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Steady State Voltage Stability Enhancement Using Shunt and Series FACTS Devices

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Steady State Voltage Stability Enhancement Using Shunt and Series FACTS Devices

A Thesis

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements for the degree of

Master of Science
in
Engineering
Electrical

by

Jahnavi Lakkireddy
B.S, JNTU University, 2010

August 2014

To my parents: Lakkireddy Prasad Reddy and Lakkireddy Yuvarani

And my brother: Lakkireddy Sharat Chandra Reddy

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LIST OF ACRONYMS

FACTS – Flexible AC Transmission System

VAR – Volt-Ampere Rating

SVC – Static Voltage Compensator

STATCOM – Static Synchronous Compensator

TCSC – Thyristor Controlled Series Compensator

SSSC – Static Synchronous Series Compensator

TCPST – Thyristor Controlled Phase Shifting Transformer

GTO – Gate Turn Off

TCR – Thyristor Controlled Reactor

PSSE – Power System Simulator

PSAT – Power System Analysis Tool

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ABSTRACT

It is specifically important to focus on voltage stability analysis of the power system to avoid worst case scenarios such as voltage collapse. The purpose of this thesis is to identify methods for enhancing the steady-state voltage stability using FACTS devices and determining their impact on real and reactive power losses, improvement of bus voltage magnitude, and transmission line loadability. To achieve this, FACTS devices such as Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM), and Thyristor Controlled Series Capacitor (TCSC) are used in the test system as three separate test cases. The results obtained assist in drawing conclusions on the effectiveness of each FACTS devices at generator, load and swing buses, on lines between two load buses, and between a load bus and a generator bus, in terms of metrics such as voltage magnitude profile, PV curves, and active and reactive power losses.

Keywords: FACTS, Steady state voltage stability, reactive power compensation techniques, flexible AC transmission systems.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Voltage Stability analysis is important as voltage instability may result in the partial or complete interruption in the power system. For voltage stability analysis, a number of steady-state analysis methods such as standard power flow methods, continuation power flow methods, modal methods and dynamic simulation methods are being used by the electric utilities.

The reactive power plays an important role in a power system. Fundamentally, an electric power is generated, transmitted and then distributed to the customers. Transformers, transmission and distribution lines, cables and many common load devices such as motors shift the relationship between current and voltage due to their inherent characteristics. This shift is measured in volt-ampere reactive (VAR). High VAR levels may result in reduction in power transfer capability and increase in losses. Low VAR levels may result in voltage sag. Hence, appropriate levels of reactive power are to be maintained for enhancing the voltage stability of the power system.

The sources of reactive power such as conventional devices which are built out of resistance, inductance or capacitance together with transformer, and Flexible AC Transmission System (FACTS) devices provide sufficient reactive power to the system. FACTS devices provide reactive power compensation, and improve voltage stability, transmission capability, power flow control, and operating flexibility of the power system.

The purpose of this research is to provide an analysis on the use of FACTS devices in improving voltage stability, minimizing power loss, and improving transmission system loadability that result from utilization of different types of shunt and series FACTS devices such as Static Voltage Compensator (SVC), Static Synchronous Compensator (STATCOM), and Thyristor Controlled Series Compensator (TCSC). To test the idea, we have introduced different FACTS devices into the IEEE 39 bus New England test system. Voltage stability of the power system before and after introducing the different FACTS devices is observed by comparing metrics such as active and reactive power losses, voltage magnitude profile, loading margin, and P-V curves.

1.2 HISTORICAL REVIEW

An historical review on reactive power compensation techniques and devices, continuation power flow analysis, static voltage stability margin enhancement, and methods to improve the static voltage stability margin using FACTS devices resulted in thorough understanding of the concepts and paved the vision for this work. Literature review of techniques used for improving the voltage stability of the power system using FACTS devices are explained in more detail below:

In [1], a method to determine static voltage stability margin enhancement using STATCOM, TCSC and Static Synchronous Series Compensator (SSSC) is presented. Mathematical equations of the FACTS devices are used in the continuation power flow process to carry out the load flow analysis. PV curves for each of the FACTS devices are obtained and compared with parameters such as load margin, power losses and voltage magnitude profile to determine which of the FACTS devices provide static voltage stability enhancement. Conclusions drawn from [1] are as follows: STATCOM provide higher stability margin than TCSC and SSSC. However, SSSC gives slightly higher load margin and better voltage magnitude profiles compared to TCSC. The proposed

method is the extension of [1] which improves both static and transient stability margin enhancement using FACTS devices. Other FACTS devices can be used to see if they can provide more effective static voltage stability margin enhancement. Also, other parameters can be compared from the results obtained to determine the effectiveness of the FACTS devices.

In [2], the general principle behind the continuation power flow process is presented. A predictor-corrector scheme is used to find a solution path of a set of power flow equations that have been reformulated to include a load parameter. Then, they applied the continuation algorithm to the system of reformulated power flow equations. To solve the problem, they start the continuation power flow algorithm with a known solution. Once the base solution has been found, they predict the next solution by taking an appropriately sized step in a direction tangent to the solution path. They solve the tangent vector to make the prediction and solve the equations with Newton-Raphson power flow method to provide the corrector. They then, check if the critical point has passed. Once the critical point corresponding to the maximum load is passed, they stop the iterative predictor-corrector process. This paper is studied to understand the continuation power flow process used in “Static Voltage Stability Margin Enhancement Using STATCOM, TCSC and SSSC”.

In [3], a method to implement SVC, TCSC and Thyristor Controlled Phase Shifting Transformer (TCPST) on the line to improve the voltage profile is proposed. The models of SVC, TCSC and TCPST are built and simulated using MATLAB Simulink on IEEE 14 bus test system. Conclusions drawn from [3] are as follows: SVCs are responsible for the parts dealing with the voltage and active power losses while, TCSCs and TCPST account for the part concerning line loads. Simulations presented in [3] show the improvements of the voltage profiles and reduction of the active power losses.

CHAPTER 2

OVERVIEW OF FACTS DEVICES

2.1 REACTIVE POWER SOURCES

The reactive power sources provide required reactive power to the system. They can be divided into two types. One is the conventional devices that are built basically from resistance, inductance, or capacitance together with transformers. The other type is the Flexible AC Transmission System (FACTS) devices. In FACTS devices, besides resistance, inductance, or capacitance, additional power electronic converters to switch elements in smaller steps within a cycle in an alternating current are used. The FACTS devices in turn can be differentiated into Thyristor-valve type and voltage source converter type [6].

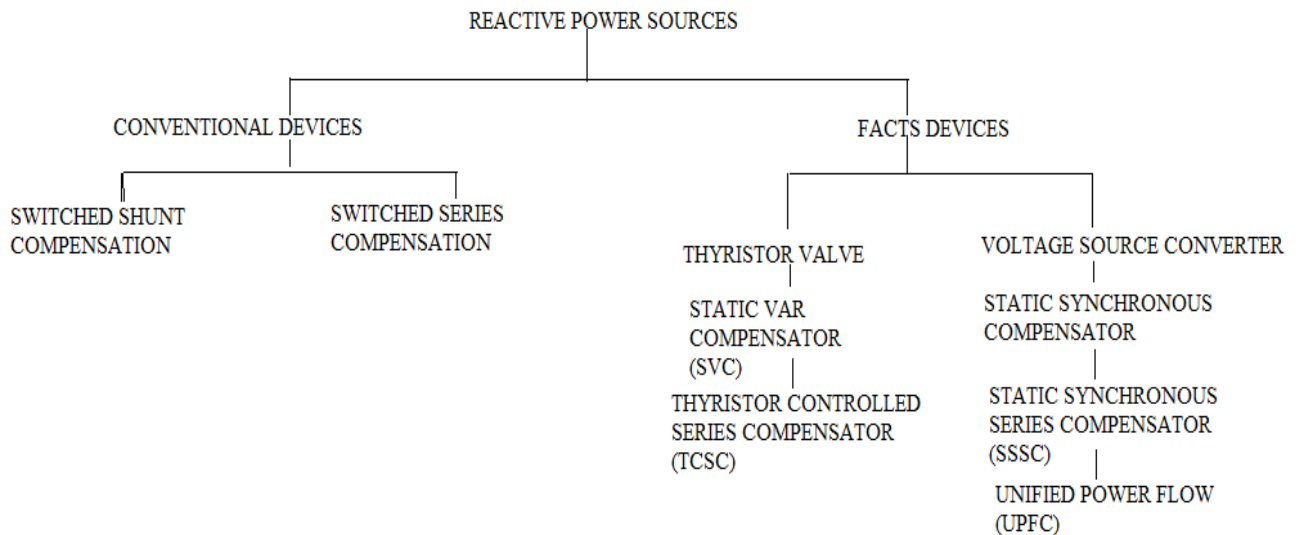


FIGURE 2.1- CLASSIFICATION OF REACTIVE POWER SOURCES

2.2 FLEXIBLE AC TRANSMISSION SYSTEM (FACTS)

According to the IEEE PES task force of the FACTS working group, terms and definitions for FACTS are defined as follows:

“Facts are the alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability”.

Since the voltage, current, impedance, real power, and reactive power are interrelated, each controller has multiple attributes. Some of the possible benefits from facts technology are

- Control of voltage and power flow as desired.
- Increase of loading capabilities of lines to their thermal capabilities, including short term and seasonal.
- Raise in the transient stability limit, limit short-circuit currents and overloads, manage cascading blackouts and damping electromechanical oscillations of power systems and machines.
- Decrease overall generation reserve requirements on both sides.
- Provide secure tie line connections to nearby utilities and regions.
- Reduce reactive power flows, thus allowing the lines to carry more active power.
- Reduce loop flows.
- Increase utilization of lowest cost generation. [6]

2.2.1 Types of FACTS Controllers

Facts controllers can be divided into four categories as follows:

1. Shunt controllers
2. Series controllers
3. Combined series-series controllers
4. Combined series-shunt controllers

They can be explained briefly as follows:

1. Shunt controllers: The shunt controllers may be variable impedance, variable source, or a combination of these. Any variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. In principle, all shunt controllers inject current into the system at the point of connection. Some of the examples of shunt devices are SVC and STATCOM.
2. Series controllers: The series controllers may be variable impedance, or a variable source type. Any variable impedance multiplied by the current flow through it, represents an injected series voltage in the line. In principle, all series controllers inject voltage in series with the line. Some examples of series controllers are TCSC, and SSSC.
3. Combined series-series controllers: This could be a combination of separate series controllers, which are co-ordinated in a multiline transmission system, or it could be a unified controller. The term 'unified' here means that the dc terminals of all controller converters are all connected together for real power transfer.
4. Combined series-shunt controllers: This could be a combination of separate shunt and series controllers, which are controlled in a co-ordinated manner or a unified power flow controller with series and shunt elements. In principle, combined shunt and series

controllers inject current into the system with the shunt part of the controller and voltage in series in the line with the series part of the controller [6].

The relative importance of different types of controllers is given below.

1. Shunt controllers: The shunt controller is like a current source, which draws from or injects current into the line. The shunt controller is hence, a good way to control voltage at and around the point of connection through injection of reactive current alone or a combination of active and reactive current for a more effective voltage control and damping of voltage oscillations. One more advantage of shunt controller is it serves the bus node independently of the individual lines connected to the bus.
2. Series controllers: The series controller on the other hand, impacts the driving voltage and hence the current and power flow directly. If the purpose of the application is to control the current/power flow and damp oscillations, the series controller is a good way. The series controller for a given MVA size is several times more powerful than the shunt controller. Series controller solution may require, but not necessarily, a separate series controller for several lines connected to the substation and they have to be designed to ride through the contingency and dynamic overloads.
3. Combined series-series/series-shunt controllers: From the above arguments, it can be drawn out that a combination of the series and shunt controllers can provide the best of both, which are an effective power/current flow and line voltage control. For the combination of series and shunt controllers, the shunt controllers can be a single unit serving in coordination with individual line controllers which can provide additional benefits with unified controllers [6].

In the proposed method, STATCOM, SVC and TCSC are tested. The control attributes of these facts controllers are as follows:

1. STATCOM: The control attributes of STATCOM are voltage control, VAR compensation, damping oscillations and voltage stability.
2. SVC: The control attributes of SVC are voltage control, VAR compensation, damping oscillations, transient and dynamic stability, and voltage stability.
3. TCSC: The control attributes of TCSC are current control, damping oscillations, transient and dynamic stability, voltage stability, and fault current limiting [6].

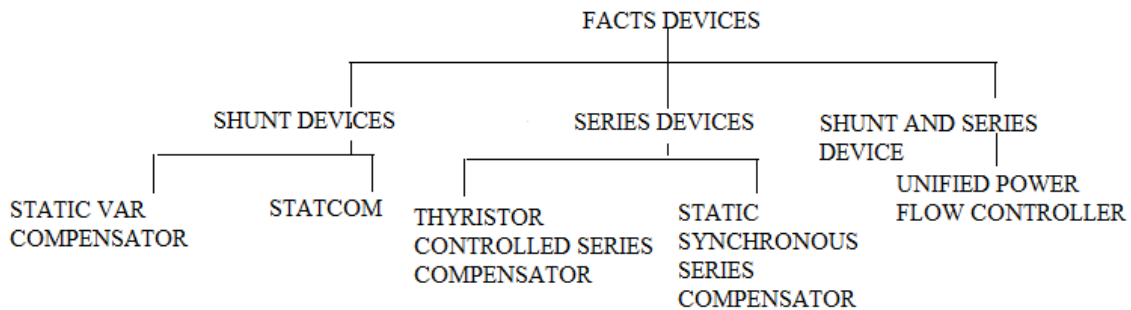


FIGURE 2.2 – CLASSIFICATION OF FACTS DEVICES

2.3 CONFIGURATIONS OF SHUNT FACTS DEVICES

The SVC and STATCOM are the most used FACTS devices as reactive power compensators. They provide sufficient reactive power by reducing unwanted reactive power flows and losses. They improve static and transient stability of the power system. They are being used in many industries and energy sectors.

2.3.1 Static VAR Compensator (SVC)

According to the IEEE PES task force of the FACTS working group, the static VAR compensator can be defined as a shunt-connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system [10].

The SVC is built of power electronic devices such as the thyristor valve which is a stack of series connected anti-parallel thyristors to provide controllability, air core reactors and high voltage AC capacitors and is connected to the transmission line through a power transformer. It is based on thyristors without the Gate Turn Off (GTO) capability. It includes thyristor-controlled reactor for leading VAR and thyristor switched capacitor for lagging VAR. The thyristor controlled reactor is defined by the IEEE PES task force of the FACTS working group as a “shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve”. The thyristor switched capacitor is defined by the IEEE PES task force of the FACTS working group as a “shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve” [10].

In a power system, the load varies from time to time. This may change the reactive power balance in the system resulting in undesired voltage variations. In the worst case scenario, these voltage variations may result in voltage collapse of the system. The Static VAR Compensator can be installed at various points in the system to maintain the voltage at the accepted levels by providing sufficient reactive power to the system, thus maintain the reactive power balance and further reducing the losses and ultimately the voltage collapse. It further enhances the static and transient stability of the system. The first commercial SVC was installed in 1972 for an electric arc furnace. It was then used in a transmission line in 1979 [10].

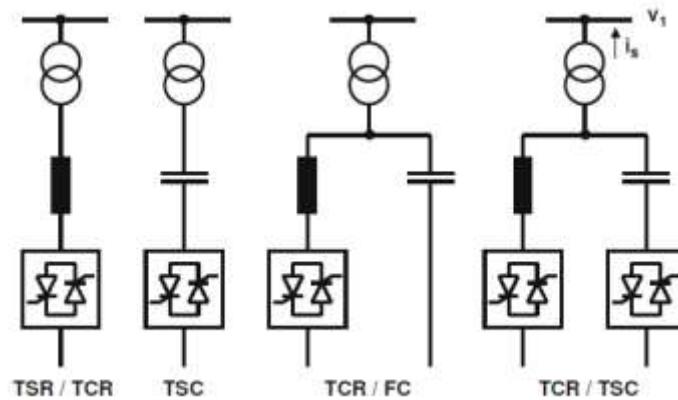


FIGURE 2.3 – SVC BUILDING COMPONENTS [4]

As can be seen from the figure (2.4), the basic operation of TSC-TCR VAR generator can be described as follows:

The total capacitive output range is divided into n intervals. In the first interval, the output of the VAR generator is controllable in the zero to Q_{Cmax}/n range, where Q_{Cmax} is the total rating provided by all TSC branches. In this interval, one capacitor bank is switched in and, simultaneously, the current in the TCR is set by the appropriate firing delay angle so that the sum of the VAR output of the TSC (negative) and that of the TCR (positive) equals the capacitive output required. By being able to switch the capacitor banks in and out within one cycle of the

applied ac voltage, the maximum surplus capacitive VAR in the total output range can be restricted to that produced by one capacitor bank, and thus theoretically should have the same VAR rating of that of the TSC [10]

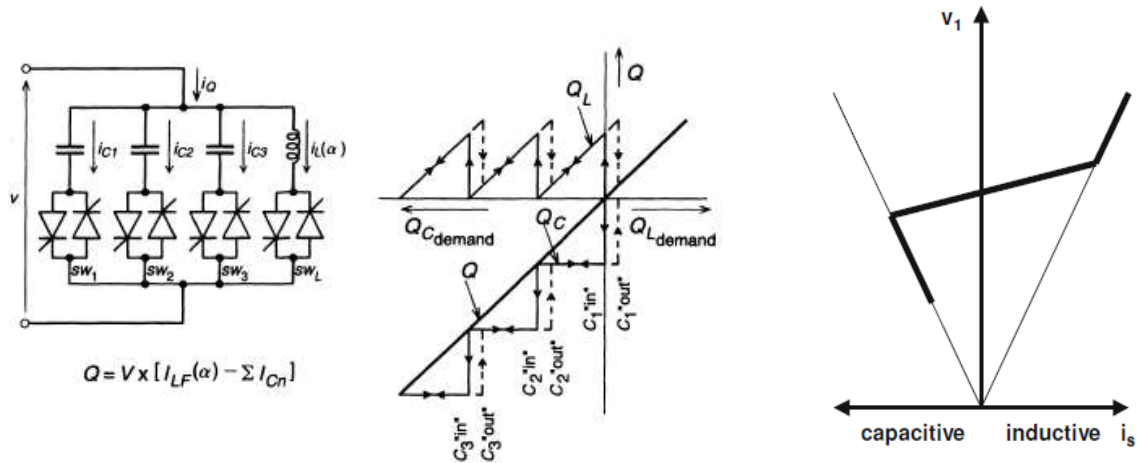


FIGURE 2.4 – BASIC SVC OPERATION [4]

2.3.2 Static Synchronous Compensator (STATCOM)

According to the IEEE PES task force of the FACTS working group, STATCOM is a static synchronous generator operated as a shunt-connected static VAR compensator whose capacitive or inductive output current can be controlled independent of the AC power system voltage. It can be either voltage-sourced or current-sourced converter. From the overall point of view, the voltage-sourced converter is more economical compared to the current-sourced converter [6].

A static synchronous generator can be defined as a static self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multiphase output voltages, which may be coupled to an AC power system for the purpose of exchanging independently controllable real and reactive power.

For the voltage-sourced converter, its AC output voltage is controlled such that it is just right for the required reactive current flow for any AC bus voltage. The DC capacitor voltage is automatically adjusted as required to serve as a voltage source for the converter.

The STATCOM has characteristics similar to synchronous condenser but it is superior to it in several ways. It consists of thyristors with gate turn-off capability (GTO) or IGCT or many IGBT's. In comparison to the SVC, STATCOM has an advantage of providing reactive power independent of the actual voltage at the connection point. Thus, STATCOM functions to its full capability even during severe contingencies [10].

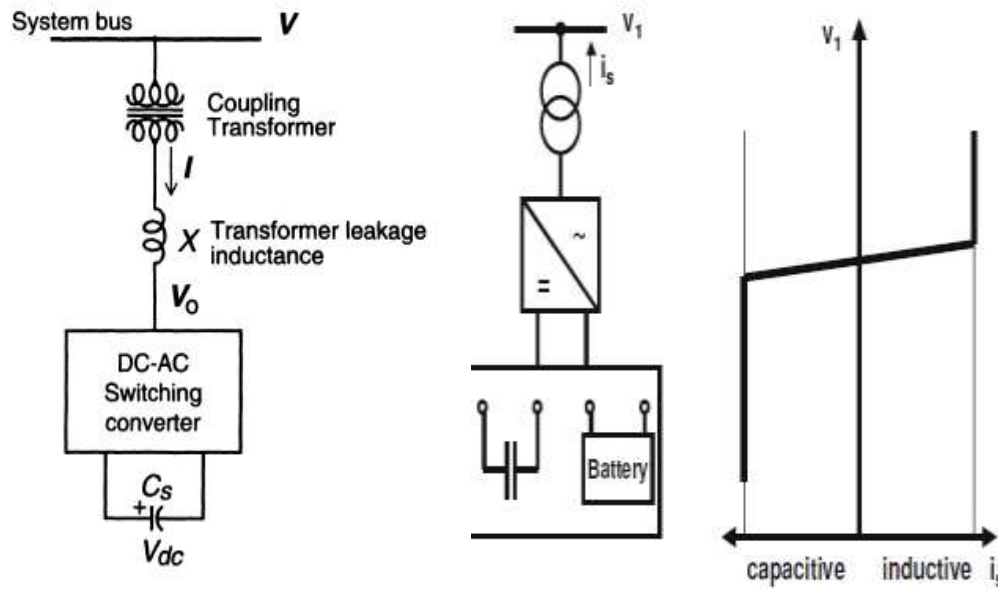


FIGURE 2.5 – BASIC STATCOM OPERATION PRINCIPLE AND V-I CHARACTERISTICS [4]

The basic-voltage sourced converter scheme for reactive power generation is shown in figure (2.5) in a single-line diagram. From a DC input voltage source, provided by the charged capacitor C_s , the converter produces a set of controllable three-phase output voltages with the frequency of the AC power system. Each output voltage is in phase with and coupled to the corresponding AC system voltage via a relatively small tie reactance. By varying the amplitude of the output voltages

produced, the reactive power exchange between the converter and the AC system can be controlled in a manner similar to that of the rotating synchronous machine. If the amplitude of the output voltage is increased above that of the AC system voltage, then the current flows through the tie reactance from the converter to the AC system, and the converter generates reactive power. If the amplitude of the output voltage is decreased to that of the AC system voltage, then the reactive current flows from the AC system to the converter, and the converter absorbs reactive power. If the amplitude of the output voltage is equal to that of the AC system voltage, the reactive power exchange is zero [10].

2.4 CONFIGURATION OF SERIES FACTS DEVICES

A series capacitor generates reactive power that balances a fraction of line's transfer reactance. This results in electrically shortening of the line improving angular stability, voltage stability and power transfer capability. The series devices are installed in series with a transmission line thus providing series compensation [6].

2.4.1 Thyristor Controlled Series Capacitors (TCSC)

According to the IEEE PES task force of the FACTS working group, a TCSC can be defined as a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance. It is based on thyristors with GTO. TCSC regulates steady-state power flow within its rating limits, and controls line power flow. TCSC provides a variable capacitive reactance and changes its apparent impedance to avoid sub-synchronous resonance. It resembles the conventional series capacitor with thyristor valve located on an isolated steel platform. The controls will function on the thyristor valve such that it makes the capacitor variable at fundamental frequencies but a virtual inductor at

sub-synchronous frequencies. A possible internal control scheme for the TCSC is shown in figure (2.6). In this arrangement, the conventional technique of converting the demanded TCR current into the corresponding delay angle, which is measure from the peak of the fundamental line current, is used. The reference for the demanded TCS current is usually provided by a regulation loop of the external control, which compares the actual capacitive impedance or compensating voltage to the reference given for the desired system operation [10].

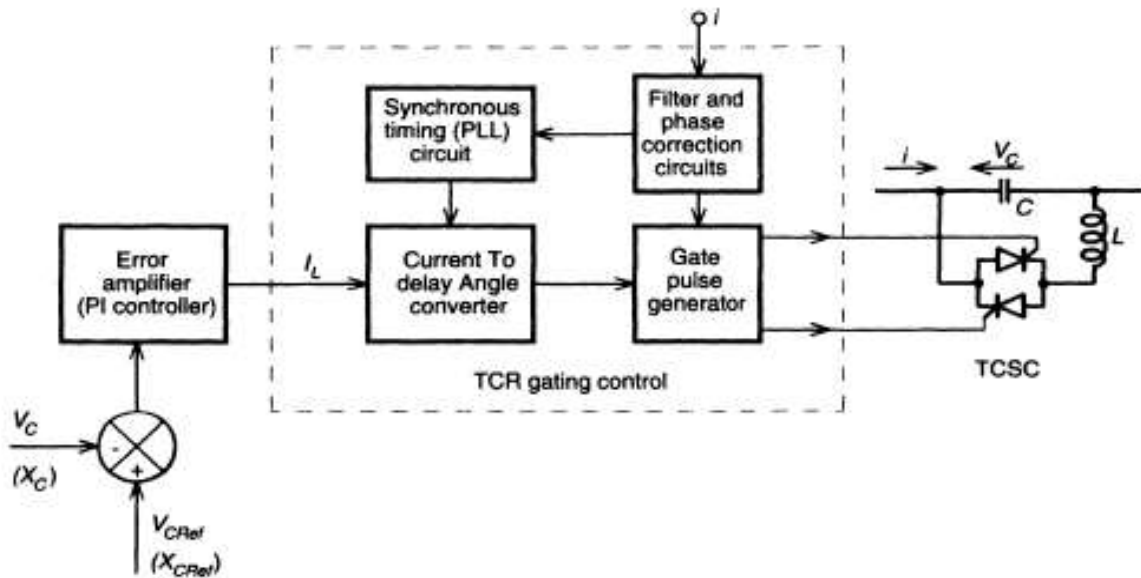


FIGURE 2.6 – BASIC TCSC OPERATION PRINCIPLE [4]

2.5 VOLTAGE STABILITY ANALYSIS

At any time, a power system should operate at a stable condition and it should also be secure in the event of any contingency. Voltage instability phenomenon can be described as a process where the receiving end voltage decreases well below its normal value and does not come back even after using restoring mechanisms. This may further result in voltage collapse where the voltage falls to an unacceptable value [8].

Voltage stability can be classified into long-term voltage stability and short-term or transient voltage stability. The classification is based on the time span of the disturbance in a power system. Typically the time frame of transient stability is for a few seconds whereas for a long-term stability it may vary from minute to tens of minutes. In the transient voltage stability, the operator can do not much to avoid the instability whereas in the long term voltage, the stability can be restored soon by adding reactive power elements [8].

Voltage stability can also be categorized into small-disturbance or steady-state disturbance and large-disturbance voltage stability. Steady-state voltage stability deals with situations where the system is disturbed by small contingencies. The steady state stability analysis is helpful in getting qualitative analysis. Large-disturbance stability deals with serious contingencies which requires study of the system for the whole time frame of disturbance.

There are different methods for carrying out a steady state voltage stability analysis. Some are given as follows [5]:

1. Power Voltage (P-V) curve method
2. Continuation Power Flow Method

2.5.1 P-V Curve Method

The P-V curve method is widely used method in voltage stability analysis. This involves using a series of power flow solutions for increasing transfers of MW and monitoring its effect on the voltages as a result. This gives the available amount of active power margin before the point of voltage instability [5].

As seen in figure (2.7), the P-V curve starts from 1.0 p.u. voltage at zero load and keeps decreasing the voltage as the load increases till it reaches a particular point where any

further increase in the load collapses the voltage to zero. This point is called as the voltage collapse point or the maximum loadability point and the corresponding voltage is referred to as the Critical voltage. The distance of the operating point to the voltage collapse point denotes the stability margin of the system.

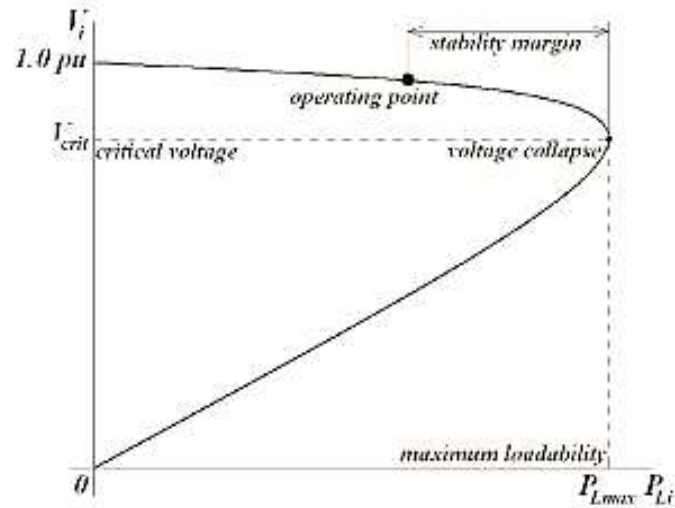


FIGURE 2.7 – P-V CURVE METHOD [4]

2.5.2 Continuation Power Flow Method

The formulation of Continuation Power Flow Analysis is given as follows [2].

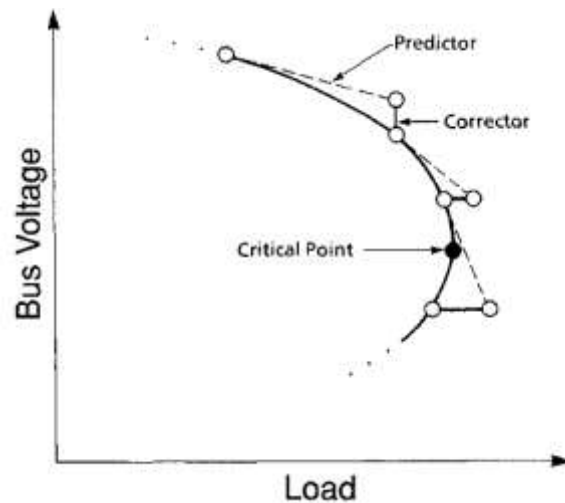


FIGURE 2.8 – CONTINUATION POWER FLOW METHOD [2]

First, it starts with the predictor step where to simulate load change, P_{di} and Q_{di} , may be represented by

$$P_{di} = P_{di}^0(1 + \lambda * KP_{di}) \quad (1)$$

$$Q_{di}^P = Q_{di}^0(1 + \lambda * KQ_{di}) \quad (2)$$

Where P_{di}^0 and Q_{di}^0 are the base case active and reactive power loads of phase P , at bus i and λ is the loading factor, which characterize the change of load.

The ratio of KP_{di}/KQ_{di} is constant to maintain a constant power factor.

Similarly to simulate generation change, P_{gi} and Q_{gi} are represented as functions of λ is given below:

$$P_{gi} = P_{gi}^0(1 + \lambda * KP_{gi}) \quad (3)$$

$$Q_{gi} = Q_{gi}^0(1 + \lambda * KQ_{gi}) \quad (4)$$

Where P_{gi}^0 and Q_{gi}^0 are the base case active and reactive power of the generators, at bus i and λ is the loading factor, which characterize the change of load.

The ratio of KP_{gi}/KQ_{gi} is constant to maintain a constant power factor for a PQ machine. For a PV machine, equation (4) is not required. When the reactive power limit is violated, Q_{gi} is to be kept at the limit. The non-linear power flow equations are augmented by an extra variable λ as follows:

$$f(x, \lambda) = 0 \quad (5)$$

where equation (5) represents the whole set of power flow mismatch equations.

Using the predictor step, the approximate point for the next solution is obtained. A prediction of the next solution is made by taking an approximately sized step in the direction tangent to the solution path.

To solve equation (5), the continuation algorithm with predictor and corrector steps can be used. Linearizing equation (5), we get

$$df(x, \lambda) = f_x dx + f_\lambda d\lambda = 0 \quad (6)$$

To solve equation (6), one more equation is needed. It can be obtained by choosing a non-zero value for one of the tangent vector and keeping its change as ± 1 . It is given as below

$$t_k = \pm 1 \quad (7)$$

where t_k is the non-zero element of the tangent vector dx .

Combining equation (6) and equation (7), a set of equations are obtained where the tangent vector dx and $d\lambda$ are unknown variables.

$$\begin{bmatrix} f_x & f_\lambda \\ e_k & 0 \end{bmatrix} \begin{bmatrix} dx \\ d\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix} \quad (8)$$

where e_k is a row vector with all elements zero except for k^{th} , which equals 1. In equation (8), whether +1 or -1 is used depends on how the k^{th} state variable is changing as the solution is being traced. After solving equation (8), the prediction of the next solution is made as follows:

$$\begin{bmatrix} X^* \\ \lambda^* \end{bmatrix} = \begin{bmatrix} x \\ \lambda \end{bmatrix} + \sigma \begin{bmatrix} dx \\ d\lambda \end{bmatrix} \quad (9)$$

where * denotes the estimated solution of the next step, and σ is a scalar.

Corrector Step – The corrector step is to solve the augmented Newton power flow equation with the predicted solution in equation (9) as the initial point which is given by,

$$\begin{bmatrix} f(x, \lambda) \\ x_k - \eta \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (10)$$

where η is the predicted value of the continuation parameter x_k .

The corrector equation given below can be solved using Newton's approach [4]

$$\begin{bmatrix} f_x & f_\lambda \\ e_k & 0 \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta \lambda \end{bmatrix} = \begin{bmatrix} f(x, \lambda) \\ x_k - \eta \end{bmatrix} \quad (11)$$

The operating limits of generators that are to be satisfied are taken as follows:

$$I_a \leq I_a^{max} \quad (12)$$

$$I_f^{min} \leq I_f \leq I_f^{max} \text{ or } E_f^{min} \leq E_f \leq E_f^{max} \quad (13)$$

$$P_g^{min} \leq P_g \leq P_g^{max} \quad (14)$$

$$Q_g^{min} (P_g) \leq P_g \leq Q_g^{max} (P_g) \quad (15)$$

where I_a^{max} is the current limit of the generator stator winding,

I_f^{min} and I_f^{max} are the minimum and maximum current limits of the generator rotor winding respectively,

E_f^{min} and E_f^{max} are the corresponding excitation voltage limits,

P_g^{min} and P_g^{max} are the minimum and maximum active power limits respectively,

Q_g^{min} and Q_g^{max} are the minimum and maximum reactive power limits respectively.

CHAPTER 3

PROPOSED METHOD

3.1 METHODOLOGY

The following method is proposed to study the effectiveness of FACTS devices in improving the voltage stability of a power system. For this purpose, an IEEE 39 bus New England system has been taken as a test system. First, the IEEE 39 bus test system is built in MATLAB. Then, continuation power flow analysis is performed on the system built by using PSAT. The metrics such as voltage magnitude profile, active and reactive power losses, p-v curves, and maximum load ability point are used to have an understanding of the voltage stability of the system. In the next step FACTS devices such as SVC, STATCOM, and TCSC are included in the system built in MATLAB, one at a time. Again, the continuation power flow analysis is performed for each of the cases individually and the metrics are obtained for each of them. The metrics are to be compared between the each devices along with the initial case where no facts device is used. The effectiveness of each device is drawn out from the results obtained from comparing the metrics. Thus, this study helps in understanding the most efficient FACTS device which can be used for the enhancement of the static voltage stability of a power system.

The test system which is the New England IEEE 39 bus system is built in MATLAB in a format that is compliant with the PSAT. First, the test system is built without including the FACTS devices in it. In PSAT, this MATLAB file is opened and continuation power flow analysis is performed on it. Then, a load flow report provides the voltage magnitude at each bus giving us the voltage magnitude profile. It also provides the active and reactive power losses at each bus and also the

total active and reactive power losses of the system. A P-V curve can be drawn at each bus which provides the maximum loadability point of the curve after which the voltage collapses to zero.

Another IEEE 39 bus test system is built in MATLAB including one of the FACTS devices at a load bus in a format that is compliant with the PSAT. In PSAT, this MATLAB file is opened and continuation power flow analysis is performed on it. Then, the load flow report, and p-v curve report gives the variation in the metrics such as voltage magnitude profile, active and reactive power losses at each bus, total active and reactive power losses in the system, and the maximum loadability point. The same FACTS device is included in the system at a generator bus and later at the swing bus and the metrics are obtained as given above. The comparison of the metrics between the no facts case, the facts at load bus case, at generator bus case and at the swing bus case provides us the necessary information in determining the effect of the facts device used on each of the buses and if it is improving the system from the no facts case. This process is repeated for SVC, STATCOM and TCSC and the metrics obtained are compared with each other and also with the no FACTS case. The overall process is summarized in figure (3.1).

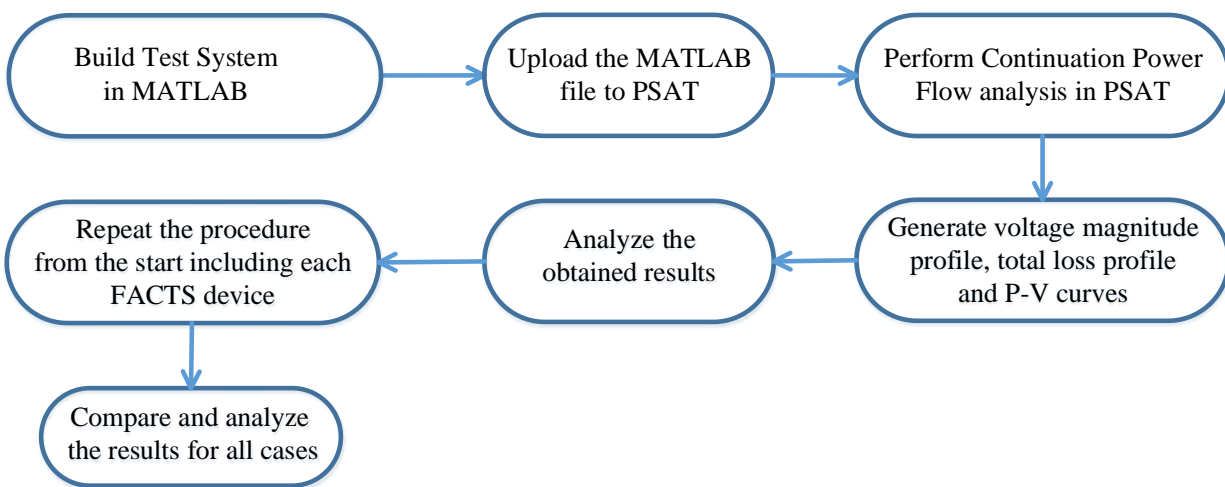


FIGURE 3.1 – METHODOLOGY SUMMARY

CHAPTER 4

TEST SYSTEM AND SIMULATION TOOLS

4.1 TEST SYSTEM

The IEEE 39 bus system is well known as 10-machine New-England Power System. It is a 10 generator and 39 bus test system on a 100 MVA base and 100 KV. Bus 1 to Bus 29 are the P-Q or Load buses, Bus 30 to Bus 39 are the P-V or the Generator buses, and Bus 31 is the swing bus.

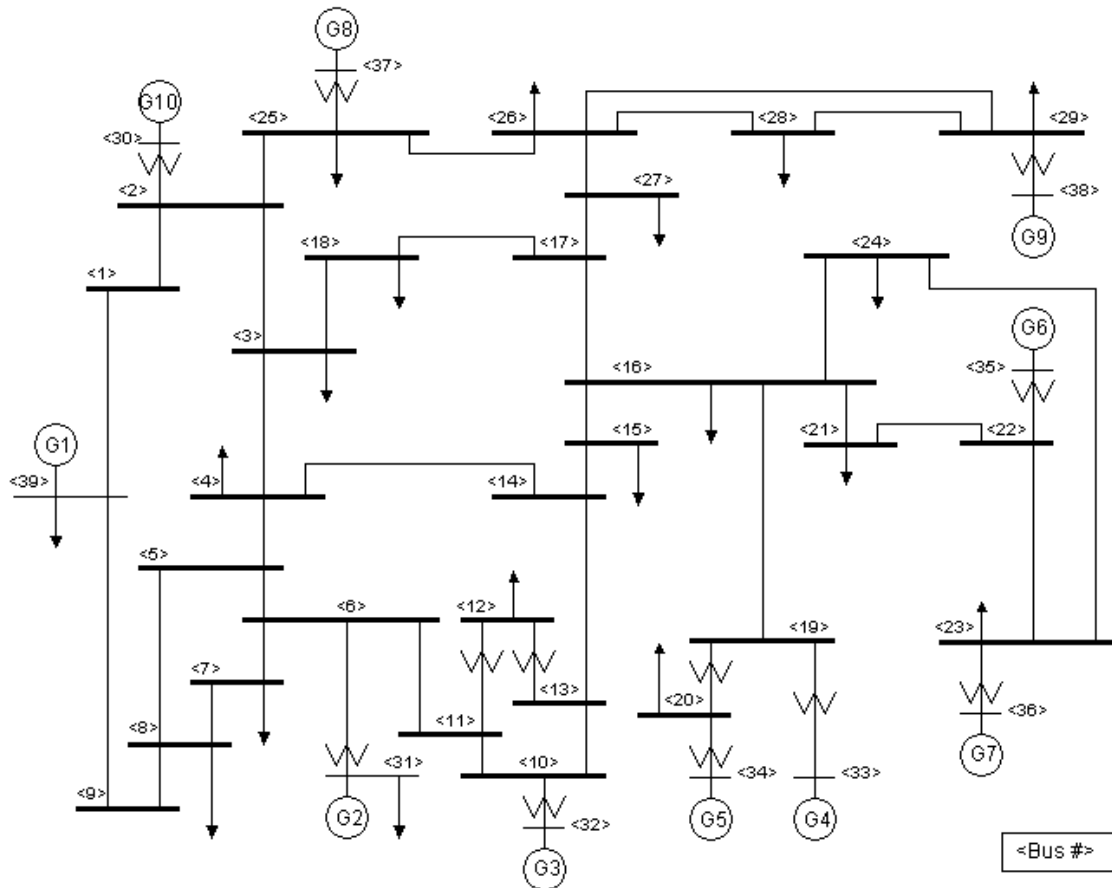


FIGURE 4.1- IEEE 39 BUS SYSTEM NETWORK

4.2 SIMULATION TOOLS

4.2.1 Power System Simulator for Engineering (PSSE)

The power system simulator for engineering (PSSE) [22] is the premier software tool produced by Siemens. It is being used in power industries world-wide in over 115 countries to perform electrical transmission analysis. It offers broad range of methodologies to use in design and operation of networks. This tool has become the most comprehensive, technically advanced, and widely used commercial program of its type. It is widely recognized as the most fully featured, time-tested and best performing commercial program available.

PSSE is an integrated, interactive program for simulating, analyzing, and optimizing power system performance. It provides the user with the most advanced and proven methods in many technical areas, including power flow, optimal power flow, balanced and unbalanced fault analysis, dynamic simulation, extended term dynamic simulation, open access and pricing, transfer limit analysis, and network reduction.

4.2.2 MATLAB

MATLAB [21] is a high-level language and interactive environment for numerical computation, visualization, and programming. MATLAB can be used to analyze data, develop algorithms, and create models and applications. The language, tools, and built-in math functions enable you to explore multiple approaches and reach a solution faster than with spreadsheets or traditional programming languages, such as C/C++ or Java.

4.2.3 Power System Analysis Tool Box (PSAT)

The power system analysis toolbox (PSAT) [15], [16] is a MATLAB tool box for electric power system analysis and simulation. It is a 10 year old free and open source project. The command line version of PSAT is also GNU Octave compatible. All operations can be assessed by means of Graphical user interfaces (GUIs) and a Simulink based library provides a user-friendly tool for network design.

In PSAT, the following line numbers are considered for lines between the buses for the IEEE 39 bus test system. It is given as follows:

LINE 1	BUS 01	BUS 02
LINE 2	BUS 01	BUS 39
LINE 3	BUS 01	BUS 39
LINE 4	BUS 02	BUS 03
LINE 5	BUS 02	BUS 25
LINE 6	BUS 03	BUS 04
LINE 7	BUS 03	BUS 18
LINE 8	BUS 04	BUS 05
LINE 9	BUS 04	BUS 14
LINE 10	BUS 05	BUS 06
LINE 11	BUS 05	BUS 08
LINE 12	BUS 06	BUS 07
LINE 13	BUS 06	BUS 11
LINE 14	BUS 07	BUS 08
LINE 15	BUS 08	BUS 09
LINE 16	BUS 09	BUS 39
LINE 17	BUS 10	BUS 11
LINE 18	BUS 10	BUS 13
LINE 19	BUS 13	BUS 14
LINE 20	BUS 14	BUS 15
LINE 21	BUS 15	BUS 16
LINE 22	BUS 16	BUS 17
LINE 23	BUS 16	BUS 19
LINE 24	BUS 16	BUS 21
LINE 25	BUS 16	BUS 24
LINE 26	BUS 17	BUS 18
LINE 27	BUS 17	BUS 27
LINE 28	BUS 21	BUS 22
LINE 29	BUS 22	BUS 23
LINE 30	BUS 23	BUS 24
LINE 31	BUS 25	BUS 26
LINE 32	BU 26	BUS 27
LINE 33	BUS 26	BUS 28
LINE 34	BUS 26	BUS 29
LINE 35	BUS 28	BUS 29
LINE 36	BUS 02	BUS 30
LINE 37	BUS 06	BUS 31
LINE 38	BUS 06	BUS 31
LINE 39	BUS 10	BUS 32
LINE 40	BUS 12	BUS 11
LINE 41	BUS 12	BUS 13
LINE 42	BUS 19	BUS 20
LINE 43	BUS 19	BUS 33
LINE 44	BUS 20	BUS 34
LINE 45	BUS 22	BUS 35
LINE 46	BUS 23	BUS 36
LINE 47	BUS 25	BUS 37
LINE 48	BUS 29	BUS 39

FIGURE 4.1-LINES IN IEEE 39 BUS TEST SYSTEM

CHAPTER 5

RESULTS

5.1 STATCOM AND SVC AT LOAD BUSES

5.1.1 Voltage Magnitude Profile with FACTS at Bus 1

STATCOM and SVC are included on bus 1 which is a load bus. It can be seen figure (5.1) that there is a small increase in the voltage magnitude profile when used STATCOM. The voltage magnitude profile remains almost as same as that of the no facts in case of the SVC.

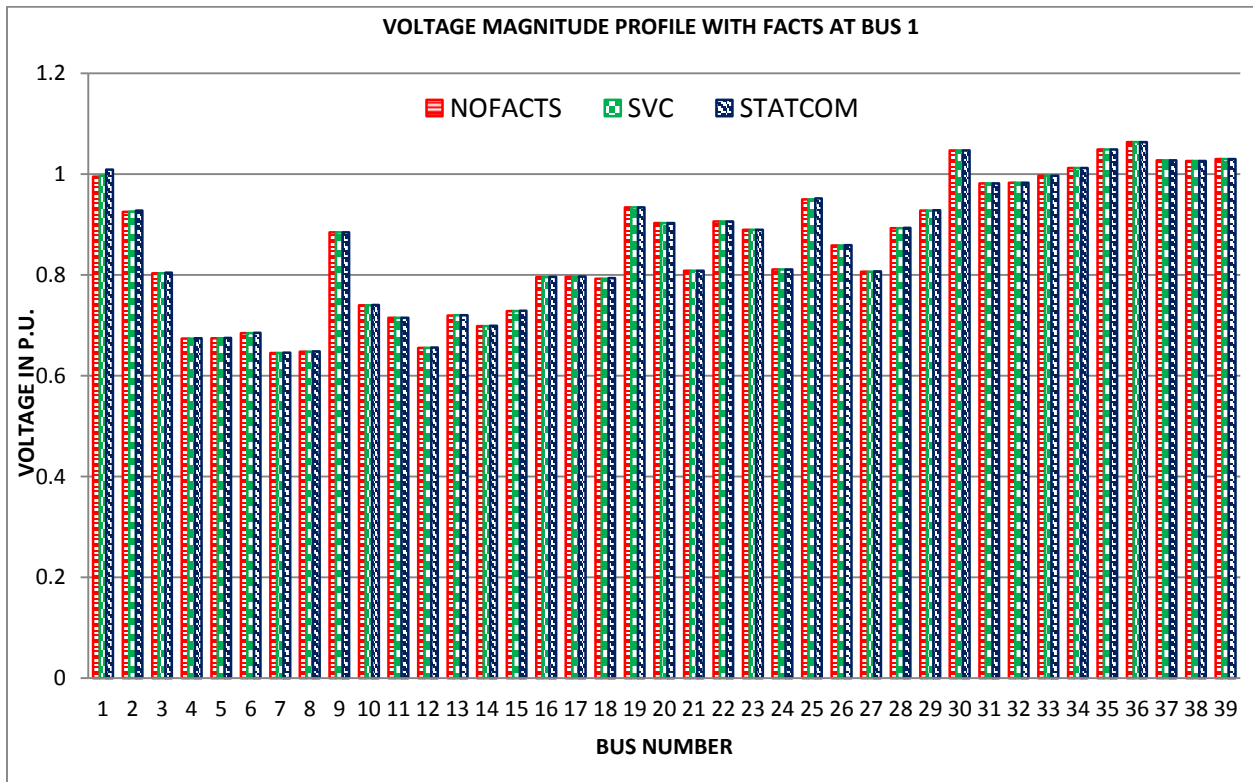


FIGURE 5.1-VOLTAGE MAGNITUDE PROFILE WITH FACTS AT BUS 1

5.1.2 Active and Reactive Power Losses with FACTS at Bus 1

STATCOM and SVC are included on bus 1 which is a load bus. It can be seen in figure (5.2) below that the active power loss has increased slightly in the order NO FACTS – SVC – STATCOM and the reactive power loss decreased slightly in the order STATCOM – SVC – NOFACTS.

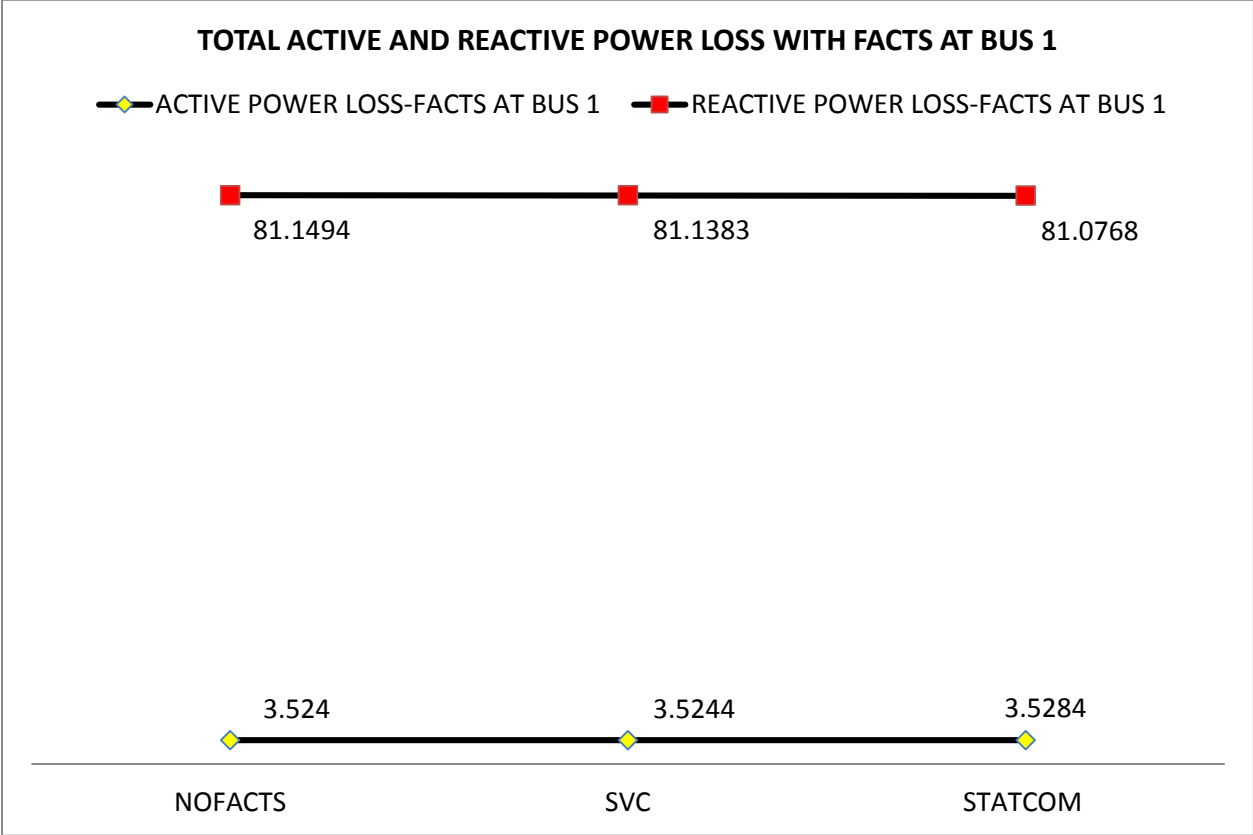


FIGURE 5.2- TOTAL ACTIVE AND REACTIVE POWER LOSS WITH FACTS AT BUS 1

5.1.3 Voltage Magnitude Profile with FACTS at Bus 7

STATCOM and SVC are connected to the bus 7 which is a load bus. This is another example of the FACTS connected to the load bus to see if the above results repeat for consistency. As can be seen in the figure (5.3), the voltage magnitude profile looks almost the same as in the figure (5.1) with very small increase in the voltage magnitude profile in the order NOFACTS – SVC- STATCOM.

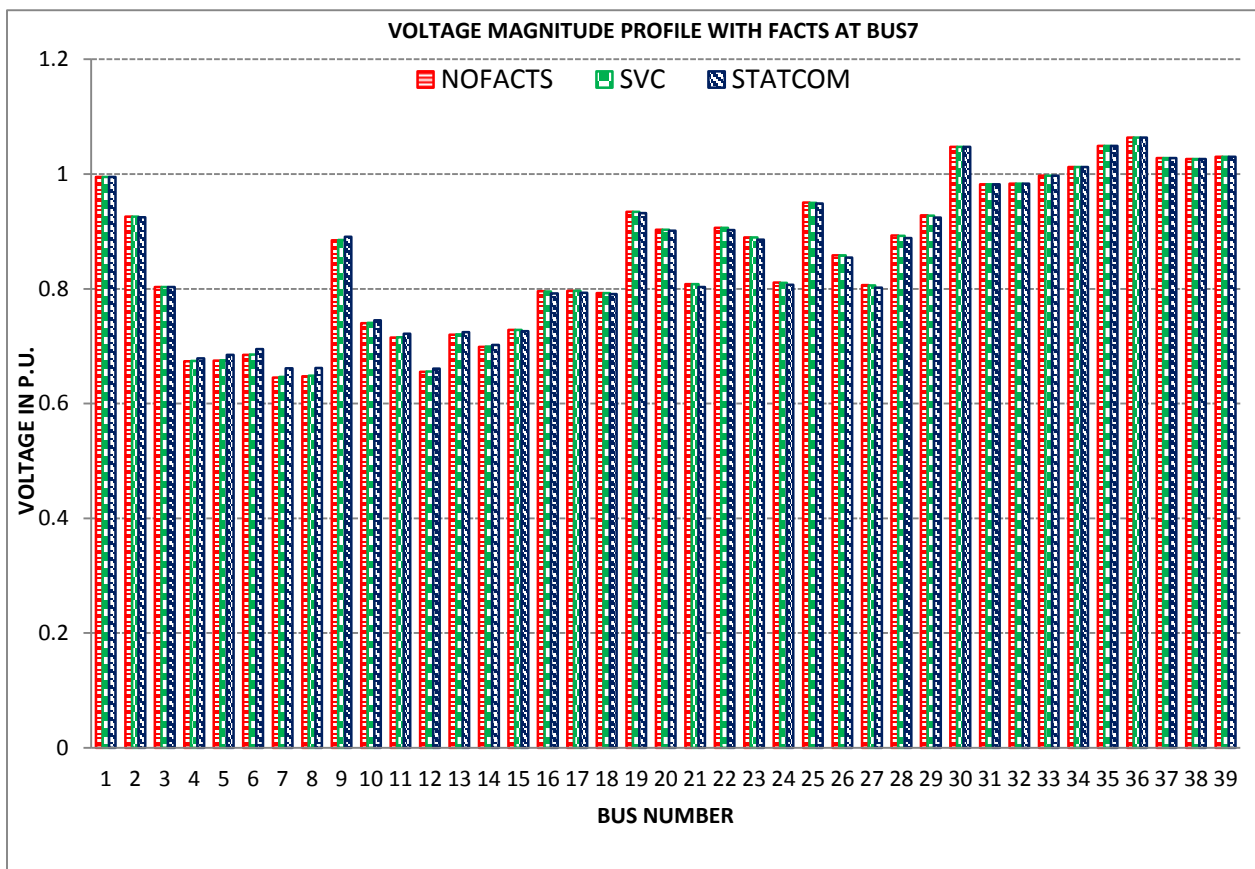


FIGURE 5.3- VOLTAGE MAGNITUDE PROFILE WITH FACTS AT BUS

5.1.4 Active and Reactive Power Losses with FACTS at Bus 7

STATCOM and SVC are connected to the bus 7 which is a load bus. This is another example of the facts connected to the load bus to see if the results obtained are similar to the case where facts are connected to the bus 7 for consistency. As can be seen, the active power loss is increased in the order NOFACTS – SVC – STATCOM whereas the reactive power loss decreased in the order STATCOM – SVC – NOFACTS which is similar to the results in figure (5.4).

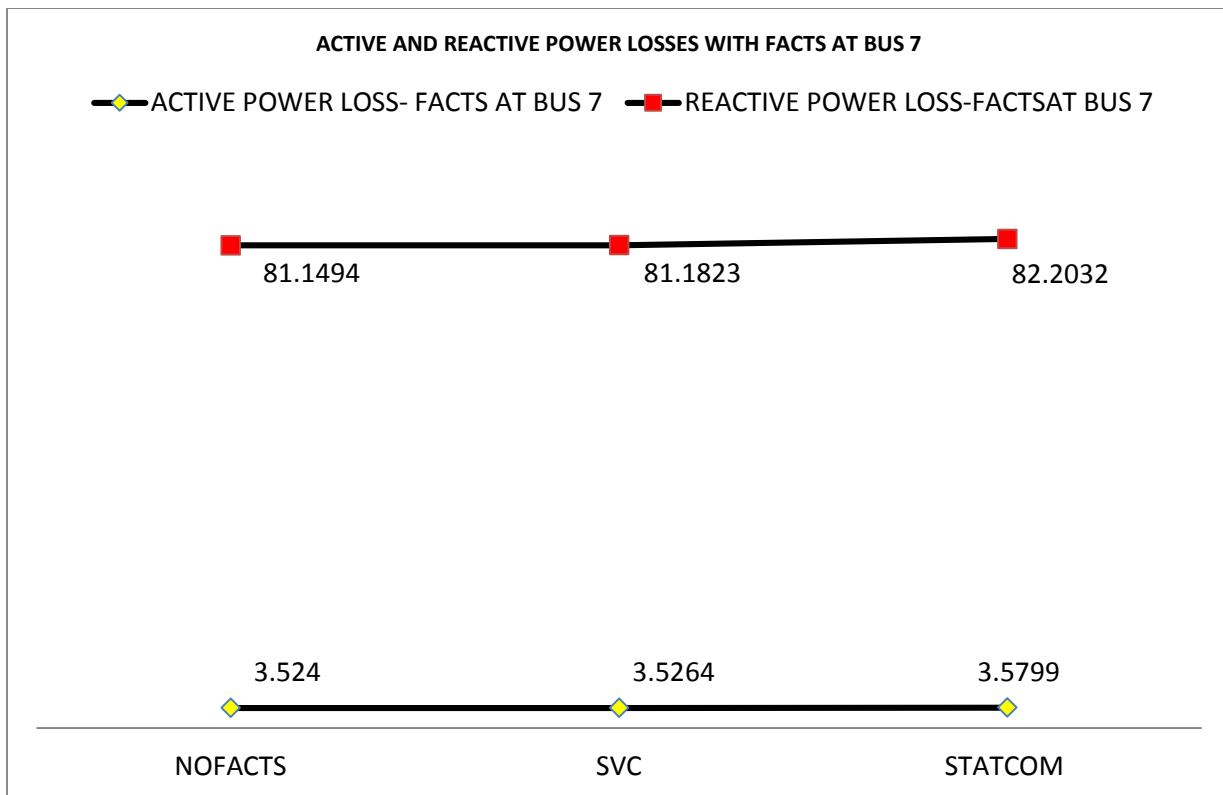


FIGURE 5.4- TOTAL ACTIVE AND REACTIVE POWER LOSS WITH FACTS AT BUS 7

5.1.5 P-V Curve with FACTS at Bus 7

STATCOM and SVC are connected to the bus 7. It can be seen from the figure (5.5) below that the maximum loading point is increased in the order NOFACTS – SVC- STATCOM. As increasing the loading point in turn increases the range of the operating point, the STATCOM gives more range compared to SVC which provides more range compared to the NO FACTS case.

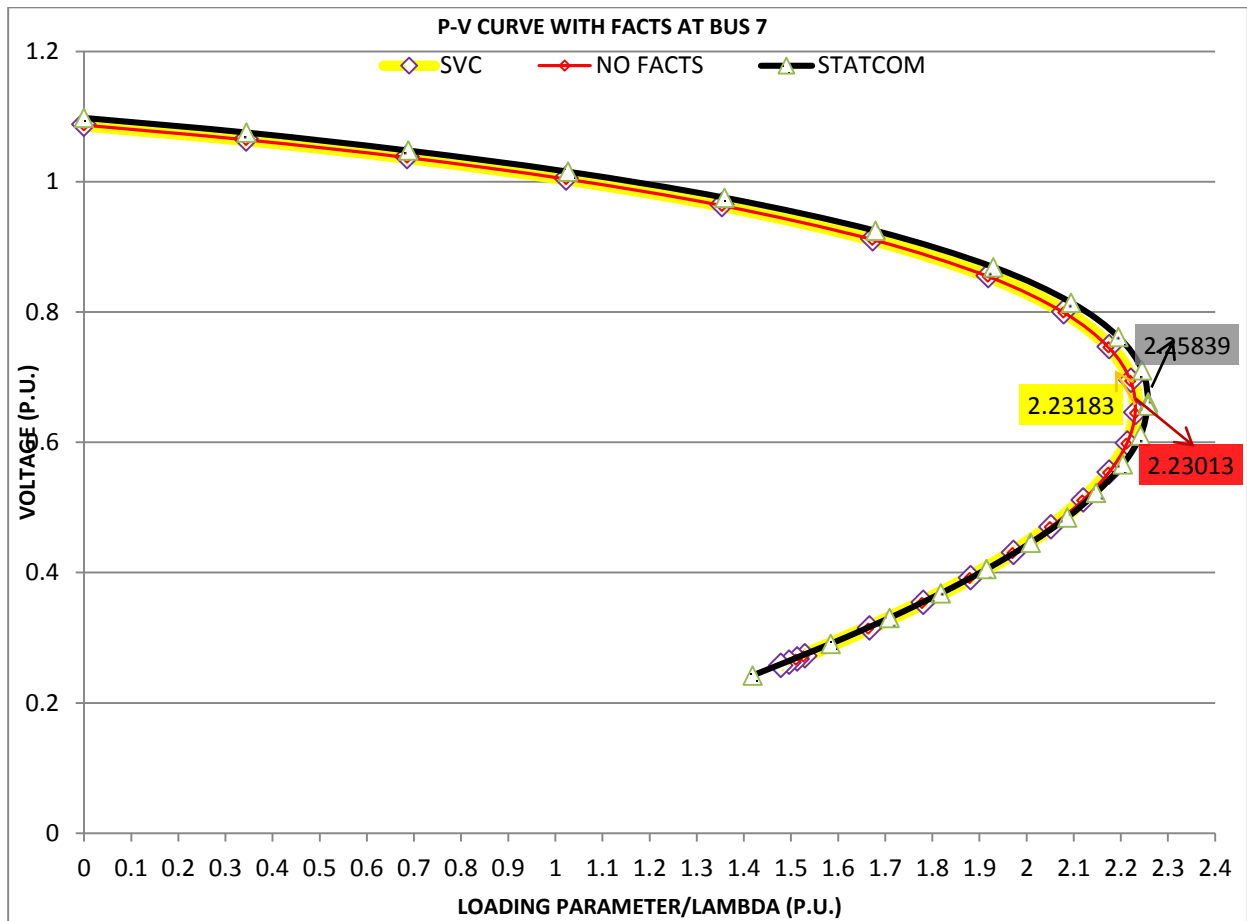


FIGURE 5.5- P-V CURVE

5.1.6 Active Power Loss at Each Line with FACTS at Bus 7

STATCOM and SVC are connected to the bus 7 which is a load bus. It can be seen from figure (5.6), that the active power loss at each line with facts at bus 7 increases in the order from NOFACTS – SVC – STATCOM.

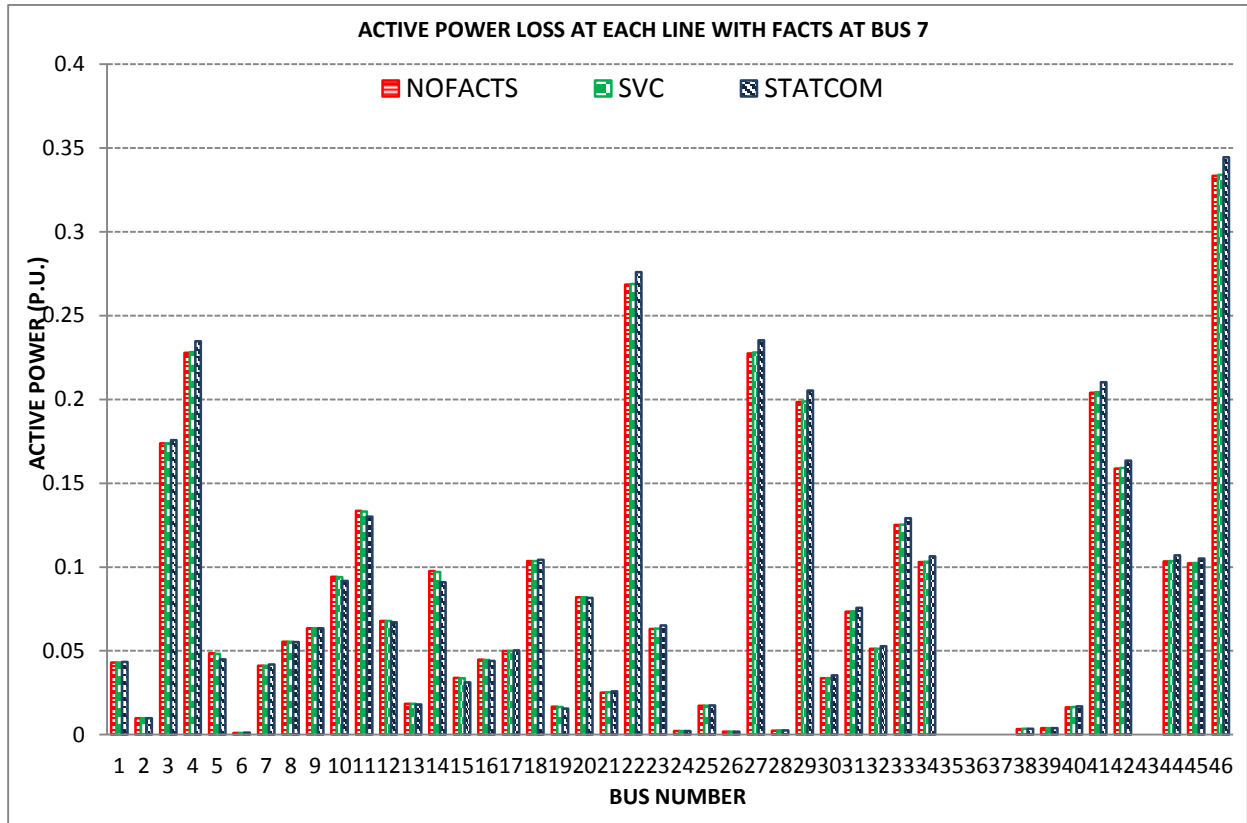


FIGURE 5.6- ACTIVE POWER LOSS AT EACH LINE WITH FACTS AT BUS 7

5.1.7 Reactive Power Loss at Each Bus with FACTS at Bus 7

STATCOM and SVC are connected to the bus 7 which is a load bus. It can be seen from the figure (5.7) that the reactive power loss increase in the order from NO FACTS – SVC – STATCOM.

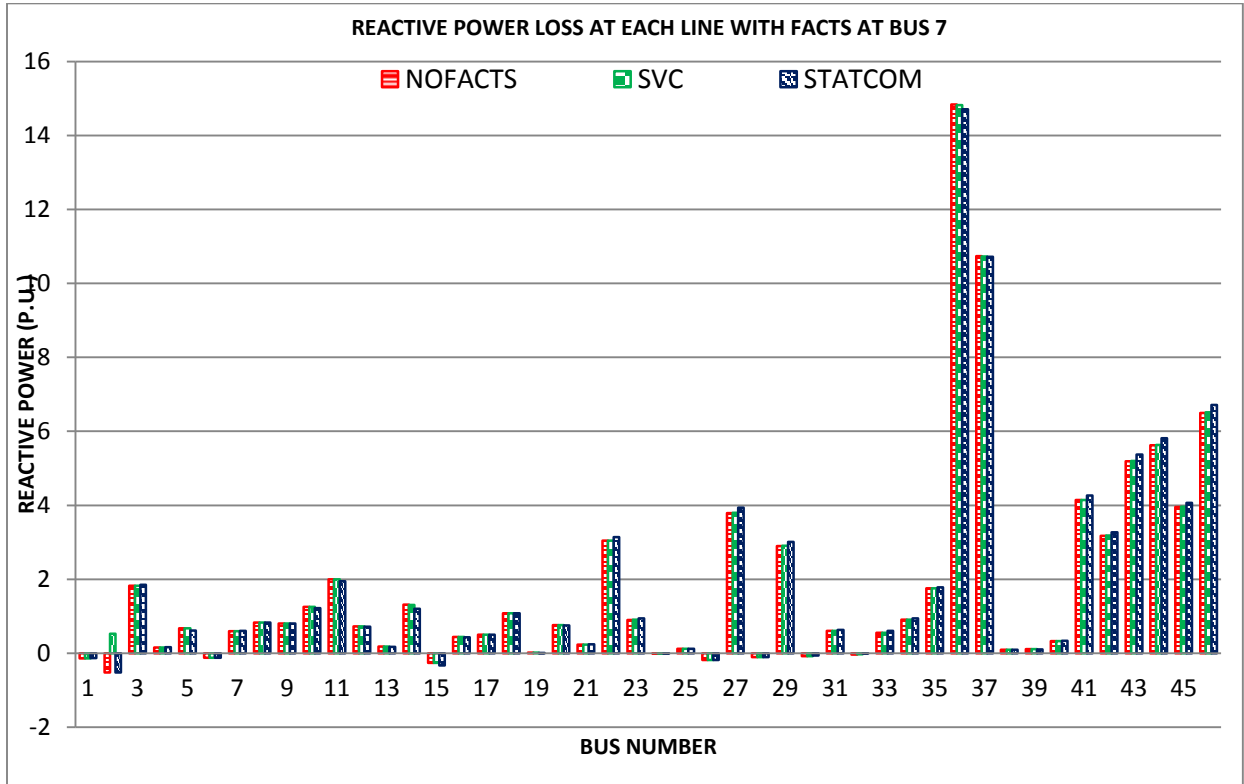
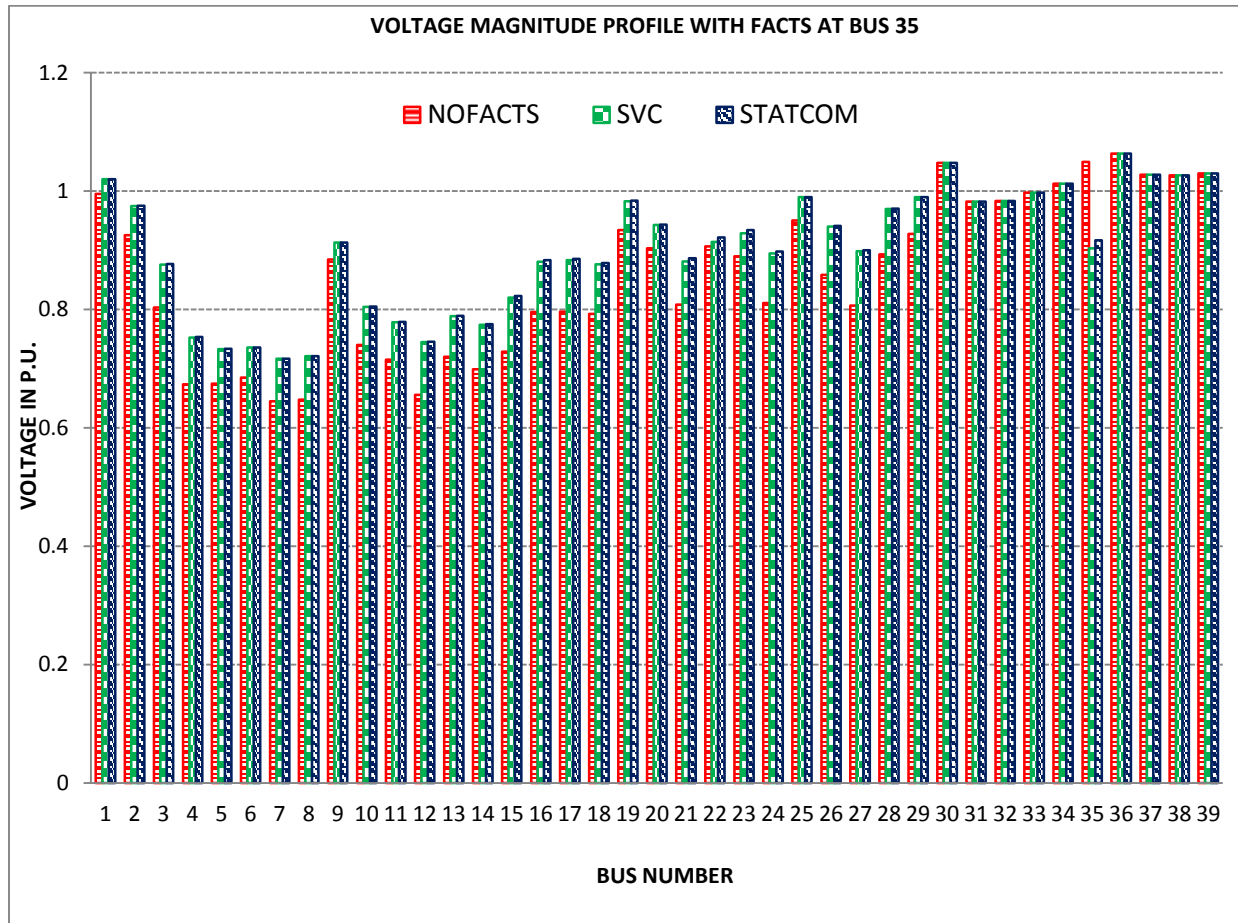


FIGURE 5.7. REACTIVE POWER LOSS AT EACH LINE WITH FACTS AT BUS 7

5.2 STATCOM AND SVC AT GENERATOR BUSES

5.2.1 Voltage Magnitude Profile with FACTS Connected at Bus 35- Generator Bus

It can be seen from figure (5.8), that the voltage magnitude profile has considerably increased in the order from NOFACTS – SVC – STATCOM by connecting the facts at the generator bus. This is a variation to be noticed from the case where the facts was connected to the load bus which had small improvement on the voltage magnitude profile.



5.8. VOLTAGE MAGNITUDE PROFILE WITH FACTS AT BUS 35

5.2.2 Active and Reactive Power Losses with FACTS at Bus 35

STATCOM and SVC are connected to the bus 35 which is a generator bus. It can be seen from figure (5.9) that the active power loss has decreased in the order from NOFACTS – SVC – STATCOM and the reactive power loss also decreased in the order from NOFACTS – SVC – STATCOM. This is different from the results obtained in the case where the facts are connected to the load bus, which had both active and reactive power losses increase in the order from NOFACTS – SVC – STATCOM.

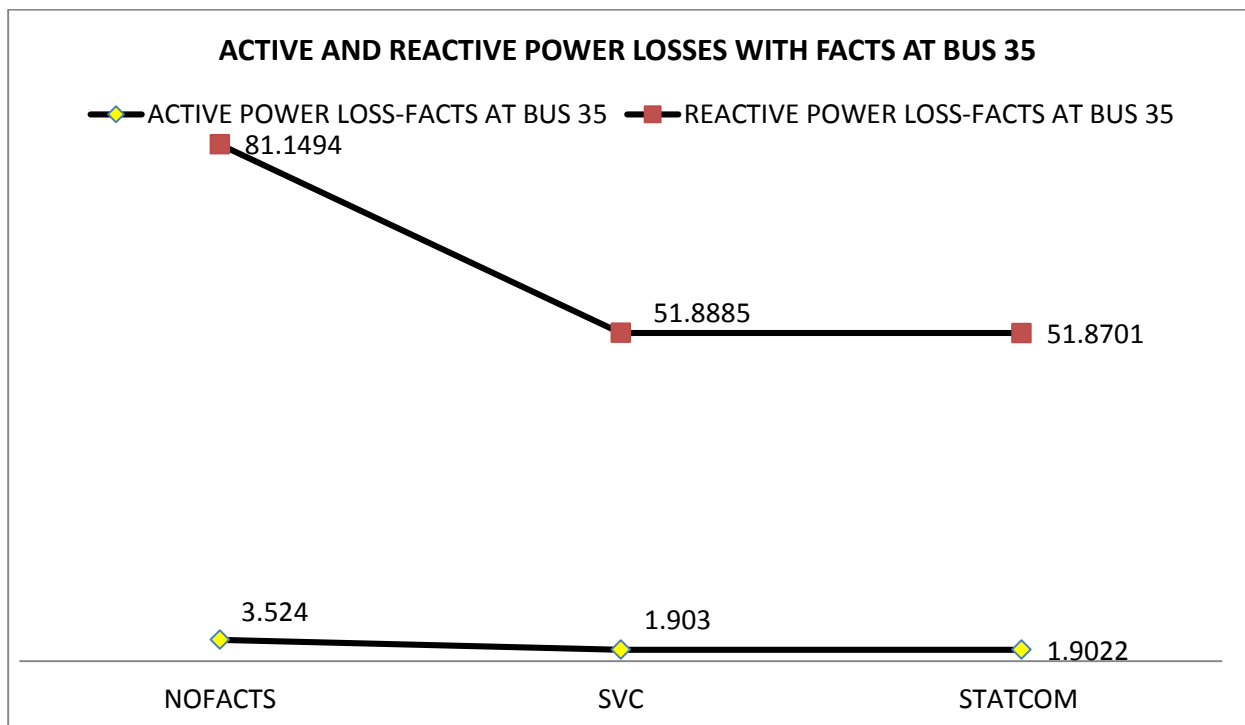


FIGURE 5.9- ACTIVE AND REACTIVE POWER LOSSES WITH FACTS AT BUS 35

5.2.3 P-V Curve with FACTS at Bus 35

STATCOM and SVC are connected to the bus 35 which is a generator bus. It can be seen from the figure (5.10) that the loading margin of NOFACTS is higher than that of the STATCOM and SVC. This is opposite to that of the results obtained in the case where facts are connected to the load bus which had an increase in the loading margin in the order from NOFACTS – SVC – STATCOM.

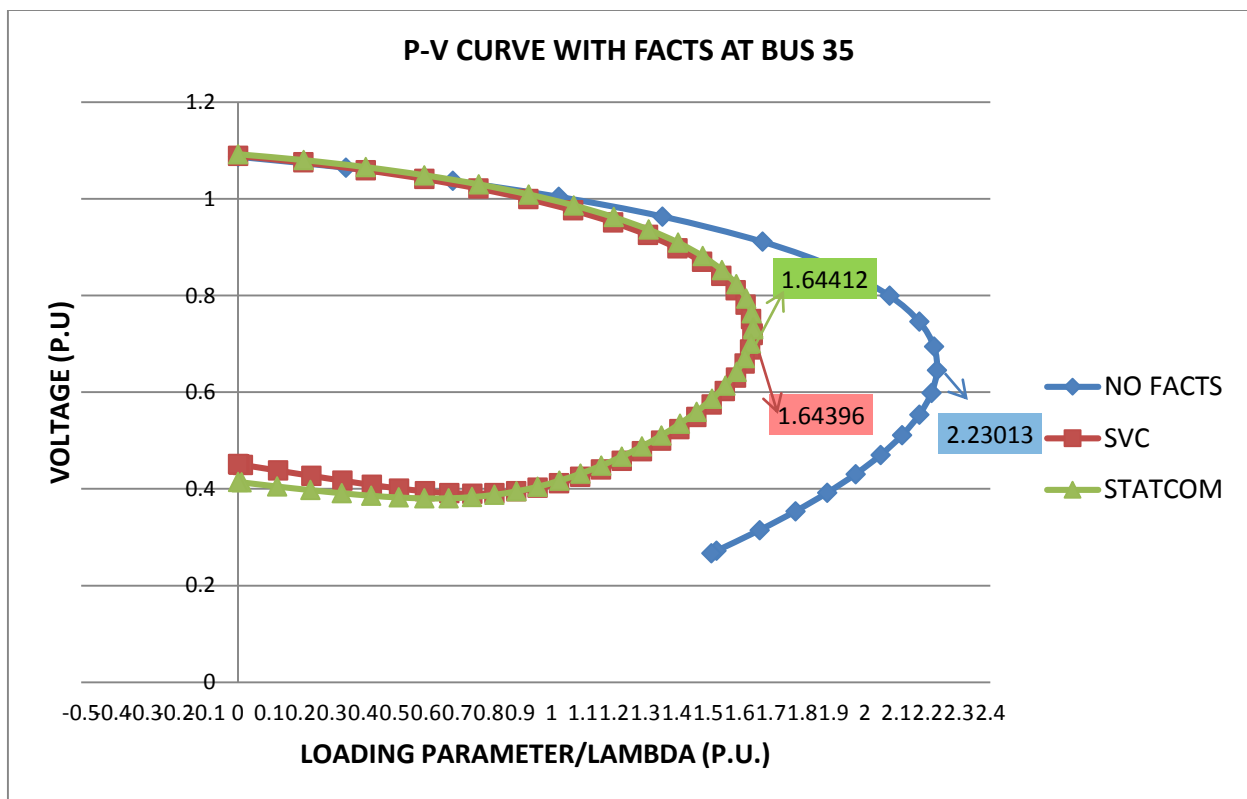


FIGURE 5.10- P-V CURVE WITH FACTS AT BUS 35

5.2.4 Active Power Loss at Each Line with FACTS at Bus 35

STATCOM and SVC are connected to bus 35 which is a generator bus. It can be seen from figure (5.11), that the active power loss at each line has decreased considerably in the order from NOFACTS – SVC – STATCOM. It should be noted that the active losses increased in a small amount in the case where facts are connected to the load bus.

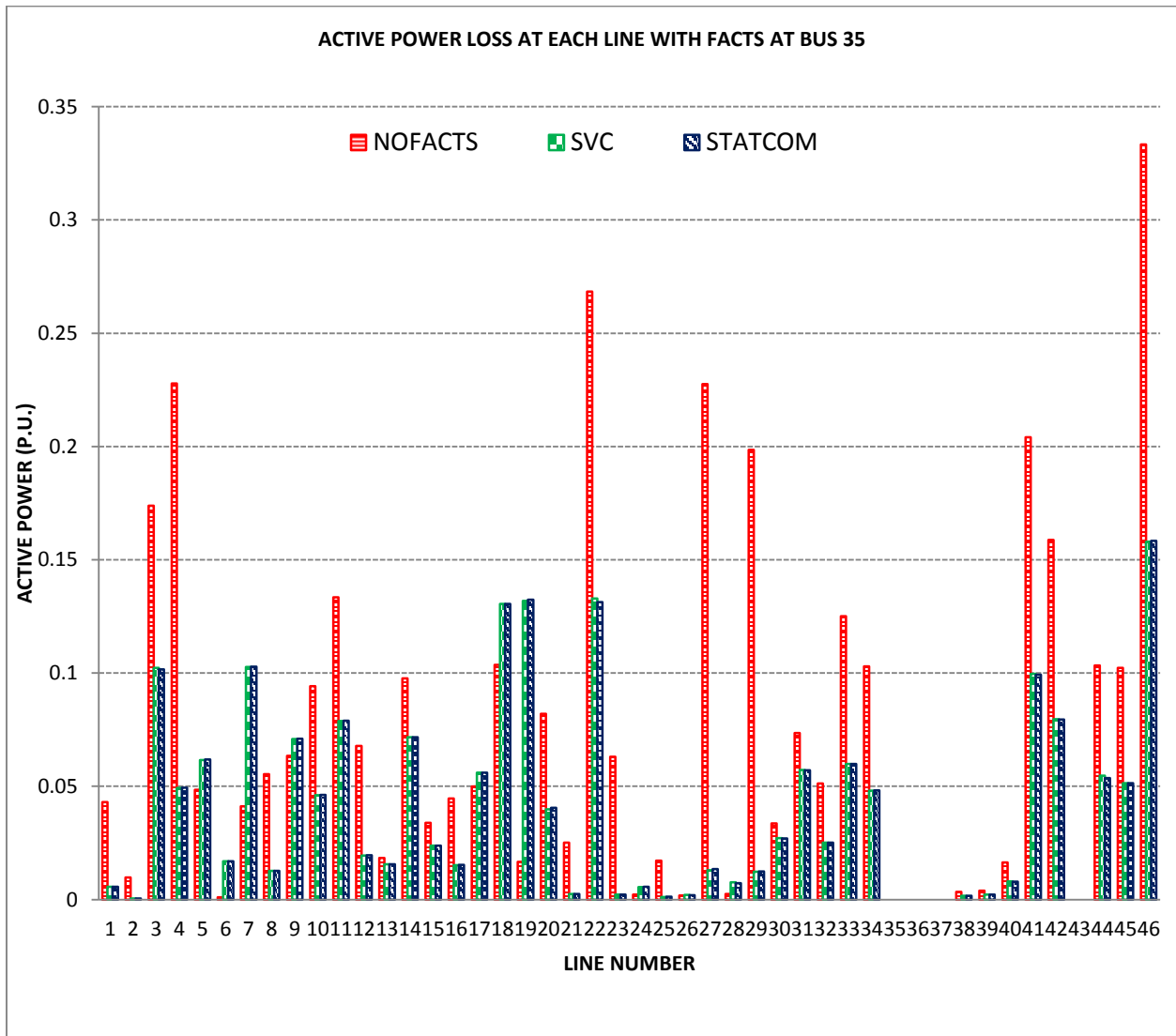


FIGURE 5.11- ACTIVE POWER LOSS AT EACH LINE WITH FACTS AT BUS 35

5.2.5 Reactive Power Loss at Each Line with FACTS at Bus 35

STATCOM and SVC are connected to bus 35 which is a generator bus. It can be seen from the figure (5.12), that the reactive power loss has decreased considerably in the order from NOFACTS – SVC – STATCOM. These results are opposite to the results obtained in the case when the facts are connected to the load bus.

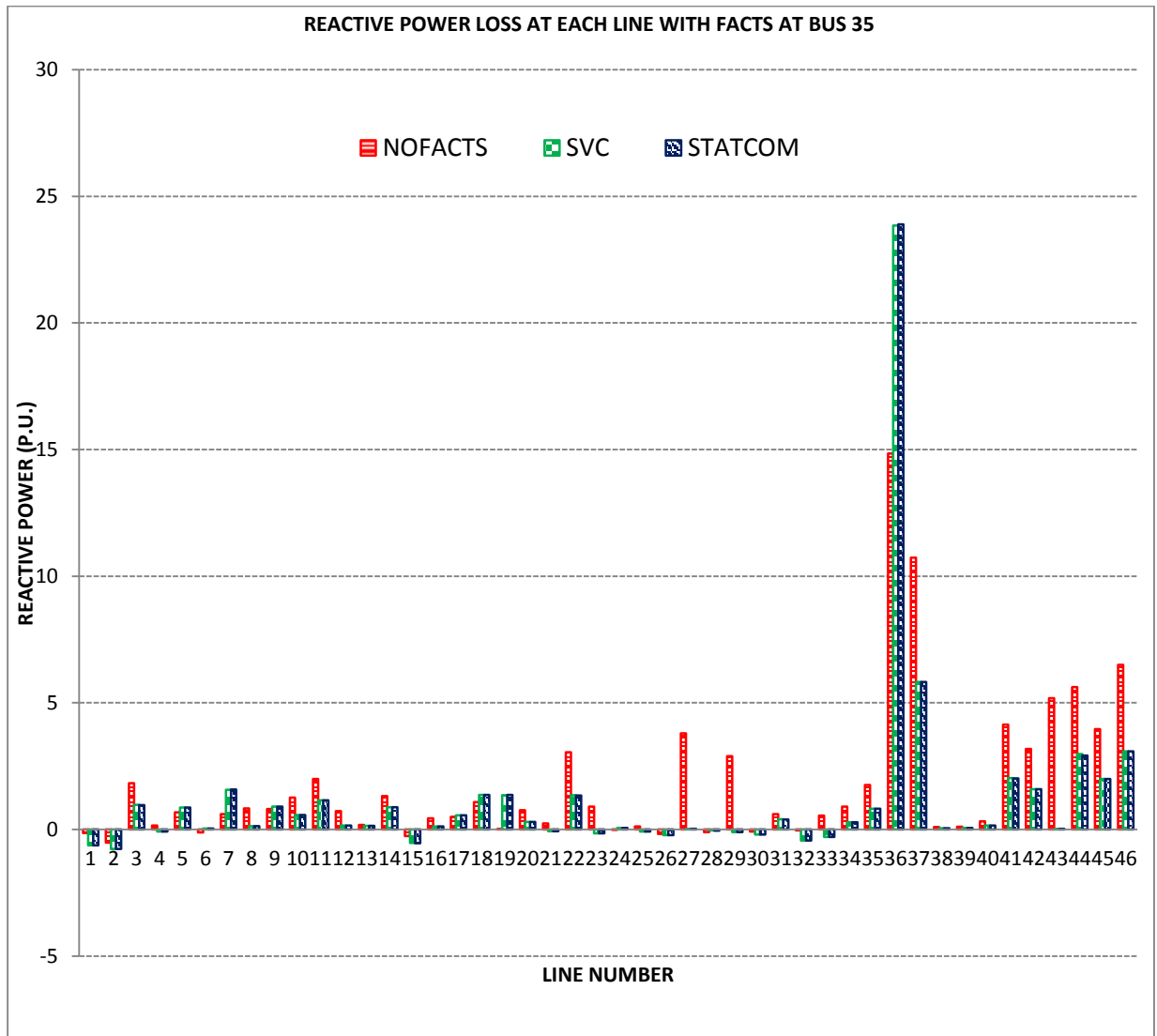


FIGURE 5.12- REACTIVE POWER LOSS AT EACH LINE WITH FACTS AT BUS 35

5.2.6 Voltage Magnitude Profile with FACTS at Bus 34

STATCOM and SVC are connected to bus 34 which is a generator bus. This is another example of the case where FACTS are connected to the generator bus to see if the same results repeat for consistency. It can be seen from the figure (5.13), that the results indeed repeat and the voltage magnitude profile has increased in the order from NOFACTS – SVC – STATCOM.

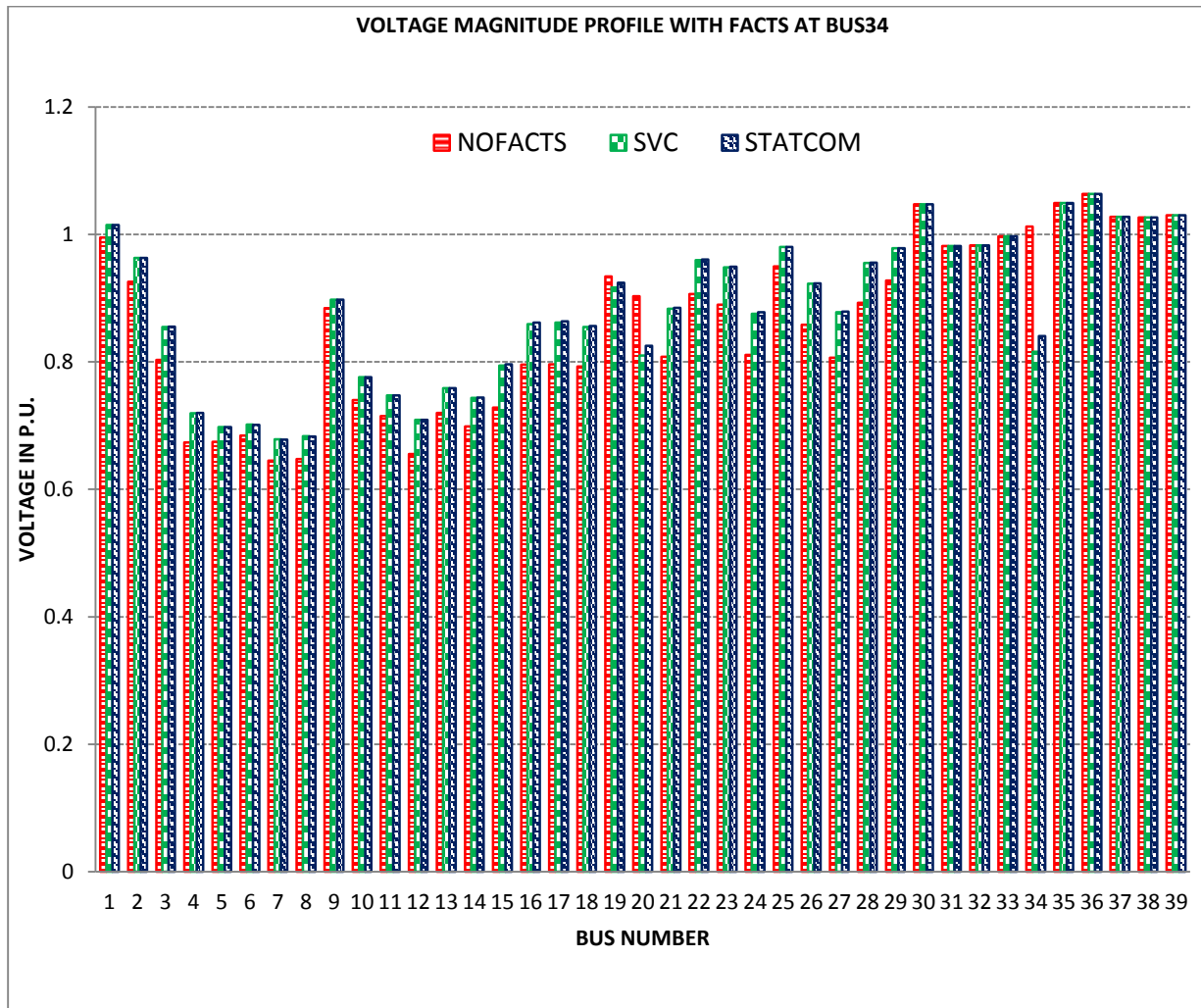


FIGURE 5.13- VOLTAGE MAGNITUDE PROFILE WITH FACTS AT BUS34

5.2.7 Active and Reactive Power Losses with FACTS at Bus 34

STATCOM and SVC are connected to bus 34 which is a generator bus. This is another example of the case where FACTS are connected to the generator bus to repeat the results from the case FACTS connected to bus 35, for consistency. It can be seen from figure (5.14) that the results are repeated and active power loss decrease in the order from NOFACTS – SVC – STATCOM and the reactive power loss also decrease in the order from NOFACTS – SVC – STATCOM.

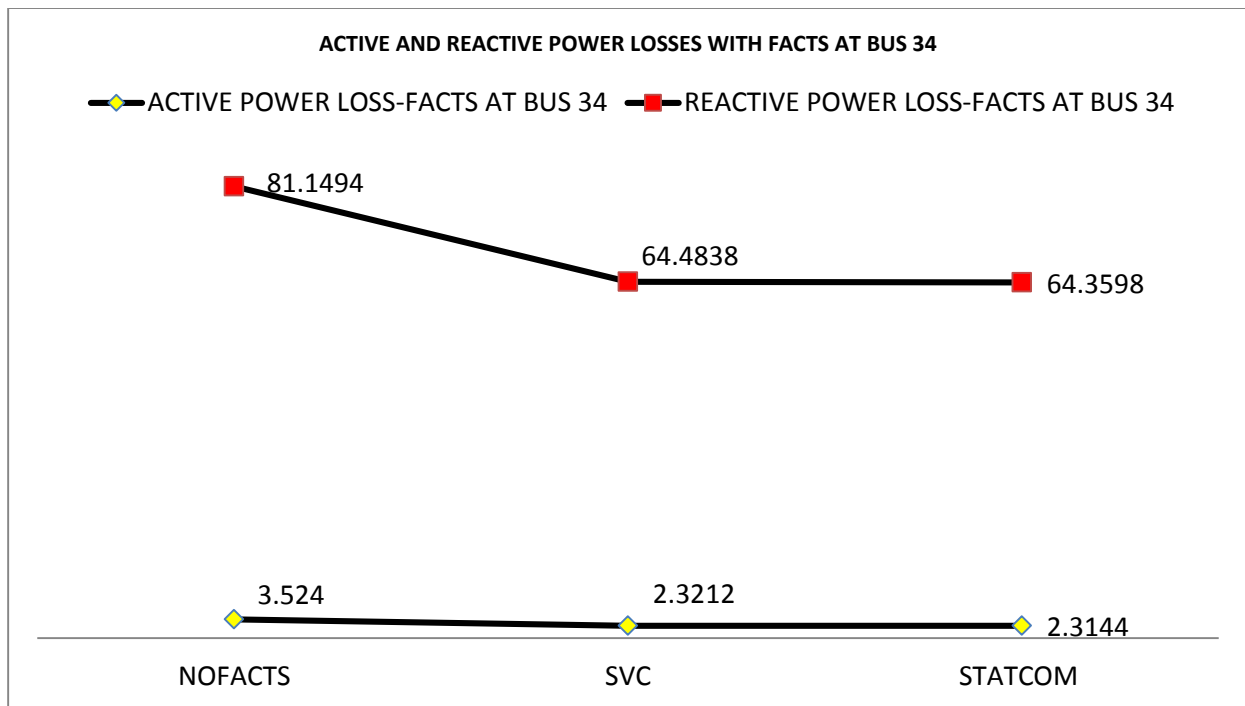


FIGURE 5.14- ACTIVE AND REACTIVE POWER LOSSES WITH FACTS AT BUS 34

5.3 STATCOM AND SVC AT SWING BUS

5.3.1 Voltage Magnitude Profile with FACTS at Bus 31

STATCOM and SVC are connected to bus 31 which is a swing bus. It can be seen from the figure (5.15) that the voltage magnitude profile is exactly the same as that of the case with no FACTS. Hence, we can see that there is no variation in the voltage magnitude profile by connecting FACTS at the swing bus.

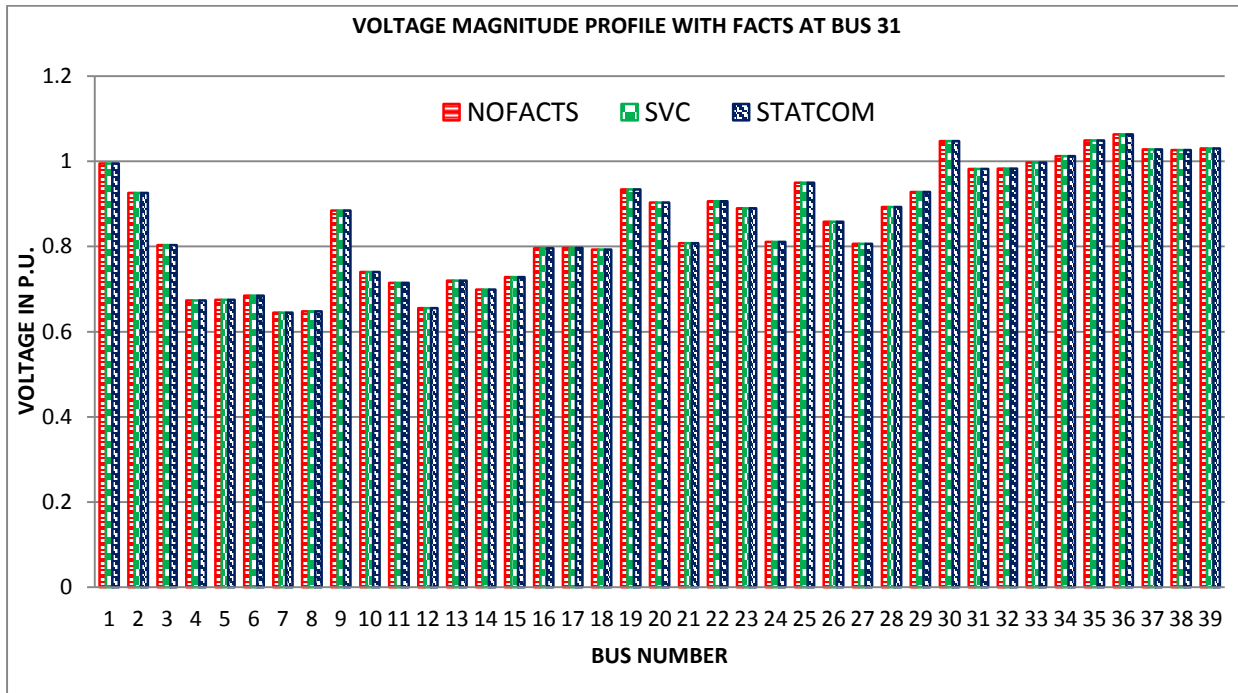


FIGURE 5.15- VOLTAGE MAGNITUDE PROFILE WITH FACTS AT BUS 31

5.3.2 Active and Reactive Power Losses with FACTS at Bus 31

STATCOM and SVC are connected to bus 31 which is the swing bus. It can be seen from figure (5.16) that the active and reactive power losses are exactly the same as that of the case with no FACTS. Hence, we can see that there is no variation in the voltage magnitude profile by connecting FACTS at the swing bus.

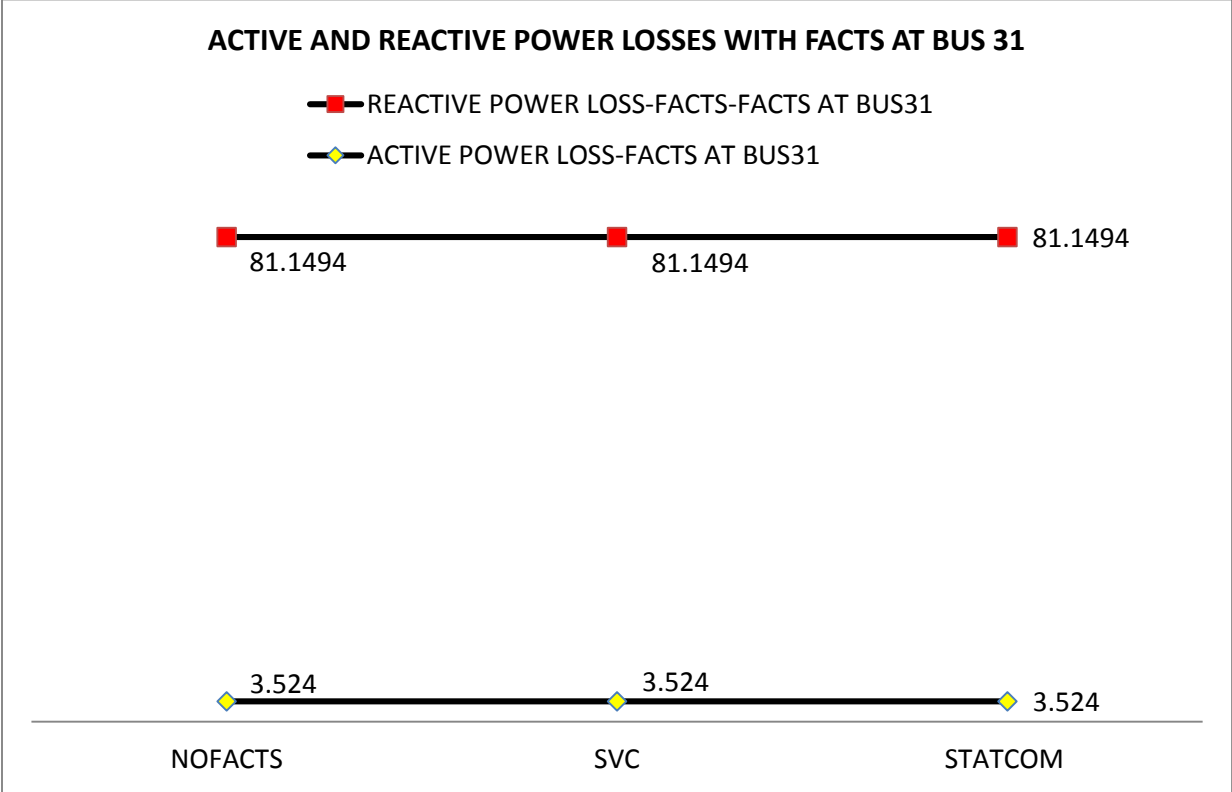


FIGURE 5.16- ACTIVE AND REACTIVE POWER LOSSES WITH FACTS AT BUS 31

5.4 TCSC ON LINES BETWEEN DIFFERENT BUS TYPES

In the IEEE 39 bus test system, the lines between PQ-PQ buses are lines 1,3,4,5,6,7,8,9,10,11,12,13,14,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,38,39

And the lines between PQ-PV buses are lines 2,15,35,36,37,41,42,43,44,45,46. TCSC is installed on both PQ-PQ buses and PQ-PV buses to observe its effect on both types of lines.

5.4.1 TCSC on Lines between PQ-PQ Buses

5.4.1.1 Voltage Magnitude Profile with TCSC on Line 4

TCSC is connected on line 4 between buses – and – which are both PQ buses. It can be seen from figure (5.17), that the voltage magnitude profile has increased by a small magnitude when compared to the NO FACTS case.

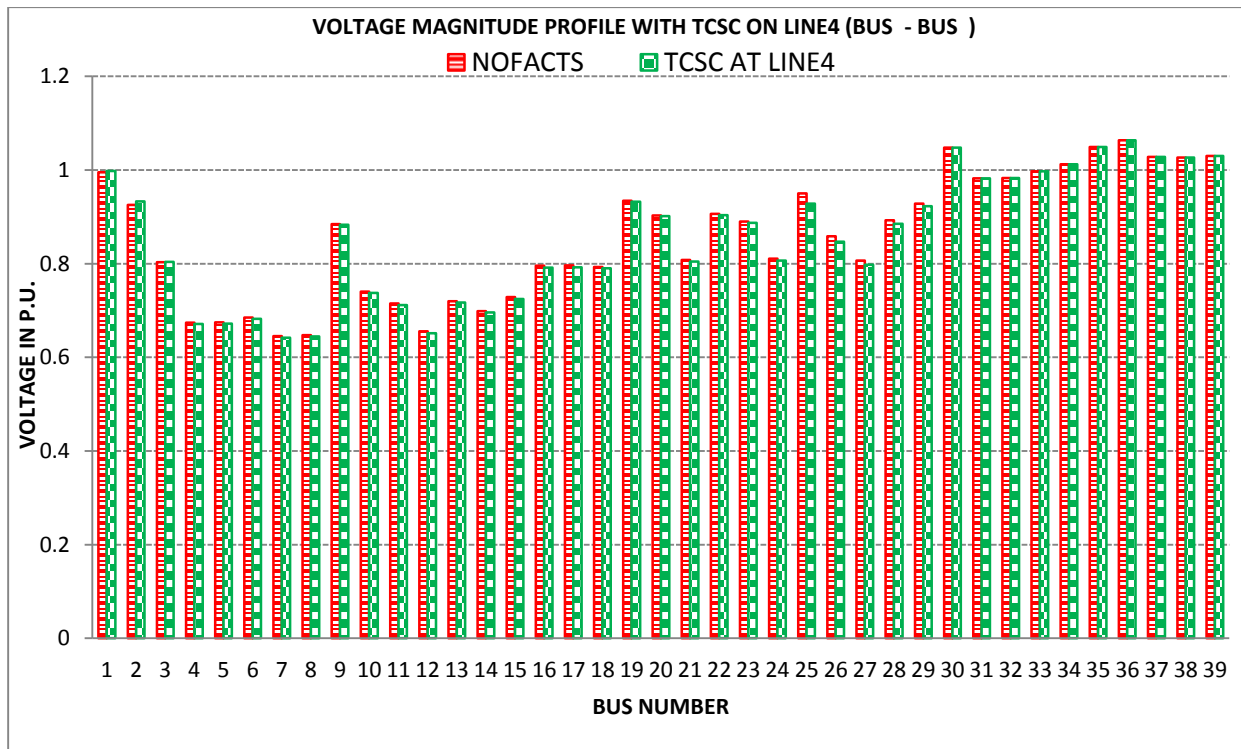


FIGURE 5.17- VOLTAGE MAGNITUDE PROFILE WITH TCSC ON LINE4

5.4.1.2 Active and Reactive Power Losses with TCSC on Line 4

TCSC is connected on line 4 between – and – buses which are both PQ buses. It can be seen in the figure (5.18), that the active has decreased in case of with TCSC and reactive power loss increased in the case with TCSC.

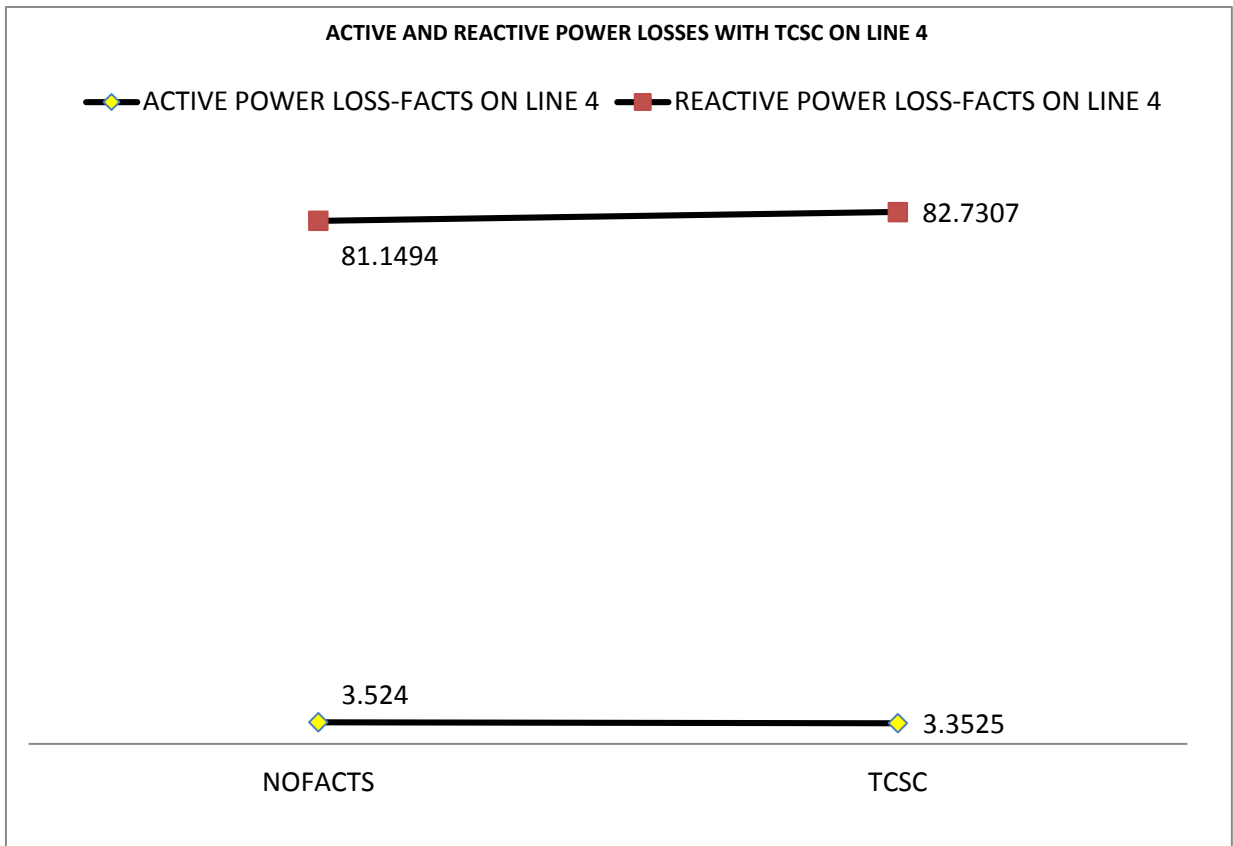


FIGURE 5.18- ACTIVE AND REACTIVE POWER LOSSES WITH TCSC ON LINE 4

5.4.1.3 Voltage Magnitude Profile with TCSC on Line 10

TCSC is connected on the line 10 between – and – buses which are both PQ buses. It can be seen in the figure (5.19), that the active and reactive power loss have both increased in the case with TCSC. This confirms the case where TCSC is connected on line 4.

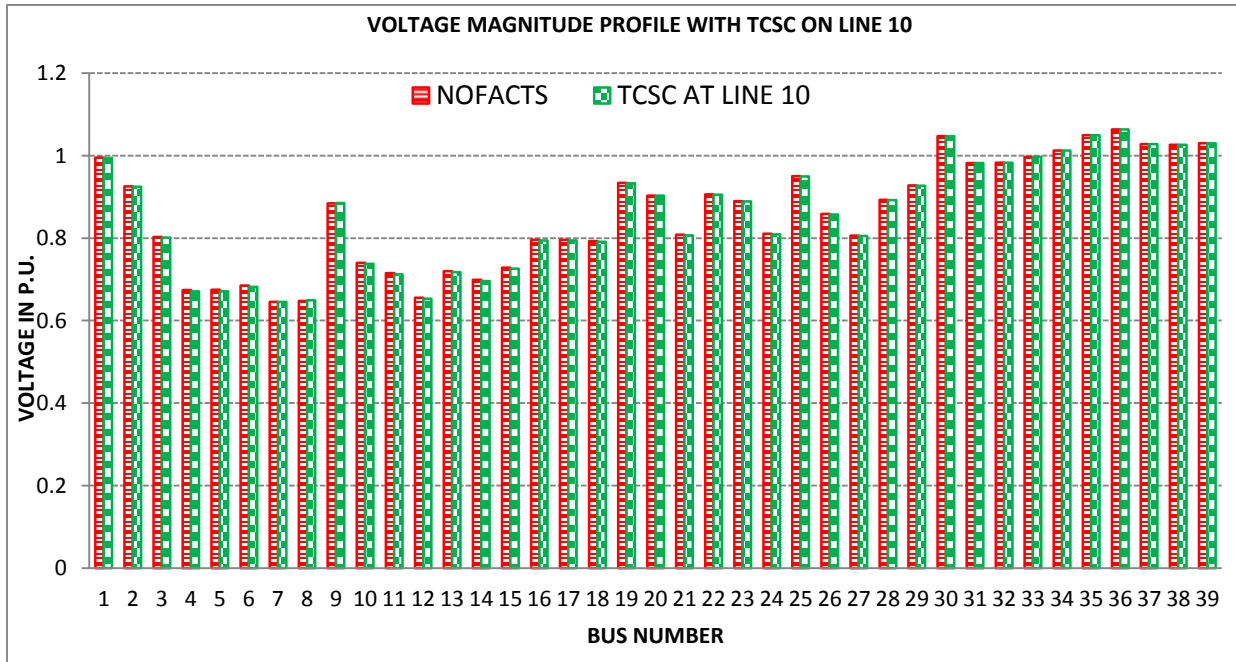


FIGURE 5.19- VOLTAGE MAGNITUDE PROFILE WITH TCSC ON LINE 10

5.4.1.4 Active and Reactive Power Losses with TCSC on Line 10

TCSC is connected on line 10 between – and – bus which are both PQ buses. It can be seen in the figure (5.20), that the active power loss decreased in the case with TCSC and reactive power loss increased in the case with TCSC. This confirms the results obtained in the case where TCSC is connected on line 4.

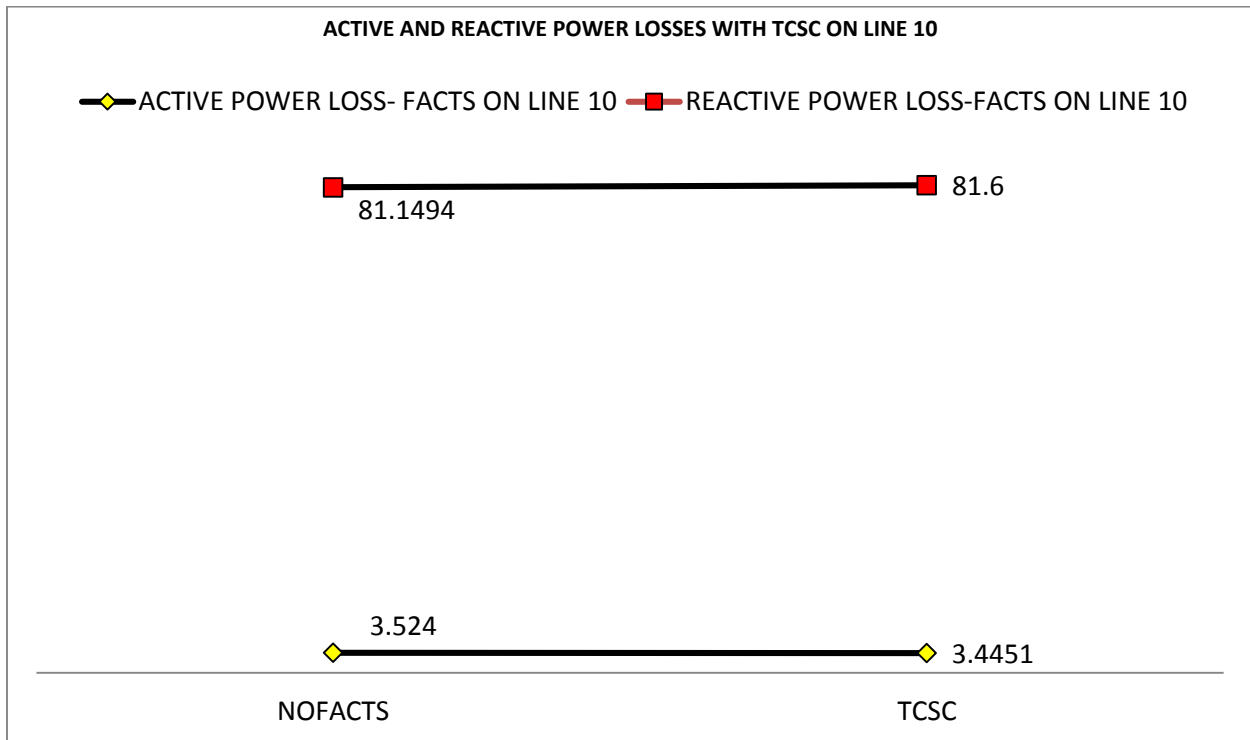


FIGURE 5.20- ACTIVE AND REACTIVE POWER LOSSES WITH TCSC ON LINE 10

5.4.2 TCSC on Lines between PQ – PV Buses

5.4.2.1 Voltage Magnitude Profile with TCSC on Line 42

TCSC is connected on line 42 between – and – buses which are PQ and PV buses respectively. It can be seen in the figure (5.21), that the active and reactive power loss have both increased in the case with TCSC. This is the same result obtained when TCSC is connected to the line between PQ-PQ buses.

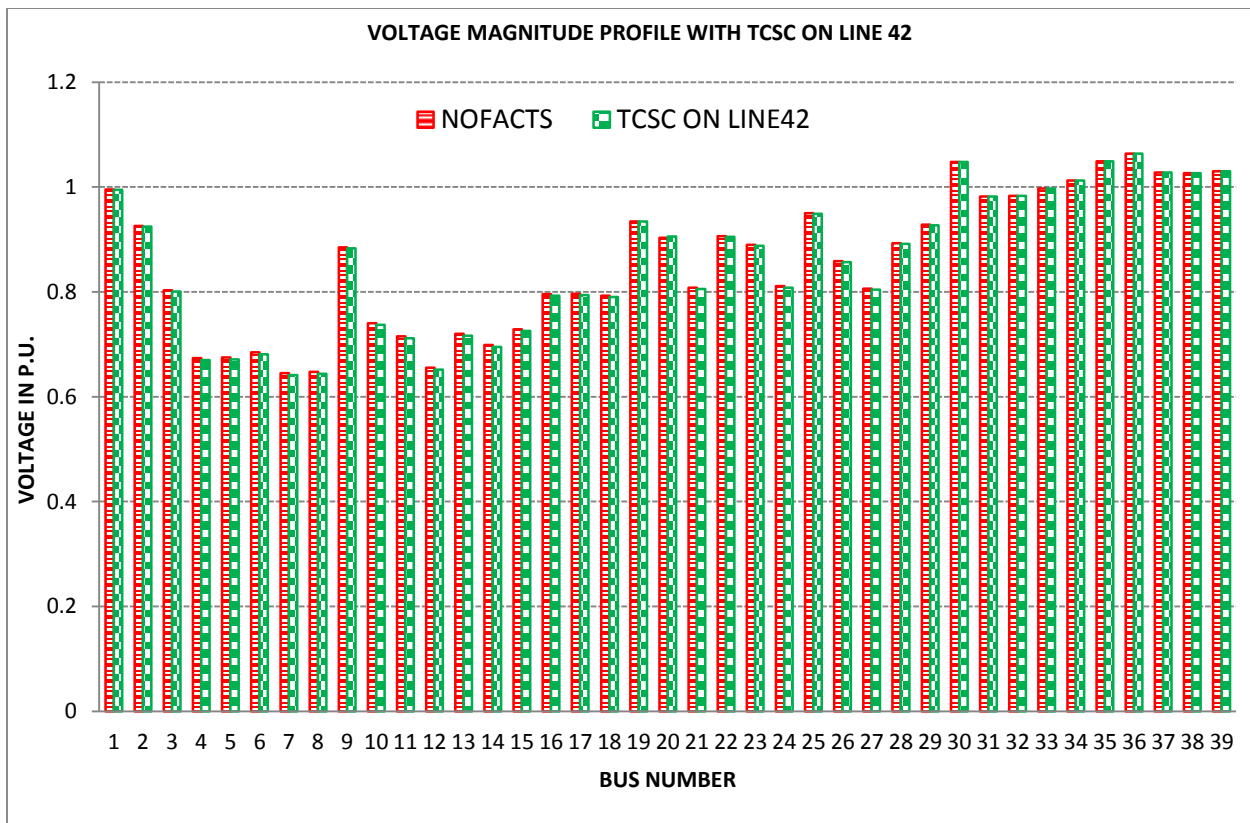


FIGURE 5.21- VOLTAGE MAGNITUDE PROFILE WITH TCSC ON LINE 42

5.4.2.2 Active and Reactive Power Losses with TCSC on Line 42

TCSC is connected on line 42 between – and – buses which are PQ and PV buses respectively. It can be seen in figure (5.22) that the active power loss decreased in the case with TCSC and the reactive power loss increased in the case with TCSC. This is the same result obtained when TCSC is connected to the line between PQ-PQ buses.

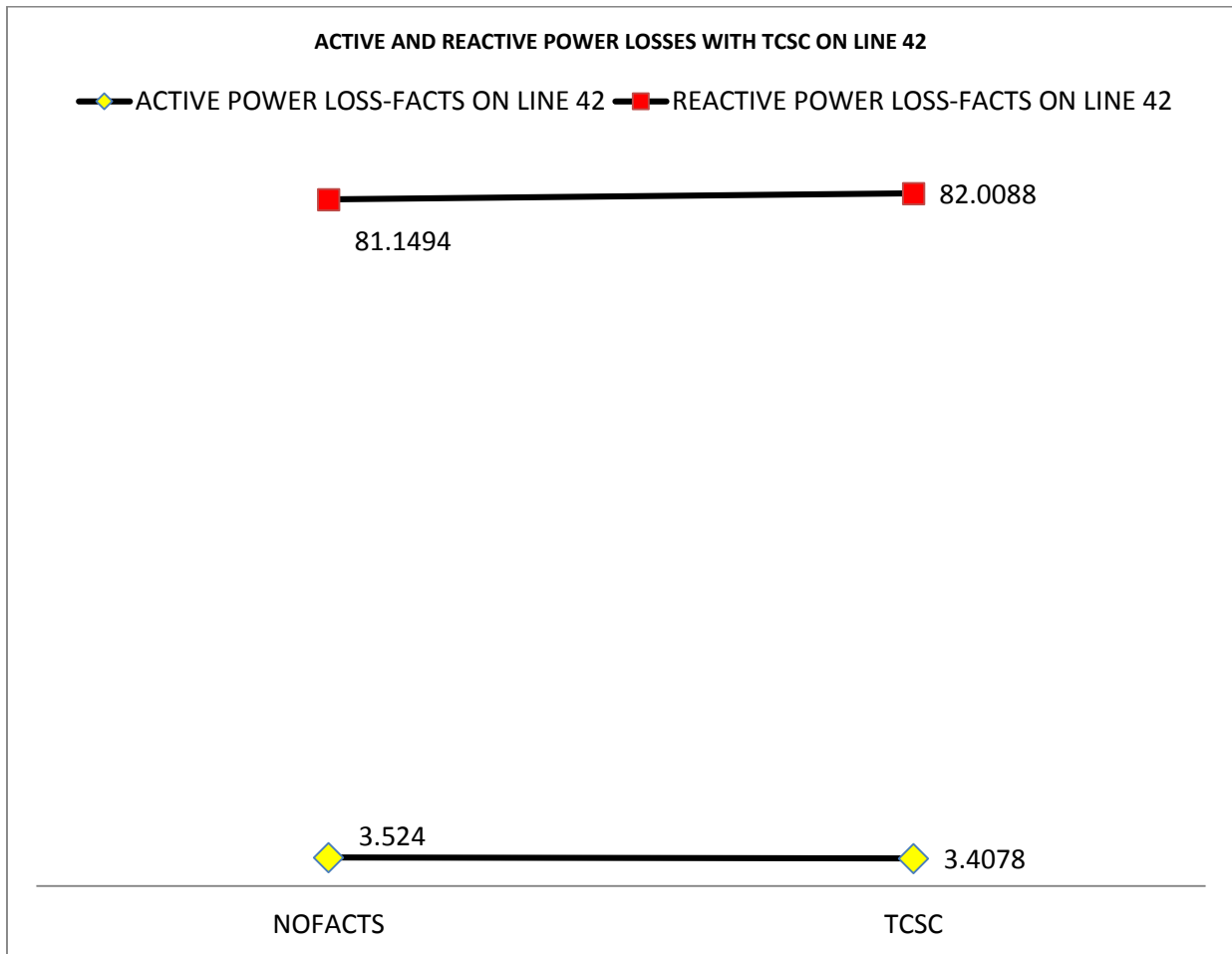


FIGURE 5.22- ACTIVE AND REACTIVE POWER LOSSES WITH TCSC ON LINE 42

5.5 MAXIMUM LOADABILITY

5.5.1 Maximum Loadability with STATCOM and SVC at Each Bus

STATCOM and SVC are connected at each of the load buses to see the maximum loading point at the corresponding bus at which the FACTS is connected. The results obtained when put together are as shown in figure (5.23). It can be seen that with both STATCOM and SVC when connected to the load buses increase the maximum loading point and the increase is more in case of STATCOM connected than that of with SVC.

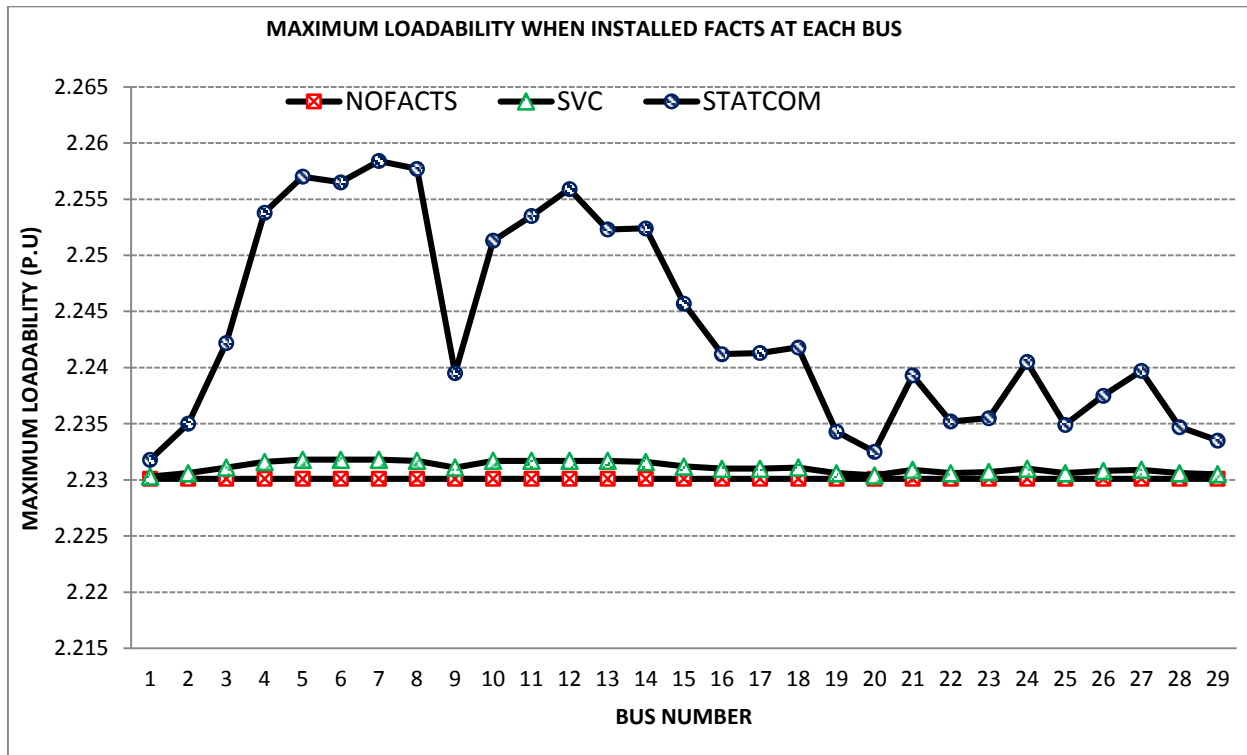


FIGURE 5.23- MAXIMUM LOADABILITY WHEN INSTALLED FACTS AT EACH BUS

5.5.2 Maximum Loadability with TCSC at Each Line

TCSC is connected between each line to see the maximum loading point from the P-V curve. It can be seen that at some lines, the maximum loading point has decreased with TCSC. It depends on mainly the transmission line characteristics and the loads connected to the lines. At bus 37 where we can see the maximum decrease in the loading point, is because it is connected between – bus and bus 31. The bus 31 which is the swing bus is one of the main reasons for the maximum decrease.

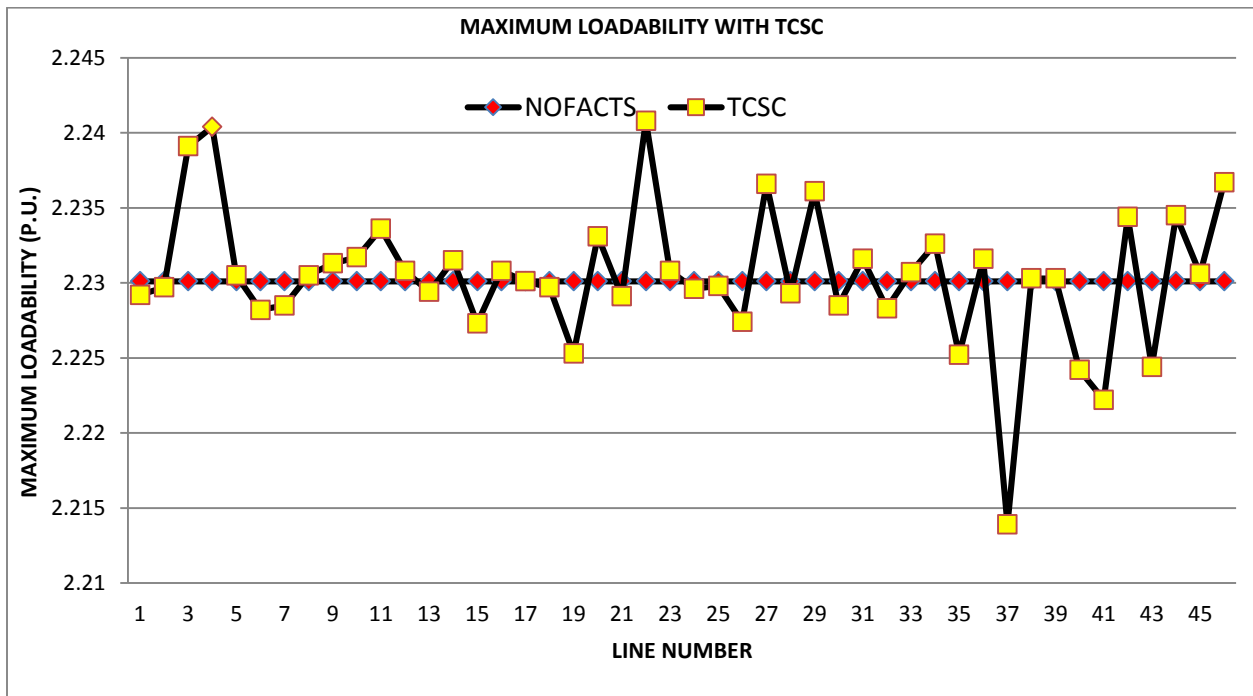


FIGURE 5.24- MAXIMUM LOADABILITY WITH TCSC

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

We can conclude from the results obtained about the effectiveness of Static VAR Compensator, Static Synchronous Compensator, and Thyristor Series Compensator in improving voltage magnitude profile, maximum loading point, active power loss, reactive power loss at generator bus, load bus, and swing bus in case of shunt controllers and at lines between two load buses, and between a load bus and a generator bus. The results comparing the effectiveness of the three studied FACTS devices are included as Table 6.2 - Table 6.6.

The comparative analysis of STATCOM and SVC when added to the generator bus are represented in Table 6.2 indicating their effectiveness with respect to four metrics Voltage Magnitude, PV curves, Active Power Loss, and Reactive Power Loss. We can conclude that STATCOM provides more efficient voltage magnitude profile than SVC and SVC improves the voltage magnitude profile than the case with the FACTS devices not included in it. The maximum loadability is obtained when the FACTS devices are not added to the system. The active power loss is lesser when STATCOM is included in the system than SVC which in turn is lesser than the case where FACTS are not included in the system. The reactive power loss is lesser with STATCOM than with SVC which has more reactive power loss than the case with the FACTS devices not included.

Bus Type	Metrics	STATCOM Included	SVC Included	FACTS Included
PV bus	Voltage Magnitude Profile	STATCOM >	SVC >	NO
	PV Curve (Maximum Loading Point)	STATCOM <	SVC <	NO
	Active Power Loss	STATCOM <	SVC <	NO
	Reactive Power Loss	STATCOM <	SVC >	NO

TABLE 6.2- STATCOM AND SVC ON EACH METRIC WHEN INSTALLED ON GENERATOR BUS

The comparative analysis of STATCOM and SVC when added to the load bus are represented in Table 6.3 indicating their effectiveness with respect to four metrics Voltage Magnitude, PV curves, Active Power Loss, and Reactive Power Loss. We can conclude that STATCOM provides more efficient voltage magnitude profile than SVC and SVC improves the voltage magnitude profile than the case with the FACTS devices not included in it. The maximum loadability is obtained when STATCOM is added to the system. The active power loss is greater when STATCOM is included in the system than SVC which in turn is greater than the case where FACTS are not included in the system. The reactive power loss is lesser with STATCOM than with SVC which has more reactive power loss than the case with the FACTS devices not included.

Bus Type	Metrics	STATCOM Included	SVC Included	FACTS Included
PQ bus	Voltage Magnitude Profile	STATCOM >	SVC >	NO
	PV Curve (Maximum Loading Point)	STATCOM >	SVC >	NO
	Active Power Loss	STATCOM >	SVC >	NO
	Reactive Power Loss	STATCOM <	SVC <	NO

TABLE 6.3- EFFECTIVENESS OF STATCOM AND SVC ON EACH METRIC WHEN INSTALLED ON LOAD BUS

The comparative analysis of STATCOM and SVC when added to the swing bus are represented in Table 6.4 indicating their effectiveness with respect to four metrics Voltage Magnitude, PV curves, Active Power Loss, and Reactive Power Loss. We can conclude that STATCOM, and SVC behave the same compared to the case where the FACTS device are not included in the system.

The comparative analysis of TCSC when added to the lines between two load buses are represented in Table 6.5 indicating their effectiveness with respect to four metrics Voltage Magnitude, PV curves, Active Power Loss, and Reactive Power Loss. We can conclude that TCSC provides greater maximum loadability than when the FACTS devices are not added to the system. The active power loss is lesser when TCSC is included in the system than the case where FACTS are not included in the system. The reactive power loss is greater with TCSC than without the FACTS devices included in the system.

Bus Type	Metrics	STATCOM Included	SVC Included	FACTS Included
Swing bus	Voltage Magnitude Profile	STATCOM =	SVC =	NO
	PV Curve (Maximum Loading Point)	STATCOM =	SVC =	NO
	Active Power Loss	STATCOM =	SVC =	NO
	Reactive Power Loss	STATCOM =	SVC =	NO

TABLE 6.4- EFFECTIVENESS OF STATCOM AND SVC DEVICES ON EACH METRIC WHEN INSTALLED ON SWING BUS

Bus Types	Metrics	TCSC Included	FACTS Included
PQ bus –PQ bus	Voltage Magnitude Profile	TCSC <	NO
	PV Curve (Maximum Loading Point)	TCSC >	NO
	Active Power Loss	TCSC <	NO
	Reactive Power Loss	TCSC >	NO

TABLE 6.5- EFFECTIVENESS OF TCSC ON EACH METRIC WHEN INSTALLED ON LINE BETWEEN TWO LOAD BUSES

The comparative analysis of TCSC when added to the lines between generator bus and load bus are represented in Table 6.6 indicating their effectiveness with respect to four metrics Voltage Magnitude, PV curves, Active Power Loss, and Reactive Power Loss. We can conclude that the results obtained are almost identical to the case where TCSC is included in the line between two load buses.

Bus Types	Metrics	TCSC Included	FACTS Included
PQ bus - PV bus	Voltage Magnitude Profile	TCSC =	NO
	PV Curve (Maximum Loading Point)	TCSC >	NO
	Active Power Loss	TCSC <	NO
	Reactive Power Loss	TCSC >	NO

TABLE 6.5-EFFECTIVENESS OF TCSC ON EACH METRIC WHEN INSTALLED ON LINE BETWEEN GENERATOR AND A LOAD BUS

6.2 FUTURE WORK

The proposed work concentrates only on the enhancement of the steady state voltage stability of the power system. Hence, it can be further improved to include transient stability improvement of a power system. Also, this work can be used further to observe the effectiveness of other FACTS devices such as Static Synchronous Series Compensator (SSSC) and Unified Power flow Controller.

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