	0	0	4	0.9279	4
SINGLE 45-49(1)	0	0	4	0.9282	4
SINGLE 46-47(1)	0	0	4	0.9293	4
SINGLE 46-48(1)	0	0	4	0.9293	4
SINGLE 47-49(1)	0	0	4	0.9291	4
SINGLE 48-49(1)	0	0	4	0.9292	4
SINGLE 49-54(1)	0	0	4	0.929	4
SINGLE 49-66(1)	0	0	4	0.9316	4
SINGLE 50-57(1)	0	0	4	0.9291	4
SINGLE 51-58(1)	0	0	4	0.9293	4
SINGLE 52-53(1)	0	0	4	0.9293	4
SINGLE 54-55(1)	0	0	4	0.9293	4
SINGLE 54-56(1)	0	0	4	0.9293	4
SINGLE 55-56(1)	0	0	4	0.9293	4
SINGLE 56-57(1)	0	0	4	0.9292	4
SINGLE 56-58(1)	0	0	4	0.9293	4
SINGLE 56-59(1)	0	0	4	0.9295	4
SINGLE 59-60(1)	0	0	4	0.9294	4

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 59-61(1)	0	0	4	0.9294	4
SINGLE 60-61(1)	0	0	4	0.9294	4
SINGLE 60-62(1)	0	0	4	0.9293	4
SINGLE 61-62(1)	0	0	4	0.9293	4
SINGLE 61-64(1)	0	0	4	0.9294	4
SINGLE 64-65(1)	0	0	4	0.9309	4
SINGLE 65-68(1)	0	0	4	0.929	4
SINGLE 68-69(1)	0	0	4	0.929	4
SINGLE 68-81(1)	0	0	4	0.9292	4
SINGLE 69-70(1)	0	0	4	0.9285	4
SINGLE 69-77(1)	0	0	4	0.9293	4
SINGLE 70-71(1)	0	0	4	0.9293	4
SINGLE 70-74(1)	0	0	4	0.9294	4
SINGLE 70-75(1)	0	0	4	0.9294	4
SINGLE 71-72(1)	0	0	4	0.9293	4
SINGLE 71-73(1)	0	0	4	0.9294	4
SINGLE 75-77(1)	0	0	4	0.9293	4
SINGLE 76-118(1)	0	0	4	0.9294	4
SINGLE 77-78(1)	0	0	4	0.9293	4
SINGLE 77-80(1)	0	0	4	0.9293	4
SINGLE 77-82(1)	0	0	4	0.9294	4
SINGLE 78-79(1)	0	0	4	0.9293	4
SINGLE 79-80(1)	0	0	4	0.9293	4
SINGLE 80-81(1)	0	0	4	0.9292	4
SINGLE 80-96(1)	0	0	4	0.9293	4
SINGLE 80-97(1)	0	0	4	0.9293	4
SINGLE 80-98(1)	0	0	4	0.9293	4
SINGLE 80-99(1)	0	0	4	0.9293	4
SINGLE 82-96(1)	0	0	4	0.9293	4
SINGLE 83-84(1)	0	0	4	0.9293	4
SINGLE 84-85(1)	0	0	4	0.9293	4
SINGLE 85-86(1)	0	0	4	0.9294	4
SINGLE 85-88(1)	0	0	4	0.9293	4
SINGLE 86-87(1)	0	0	4	0.9293	4
SINGLE 91-92(1)	0	0	4	0.9293	4
SINGLE 92-93(1)	0	0	4	0.9293	4
SINGLE 92-94(1)	0	0	4	0.9293	4
SINGLE 92-100(1)	0	0	4	0.9293	4
SINGLE 92-102(1)	0	0	4	0.9293	4

Label	**Flow Violations #**	**Flow Violations Largest %**	**Low Range Violations #**	**Low Range Violations Largest**	**Performance Parameter**
SINGLE 93-94(1)	0	0	4	0.9293	4
SINGLE 94-95(1)	0	0	4	0.9293	4
SINGLE 94-96(1)	0	0	4	0.9293	4
SINGLE 94-100(1)	0	0	4	0.9293	4
SINGLE 95-96(1)	0	0	4	0.9293	4
SINGLE 96-97(1)	0	0	4	0.9293	4
SINGLE 98-100(1)	0	0	4	0.9293	4
SINGLE 99-100(1)	0	0	4	0.9293	4
SINGLE 100-101(1)	0	0	4	0.9293	4
SINGLE 100-103(1)	0	0	4	0.9293	4
SINGLE 100-104(1)	0	0	4	0.9293	4
SINGLE 100-106(1)	0	0	4	0.9293	4
SINGLE 101-102(1)	0	0	4	0.9293	4
SINGLE 103-104(1)	0	0	4	0.9293	4
SINGLE 103-105(1)	0	0	4	0.9293	4
SINGLE 103-110(1)	0	0	4	0.9293	4
SINGLE 104-105(1)	0	0	4	0.9293	4
SINGLE 105-106(1)	0	0	4	0.9293	4
SINGLE 105-108(1)	0	0	4	0.9293	4
SINGLE 106-107(1)	0	0	4	0.9293	4
SINGLE 108-109(1)	0	0	4	0.9293	4
SINGLE 109-110(1)	0	0	4	0.9293	4
SINGLE 110-112(1)	0	0	4	0.9294	4
SINGLE 114-115(1)	0	0	4	0.9293	4
SINGLE 33-37(1)	0	0	3	0.9304	3
SINGLE 34-37(1)	0	0	3	0.9307	3
SINGLE 39-40(1)	0	0	3	0.9102	3
SINGLE 40-41(1)	0	0	3	0.8863	3
SINGLE 114-115(1)	0	0	1	0.9497	1

Contingency Analysis on IEEE-118 with SVC at Bus 4:

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 5-8(1)	1	129.09	14	0.896	15
SINGLE 37-39(1)	0	0	4	0.9268	4
SINGLE 42-49(1)	2	100.48	2	0.9235	4
SINGLE 89-90(1)	1	148.75	3	0.7185	4
SINGLE 26-30(1)	3	113.67	0	0	3
SINGLE 37-38(1)	2	120.27	0	0	2
SINGLE 40-41(1)	0	0	2	0.9198	2
SINGLE 49-51(1)	0	0	2	0.9497	2
SINGLE 75-118(1)	0	0	2	0.9197	2
SINGLE 76-77(1)	0	0	2	0.9282	2
SINGLE 82-83(1)	2	128.02	0	0	2
SINGLE 110-111(1)	0	0	2	0.9237	2
SINGLE 8-9(1)	1	144.14	0	0	1
SINGLE 8-9(2)	1	144.14	0	0	1
SINGLE 9-10(1)	1	144.65	0	0	1
SINGLE 9-10(2)	1	144.65	0	0	1
SINGLE 11-13(1)	0	0	1	0.9453	1
SINGLE 23-25(1)	1	113.56	0	0	1
SINGLE 25-27(1)	1	105.44	0	0	1
SINGLE 37-40(1)	0	0	1	0.9419	1
SINGLE 38-65(1)	1	152.35	0	0	1
SINGLE 38-65(2)	1	152.35	0	0	1
SINGLE 39-40(1)	0	0	1	0.9442	1
SINGLE 47-69(1)	1	100.76	0	0	1
SINGLE 49-50(1)	0	0	1	0.9487	1
SINGLE 51-52(1)	0	0	1	0.9473	1
SINGLE 53-54(1)	0	0	1	0.9461	1
SINGLE 62-66(1)	1	100.73	0	0	1
SINGLE 65-66(1)	1	113.17	0	0	1
SINGLE 66-67(1)	1	102.42	0	0	1
SINGLE 74-75(1)	0	0	1	0.9466	1
SINGLE 83-85(1)	1	102.99	0	0	1
SINGLE 85-89(1)	1	100.81	0	0	1
SINGLE 88-89(1)	1	105.23	0	0	1
SINGLE 89-92(1)	1	132.62	0	0	1
SINGLE 90-91(1)	1	100.61	0	0	1
SINGLE 105-107(1)	0	0	1	0.9441	1

Label	**Flow Violations #**	**Flow Violations Largest %**	**Low Range Violations #**	**Low Range Violations Largest**	**Performance Parameter**
SINGLE 1-2(1)	0	0	0	0	0
SINGLE 1-3(1)	0	0	0	0	0
SINGLE 2-12(1)	0	0	0	0	0
SINGLE 3-5(1)	0	0	0	0	0
SINGLE 3-12(1)	0	0	0	0	0
SINGLE 4-5(1)	0	0	0	0	0
SINGLE 4-11(1)	0	0	0	0	0
SINGLE 5-6(1)	0	0	0	0	0
SINGLE 5-11(1)	0	0	0	0	0
SINGLE 6-7(1)	0	0	0	0	0
SINGLE 7-12(1)	0	0	0	0	0
SINGLE 8-30(1)	0	0	0	0	0
SINGLE 11-12(1)	0	0	0	0	0
SINGLE 12-14(1)	0	0	0	0	0
SINGLE 12-16(1)	0	0	0	0	0
SINGLE 12-117(1)	0	0	0	0	0
SINGLE 13-15(1)	0	0	0	0	0
SINGLE 14-15(1)	0	0	0	0	0
SINGLE 15-17(1)	0	0	0	0	0
SINGLE 15-19(1)	0	0	0	0	0
SINGLE 15-33(1)	0	0	0	0	0
SINGLE 16-17(1)	0	0	0	0	0
SINGLE 17-18(1)	0	0	0	0	0
SINGLE 17-30(1)	0	0	0	0	0
SINGLE 17-31(1)	0	0	0	0	0
SINGLE 17-113(1)	0	0	0	0	0
SINGLE 18-19(1)	0	0	0	0	0
SINGLE 19-20(1)	0	0	0	0	0
SINGLE 19-34(1)	0	0	0	0	0
SINGLE 20-21(1)	0	0	0	0	0
SINGLE 21-22(1)	0	0	0	0	0
SINGLE 22-23(1)	0	0	0	0	0
SINGLE 23-24(1)	0	0	0	0	0
SINGLE 23-32(1)	0	0	0	0	0
SINGLE 24-70(1)	0	0	0	0	0
SINGLE 24-72(1)	0	0	0	0	0
SINGLE 25-26(1)	0	0	0	0	0
SINGLE 27-28(1)	0	0	0	0	0
SINGLE 27-32(1)	0	0	0	0	0

Label	**Flow Violations #**	**Flow Violations Largest %**	**Low Range Violations #**	**Low Range Violations Largest**	**Performance Parameter**
SINGLE 27-115(1)	0	0	0	0	0
SINGLE 28-29(1)	0	0	0	0	0
SINGLE 29-31(1)	0	0	0	0	0
SINGLE 30-38(1)	0	0	0	0	0
SINGLE 31-32(1)	0	0	0	0	0
SINGLE 32-113(1)	0	0	0	0	0
SINGLE 32-114(1)	0	0	0	0	0
SINGLE 33-37(1)	0	0	0	0	0
SINGLE 34-36(1)	0	0	0	0	0
SINGLE 34-37(1)	0	0	0	0	0
SINGLE 34-43(1)	0	0	0	0	0
SINGLE 35-36(1)	0	0	0	0	0
SINGLE 35-37(1)	0	0	0	0	0
SINGLE 40-42(1)	0	0	0	0	0
SINGLE 41-42(1)	0	0	0	0	0
SINGLE 43-44(1)	0	0	0	0	0
SINGLE 44-45(1)	0	0	0	0	0
SINGLE 45-46(1)	0	0	0	0	0
SINGLE 45-49(1)	0	0	0	0	0
SINGLE 46-47(1)	0	0	0	0	0
SINGLE 46-48(1)	0	0	0	0	0
SINGLE 47-49(1)	0	0	0	0	0
SINGLE 48-49(1)	0	0	0	0	0
SINGLE 49-54(1)	0	0	0	0	0
SINGLE 49-66(1)	0	0	0	0	0
SINGLE 49-69(1)	0	0	0	0	0
SINGLE 50-57(1)	0	0	0	0	0
SINGLE 51-58(1)	0	0	0	0	0
SINGLE 52-53(1)	0	0	0	0	0
SINGLE 54-55(1)	0	0	0	0	0
SINGLE 54-56(1)	0	0	0	0	0
SINGLE 54-59(1)	0	0	0	0	0
SINGLE 55-56(1)	0	0	0	0	0
SINGLE 55-59(1)	0	0	0	0	0
SINGLE 56-57(1)	0	0	0	0	0
SINGLE 56-58(1)	0	0	0	0	0
SINGLE 56-59(1)	0	0	0	0	0
SINGLE 59-60(1)	0	0	0	0	0
SINGLE 59-61(1)	0	0	0	0	0

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 59-63(1)	0	0	0	0	0
SINGLE 60-61(1)	0	0	0	0	0
SINGLE 60-62(1)	0	0	0	0	0
SINGLE 61-62(1)	0	0	0	0	0
SINGLE 61-64(1)	0	0	0	0	0
SINGLE 62-67(1)	0	0	0	0	0
SINGLE 63-64(1)	0	0	0	0	0
SINGLE 64-65(1)	0	0	0	0	0
SINGLE 65-68(1)	0	0	0	0	0
SINGLE 68-69(1)	0	0	0	0	0
SINGLE 68-81(1)	0	0	0	0	0
SINGLE 68-116(1)	0	0	0	0	0
SINGLE 69-70(1)	0	0	0	0	0
SINGLE 69-75(1)	0	0	0	0	0
SINGLE 69-77(1)	0	0	0	0	0
SINGLE 70-71(1)	0	0	0	0	0
SINGLE 70-74(1)	0	0	0	0	0
SINGLE 70-75(1)	0	0	0	0	0
SINGLE 71-72(1)	0	0	0	0	0
SINGLE 71-73(1)	0	0	0	0	0
SINGLE 75-77(1)	0	0	0	0	0
SINGLE 76-118(1)	0	0	0	0	0
SINGLE 77-78(1)	0	0	0	0	0
SINGLE 77-80(1)	0	0	0	0	0
SINGLE 77-82(1)	0	0	0	0	0
SINGLE 78-79(1)	0	0	0	0	0
SINGLE 79-80(1)	0	0	0	0	0
SINGLE 80-81(1)	0	0	0	0	0
SINGLE 80-96(1)	0	0	0	0	0
SINGLE 80-97(1)	0	0	0	0	0
SINGLE 80-98(1)	0	0	0	0	0
SINGLE 80-99(1)	0	0	0	0	0
SINGLE 82-96(1)	0	0	0	0	0
SINGLE 83-84(1)	0	0	0	0	0
SINGLE 84-85(1)	0	0	0	0	0
SINGLE 85-86(1)	0	0	0	0	0
SINGLE 85-88(1)	0	0	0	0	0
SINGLE 86-87(1)	0	0	0	0	0
SINGLE 91-92(1)	0	0	0	0	0

Label	Flow Violations #	Flow Violations Largest %	Low Range Violations #	Low Range Violations Largest	Performance Parameter
SINGLE 92-93(1)	0	0	0	0	0
SINGLE 92-94(1)	0	0	0	0	0
SINGLE 92-100(1)	0	0	0	0	0
SINGLE 92-102(1)	0	0	0	0	0
SINGLE 93-94(1)	0	0	0	0	0
SINGLE 94-95(1)	0	0	0	0	0
SINGLE 94-96(1)	0	0	0	0	0
SINGLE 94-100(1)	0	0	0	0	0
SINGLE 95-96(1)	0	0	0	0	0
SINGLE 96-97(1)	0	0	0	0	0
SINGLE 98-100(1)	0	0	0	0	0
SINGLE 99-100(1)	0	0	0	0	0
SINGLE 100-101(1)	0	0	0	0	0
SINGLE 100-103(1)	0	0	0	0	0
SINGLE 100-104(1)	0	0	0	0	0
SINGLE 100-106(1)	0	0	0	0	0
SINGLE 101-102(1)	0	0	0	0	0
SINGLE 103-104(1)	0	0	0	0	0
SINGLE 103-105(1)	0	0	0	0	0
SINGLE 103-110(1)	0	0	0	0	0
SINGLE 104-105(1)	0	0	0	0	0
SINGLE 105-106(1)	0	0	0	0	0
SINGLE 105-108(1)	0	0	0	0	0
SINGLE 106-107(1)	0	0	0	0	0
SINGLE 108-109(1)	0	0	0	0	0
SINGLE 109-110(1)	0	0	0	0	0
SINGLE 110-112(1)	0	0	0	0	0
SINGLE 114-115(1)	0	0	0	0	0