APPLICATION OF FACTS DEVICES FOR POWER SYSTEM TRANSIENT STABILITY ENHANCEMENT

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(Electrical and Electronic Engineering)

JOMO KENYATTA UNIVERSITY OF

AGRICULTURE AND TECHNOLOGY

2016

Application of FACTS Devices for Power System Transient Stability Enhancement

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A Thesis submitted in Partial Fulfillment for the Degree of Master of Science in Electrical and Electronic Engineering in the Jomo Kenyatta University of Agriculture and Technology

2016

DECLARATION

This thesis is my original work and it has not been submitted for degree to any other University.

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This thesis has been submitted for examination with our approval as the Supervisors:

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DEDICATION

I dedicate this work to my daughter Stacie Sutter to whom my dreams live.

ACKNOWLEDGEMENTS

I would like to thank Almighty God for giving me the strength, courage and the ability to complete this research. I would also wish to appreciate my supervisors Prof. John Nderu and Dr. Christopher Muriithi for their invaluable support, advice, help and time. I would like to thank Geothermal Development Company for approving this master’s course.

I would like to thank Jomo Kenyatta University of Agriculture and Technology School of Electrical, Electronic and Information Engineering staff and colleagues for informative discussions and input accorded to me.

Finally, I would like to extend my deepest gratitude to those closest to me; my wife Jepkemoi Sutter and Mum, Teresia Kimoi Sutter. Many thanks for their inestimable support.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
ACPTDF	AC Power Transfer Distribution Factor
AP	Active Power
ATC	Available Transfer Capability
CEA	Combined Evolutionary Algorithm
CPF	Continuation Power Flow
DC	Direct Current
DS	Dynamic Stability
FACTS	Flexible Alternating Current Transmission System
FCL	Fault Current Limiting
GA	Genetic Algorithm
IM	Induction Motor
IPFC	Interline Power Flow Controller
N-R	Newton-Raphson
OPF	Optimal Power Flow
PD	Power Oscillations Damper
PSAT	Power System Analysis Toolbox
PSCAD	Power System Computer Aided Design
PSO	Particle Swarm Optimization
P-V	Power- Voltage
RP	Reactive Power
SS	Transient Stability
SSSC	Static Synchronous Series Compensator
SVC	Static Var Compensator (SVC)
TCPAR/T	Thyristor Controlled Phase Angle Regulators/ Transformer
TCSC	Thyristor Controlled Series Capacitor
TDS	Time Domain Simulation
TS	Transient Stability

TSE	Transient Stability Enhancement
UPFC	Unified Power Flow Controller
VS	Voltage Stability
VSI	Voltage Stability Index

ABSTRACT

The massive growth of interconnected power systems due to increasing demand for electrical energy has given rise to numerous challenges. These include power swings and oscillations due to outages, blackouts, natural disturbances and system faults that occur along transmission lines, load and generation points. Blackouts have been witnessed in the recent years in countries around the world. These major disturbances cause power system instability and pose difficulties to system operation, planning and maintenances scheduling. In these circumstances, Flexible Alternating Current Transmission System (FACTS) controllers such as the Interline Power Flow Controller (IPFC) Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) can considerably improve transient stability thus enhance overall system stability during disturbances. Alongside the property of fast control of active and reactive power in power system, SSSC, IPFC and UPFC devices also play an additional role in transient stability enhancement and therefore play vital in system stability control. This research has delved into the specific and comparative performances of three devices as far as damping of system oscillations is concerned. It has gone further to look at voltage support and loss reduction features attributed to each device vis-à-vis damping of oscillations to enable power system planners merge the transient stability, loss reduction and voltage support characteristics of the three/ devices. In this research, use of UPFC, SSSC and IPFC FACTS controllers were applied in Transient Stability Enhancement (TSE) analysis considering dynamic environment of the standard IEEE 14 bus test system. TSE for single compensation device (SSSC) and double compensation devices (UPFC and IPFC) were accomplished successfully. The inherent properties of the three devices were deduced for TSE. The research is inspired by the need of automating power system transient stability control by outlining the distinguishing features of three FACTS devices for TSE using with focus on their compensation properties. By incorporating fast acting and appropriately located FACTS devices, the corresponding time domain responses were obtained and analysed with and without the devices. This research has effectively brought out the specific and comparative performances of three devices as far as damping of system oscillations is concerned. The results have shown significant enhancement of the transient stability when the FACTS devices are applied by considerably reducing post-fault settling time of power system as well as effectively damping network oscillations in contrast with when the devises are not applied. Synchronous machine parameters' responses for the three FACTS devices, appropriately placed, were obtained and analysed successfully.

CHAPTER ONE

INTRODUCTION

1.1 Background

An electrical power system is a complex interconnected network comprising of numerous generators, transmission lines, variety of loads and transformers. The term Flexible Alternating Current Transmission System (FACTS) devices describes a wide range of high voltage, large power electronic converters that can increase the flexibility of power systems to enhance AC system controllability, stability and increase power transfer capability. Demand for power and ensuing development of the modern power system has led to an increasing complexity in the study of power systems, presenting new challenges to power system stability, and in particular, to the aspects of transient stability and small-signal stability [1]. Instabilities in power system are caused by insulation breakdown or collapse, long length of transmission lines, interconnected grid, changing system loads and other unforeseen disturbances in the system. These instabilities result in reduced line flows or even line trip. FACTS devices stabilize transmission systems with increased transfer capability and reduced risk of line trips. Other benefits attributed to FACTS devices are additional energy sales due to increased transmission capability, reduced wheeling charges due to increased transmission capability and due to delay in investment of high voltage transmission lines or even new power generation facilities. These devices stabilize transmission systems with increased transfer capability and reduced risk of line trips [1]. The major problem in power system is upholding steady acceptable system parameters like bus voltage, reactive power and active power under normal operating and anomalous conditions. This is usually system regulation problem and regaining synchronism after a major fault is critical for this phenomenon. Faults can cause loss of synchronism. As effects of instability, faults occur due to insulation breakdown or compromise as result of lightning ionizing air, power cables blowing together in the wind, animals or plants coming in contact with the wires, salt spray, pollution on insulators, system overloading, long transmission lines with uncontrolled buses at the receiving end, shortage of local reactive power, intrinsic factors, natural causes like harsh weather and small generation reserve margins. Such system disturbances have led to the introduction of FACTS devices such as SVC, SSSC, STATCOM, UPFC and IPFC [2, 3]. In stable power systems, when synchronous machines are disturbed, synchronism will either go back to their original state if there is no net change of power or will reach a new state without loss of synchronism and when there is net change in power; synchronism is lost [4]. Due to FACTS devices, the power can be flown through the chosen routes with consideration to mitigate the loss thereby averting losses due system tripping or outages. UPFC and IPFC, for instance, are very versatile FACTS controllers.

1.2 Problem statement

Disturbances and faults in power systems pose adverse challenges. They include power swings, oscillations, loss of synchronism and outages. This circumstances causes power system problems of instability and even collapse. Voltage collapse results when active and reactive power balance equations fail or the inability of load dynamics attempt to restore power consumption beyond the capability of the transmission network and the connected generation to provide the required reactive support. Large disturbances such as a three-phase fault decelerates loads and cause instability to generating units. Further still, continuous demand in electric power system network as well as heavy loading leading to system instability and straining of the thermal limits. FACTS can be applied at these instances to avert voltage collapse and settle the swings. These controllers have varied and unique compensation features when connected to power system. Single compensating controller (series or shunt) like the series SSSC controllers and double compensating characteristics of series-series IPFC and series-hunt UPFC have to be analysed for TSE and reactive power control (voltage injection) since FACTS devices are very expensive although very versatile. In interconnected power systems, they optimize power networks via reactive, active and voltage control enabling the system to better transient stability and boost the loading capability of transmission lines to their rated thermal capabilities both in short term and long term. Consequently, voltages, angle and impedance can be controlled, voltage support enhanced and transient stability is improved significantly. Since their compensation properties differ based on the type and configuration, the three controllers need to be simulated so as to outline their distinct compensation features for both TSE and power system control.

1.3 Justification of the study

This research is motivated by the growing use of FACTS to automate and optimize power networks enabling multi-machine power system to improve stability, mitigate dynamic sensitivities and reduce chances of system collapse under severe disturbances. Placement of FACTS is achievable and the research in this area has been widely done. The research is also inspired by difficulties in power transient instabilities due to outages, blackouts and system faults that occur due to dynamics in long transmission lines of interconnected systems and distance between load and generation points. This phenomenon has resulted in system collapse in Kenya, USA, France, Belgium, Sweden and Japan. The SSSC, UPFC and IPFC FACTS devices are very promising devices in the FACTS controllers, concept. The need to distinguish the effects of the three FACTS controllers for TSE and control in the occurrence of disturbances like faults is critical since FACTS controllers have the ability to adjust the three control parameters, *i.e.* the bus voltage, transmission line reactance, and phase angle between two buses, either simultaneously or independently [7]. They perform this through the control of the in-phase voltage, quadrature voltage, and shunt compensation to improve voltage stability, steady state and transient stabilities of a complex interconnected power system [8, 9]. This property should be matched with other properties of FACTS like loss reduction and voltage stability for system planning and economic operation. These features have to be classified and each controller capabilities established.

1.4 Objectives

1.4.1 General objective

The main objective of this research was to investigate impacts of incorporating SSSC, UPFC and IPFC FACTS devices in a multi-machine power network on transient stability enhancement using a dynamic model with and without FACTS devices.

1.4.2 Specific objectives

1. To determine suitable location of UPFC, SSSC and IPFC FACTS devices
2. To develop dynamic power system models for the FACTS devices.
3. To analyze the extent of transient stability enhancement with FACTS devices.

1.5 Contributions of the research

The thesis has made several contributions as described in the following:

(i) The incorporation of model of three types of FACTS devices namely; SSSC, UPFC and IPFC to multi-machine power system in order to improve transient stability was done successfully. The models have been used for dynamic analysis of FACTS devices in power system network.

(ii) The most suitable location of FACTS devices has been determined effectively by PSAT continuation power flow strategy. This was achieved via establishing the bus with lowest voltage magnitude; the weakest bus for IEEE 14 bus test system. SSSC, UPFC and IPFC FACTS devices have been located close to the weak bus and TSE has been performed using dynamic IEEE 14 test system with AVR as the source of excitation control for the synchronous generator. Successful simulations with and without the three FACTS controllers/devices connected.

(iii) The power oscillations damping properties of single compensating series controller, SSSC, the double series-shunt compensator, UPFC and double series- series compensator, IPFC FACTS have been comparatively analysed in this thesis. Other than the property of fast control of active and reactive power in power system from the devices, the SSSC, IPFC and UPFC FACTS have been applied in damping power system oscillations and transient-stability improvement. This research has delved into the specific comparative performances of three devices as far as damping of system oscillations is concerned. It has gone further to examine voltage stability support and loss reduction attributed to each device to enable power system planners merge the transient stability, loss reduction and voltage support characteristics of the three devices.

(iv) The performance of double compensating integrated model of UPFC and independent model of the IPFC with respect to oscillations damping, and loss reduction have been successfully studied. The performances of the two have compared with those of single compensating SSSC device.

(v) Distinct properties of the three FACTS controllers have deduced in oscillation damping, voltage support and loss reduction have been effectively identified and analysed.

1.6 Thesis outline

- Chapter 1 outlines brief introduction of the problem to be solved, background, proposed approach, and contributions of the research. The rest four parts are:
- Chapter 2 provides a literature survey on essential topics of this research. It starts with a general overview of techniques for solving FACTS devices optimization problems, FACTS optimal location, FACTS devices modeling and application in power system

- Chapter 3 entails the methodology. The FACTS devices' model developments are developed for transient stability enhancement and analysis.
- Chapter 4 Analyses, discuses and compares the results of the two FACTS; SSSC, UPFC and IPFC and validates their performance in Transient Stability Enhancement.
- Chapter 5 outlines conclusion, summary and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

The development of FACTS devices started with the growing capabilities of power electronic components. Devices for high power levels have been made available to converters for different voltage levels. The overall starting points are network elements influencing the reactive power the parameters of power system. FACTS controllers are power electronic devices that enhance power system operation through their control attributes and injection modes [12]. The devices are mainly grouped as:

1) Series controllers such as Thyristor Controlled Series Compensator (TCSC), Thyristor Controlled Phase Angle Regulators (TCPAR or TCPST), and Static Synchronous Series Compensator (SSSC).
2) Shunt controllers such as Static Var Compensator (SVC), and Static Synchronous Compensator (STATCOM).
3) Combined series-series controllers and combined series-shunt controllers such as Interline Power Flow Controller (IPFC), Unified Power Flow Controller (UPFC).

2.2 Benefits of utilizing facts devices

The benefits of utilizing FACTS devices in electrical transmission systems can be summarized as follows [12]:They lead to increased loading capacity of transmission lines, prevention of blackouts, boosting generation productivity, reduce circulating reactive power, improvement of system stability limit, reduction of voltage flickers, damping of power system oscillations, guaranteeing system stability, security, availability, reliability and system economic operation [12].

2.3 Unified power flow controller (UPFC)

A unified power flow controller (UPFC) is a versatile controller in the FACTS concept. It has the ability to adjust the three control parameters: the bus voltage, transmission line reactance, and phase angle between two buses, either simultaneously or independently [13] [14]. It has two voltage source converters (VSC), series and shunt converter, which are connected to each other with a common DC link capacitor which provides bidirectional flow of real power between series connected SSSC and shunt STATCOM respectively. As shown in Figure 2.1(a) and 2(b) these converters are shunt and series transformers with AC voltage bus. The series controller SSSC is used to add controlled voltage magnitude and phase angle in series with the line, while shunt converter STATCOM is used to provide reactive power to the ac system [15]. The UPFC model can be incorporated to the power flow equations by including the impedances of the converters transformers into the bus admittance matrix and adding the UPFC injection powers at specific buses. The schematic diagram connected between two buses; *i* and *j* as shown below.

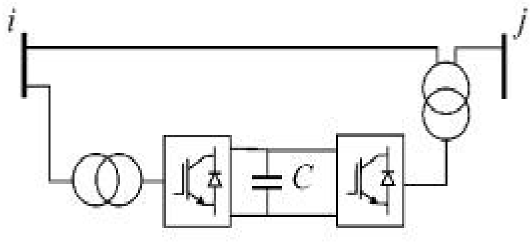

Figure 2.1(a): UPFC VSC model

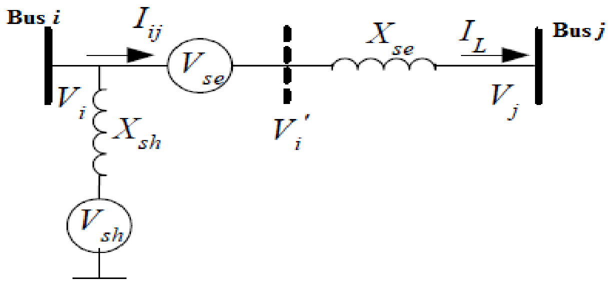

Figure 2.1(b): UPFC injection model

UPFC has the following control attributes; AP and RP control, voltage control, VAR compensation, Power Oscillations Damping, VS, and DS [15].

For UPFC, $\bar{V_s}$ is the series voltage source and $\bar{\iota}_{SH}$ is the shunt current source given by:

$$\bar{V_s} = (V_p + V_q) \tag{2.1}$$

$$\bar{\iota}_{SH} = (i_p + i_q)e^{j\theta k} \tag{2.2}$$

Where, Vp and Vq are the component of the series voltage, i_p and i_q are the component of the shunt current, $\emptyset$ and θk are the angles of the line current and bus voltage. The differential equations used to control the components of the series and shunt sources are given by:

$$\dot{V}_p = (V_p^o + u_1 V_s^{PD} - V_p)/T_r \tag{2.3}$$

$$\dot{V}_q = (V_q^o + u_2 V_s^{PD} - V_q)/T_r \tag{2.4}$$

$$\frac{diq}{dt} = [K_r(V_{ref} + u_3 V_s{}^{PD} - V_k) - i_q]/T_r \tag{2.5}$$

2.3.1 Static synchronous series compensator (SSSC)

SSSC is a solid-state Voltage Sourced Converter (VSC) based device, which generates a controllable AC voltage, and connected in series to power transmission lines in a power system. SSSC virtually compensates transmission line impedance by injecting controllable voltage (V_S) in series with the transmission line. V_S are in quadrature with the line current, and emulate an inductive or a capacitive reactance so as to influence the power flow in the transmission lines. The variation of V_S is performed by means of a VSC connected on the secondary side of a coupling transformer. A capacitor connected on the DC side of the VSC acts as a DC voltage source. To keep the capacitor charged and to provide transformer and VSC losses, a small active power is drawn from the line. VSC uses IGBT-based inverters. This type of inverter uses PWM technique to synthesize a sinusoidal waveform from a DC voltage with a typical chopping frequency of a few kilohertz. Harmonics are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a fixed DC voltage. Converter voltage V_C is varied by changing the modulation index of the PWM modulator [14] [16]. SSSC circuit diagram is illustrated in 2.2. The controllable parameter is the magnitude of the series voltage source V_S. This voltage source is regulated by the damper [15]. This controller is used for constant power flow for the line.

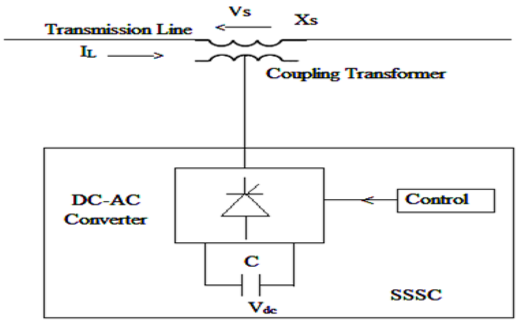

Figure 2.2(a): Voltage source model of SSSC

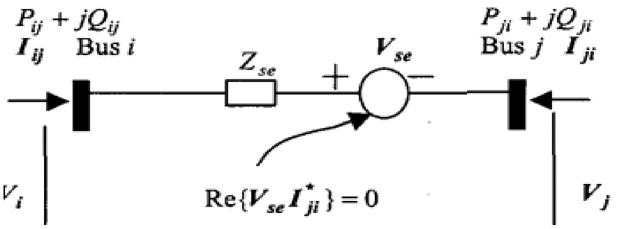

Figure 2.2(b): Injection Model of SSSC

SSSC has the following control attributes Current control, VS, TS, and FCL [15]. The controllable parameter (magnitude of the series voltage source $\bar{V_s}$) is regulated by the damping controller, PD. This controller is used for constant power flow through the line. The equations modeling the SSSC are:

$$\dot{V_s} = (V_s^o + V_s^{PD} - V_s)T_r \tag{2.6}$$

$$V_s^o = K_p\left(P_{ref} - P_{km}\right) + V_{pi} \tag{2.7}$$

$$\dot{V}_{pi} = K_i\,(P_{re} - P_{km}) \tag{2.8}$$

Where V_s^o is the input signal.

2.3.2 Interline power flow controller (IPFC)

The inter-line power flow controller employs DC-to-AC converters each providing series compensation for different lines or buses. The IPFC comprise a two SSSC. The simplest IPFC consist of two back-to-back DC-to-AC integrated or independent converters. They are connected in series with two transmission lines through series coupling transformers and the dc terminals of the converters are connected together via a common DC link or separate one [15][16]. The IPFC can be used to provide double or compensation for the same or compensate two transmission lines at the same time through integrated configuration where the SSSC controllers share a common DC link or independent configuration where each SSSC has its own DC link. The IPFC double SSSC configuration is shown. The independent configuration has been chosen for this thesis. Two separate SSSCs are placed at the weakest bus.

IPFC has the following control attributes; RP control, Voltage control, Power Oscillations Damping, VS, TS and DS [15]. The controllable parameters of this device is the magnitude of the series voltage sources; $\bar{V}_{s1}$ and$\bar{V}_{s2}$. The voltages sources are regulated by the respective PD controllers. The equations modeling the two SSSCs making up the IPFC are:

SSSC 1

$$\dot{V}_{s1} = (V_{s1}^{o} + V_{s1}^{PD1} - V_{s1})T_{r1} \tag{2.9}$$

$$V_{s1}^{o} = K_{p1}\left(P_{ref1} - P_{km1}\right) + V_{pi1} \tag{2.10}$$

$$\dot{V}_{pi1} = K_{i1}\,(P_{re1} - P_{km1}) \tag{2.11}$$

SSSC 2

$$\dot{V}_{s2} = (V_{s2}^{o} + V_{s2}^{PD2} - V_{s2})T_{r2} \tag{2.12}$$

$$V_{s2}^{o} = K_{p2}\left(P_{ref2} - P_{km2}\right) + V_{pi2} \tag{2.13}$$

$$\dot{V}_{pi2} = K_{i2}\,(P_{re2} - P_{km2}) \tag{2.14}$$

2.3.3 Power system stability classification of power system stability

Classification of power system stability is mainly categorized into three parts; rotor angle, frequency and voltage stability as shown in figure 2.3 below:

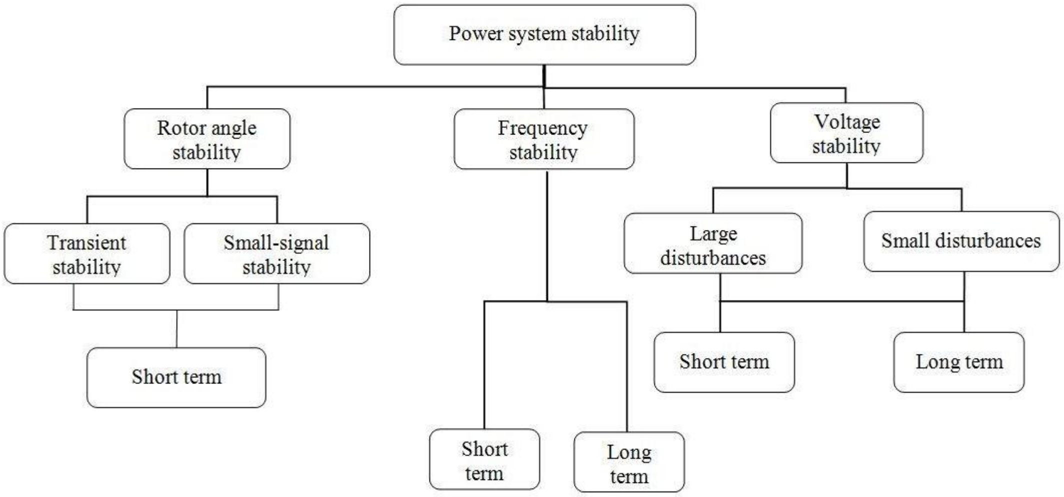

Figure 2.3: Classification of power system stability. [17, 18]

2.3.4 Rotor angle stability

Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance [17, 19]. Power system stability can be categorized into the following subcategories:

2.3.5 Transient stability

This is the ability of the power system to maintain synchronism after a large disturbance such as loss of a generator or major load or major system faults [20, 21]. In transient stability analysis, the time frame of interest is usually 3 to 5 seconds following the disturbance. It may extend to 10 to 20 seconds for very large systems with dominant inter-area swings [22, 23].

2.3.6 Transient stability indices

These are parameters applicable in assessment of TS. They are TS indicators and include critical clearing time (CCT) and critical clearing angle (CCA) [22]. CCT/A is the maximum allowable fault period/angle for stability to be maintained. The higher the CCT, the more stable the system. It is applied for measurement of contingency severity and thus can be used in ranking contingencies. Another parameter is fault settling time; the duration it takes for the system ton to regain its steady state original condition after a disturbance. Steady state can only be achieved if the CCT ids not exceeded [23]. Power system oscillations of a system which are more stable take less time to settle and the converse is true. The oscillations damping property has been utilized significantly in this research for the TSE enhancement analysis with three FACTS in this thesis.

2.3.7 Small signal stability

This is the ability of the power system to maintain synchronism when the system is subjected to small disturbances such as long gradual power changes after the action of AVRs and turbine governors [23]. It is basically concerned with the disturbances such as small changes and variations in loading and generation units.

2.4 Recent trends

In the research work [2], the SVC and Thyristor TSCS based FACTS device are employed to minimize the losses and improve power flow in long distance transmission line. For the research study [25], the Combined Evolutionary Algorithm (CEA) was presented i.e. Cuckoo Search (CS) and Evolutionary Programming (EP) algorithm to find the optimal location and optimal capacity to be placed at the location for UPFC FACTS to provide of reactive power for voltage stability. In study [26], the application of Bacterial Foraging (BF) Algorithm to find optimal location of FACTS devices to achieve voltage stability improvement for minimum cost of installation of the FACTS devices has been presented. Comparison between, SVC, TCSC, and SSSC for power system stability enhancement under large disturbance for inter-area power system in [27] demonstrated that SSSC settling time for line power in post fault period is found to be around 1.5 seconds, TCSC at 3 seconds and SVC 7 seconds. In research [28], a genetic algorithm based optimal power flow is proposed for optimal location and rating of the UPFC in power systems and also simultaneous determination of the active power generation for different loading conditions has been studied. In research [29], the reduction of reactive power loss sensitivity-based method has been developed for determining the optimal location of TCSC to relieve congestion.

Research work in [30] investigated the transient characteristic of STATCOM, and summarized the switch strategy of based on two generating stations. The simulation result shows that STATCOM can damp power oscillation efficiently. Study [31] aimed at utilizing FACTS devices with the purpose of improving the operation of an electrical power system. In the work [32], a model of the power system with an SVC boost to transient stability by increasing critical clearing angle. For the work done in [33], the power system stability improvement of a multi-machine power system by various FACTS devices such as SVC and UPFC is analyzed for a two area system for performance of the devices for power system stability improvement. Work done in [34] seeks to improve transient stability using FACTS devices. In research the [35], the utilization of a STATCOM with adaptive control is to enhance the transient answer of the synchronous generator via inhibiting the transients.

In the analysis done in [36], SVC is used in a two area power system for improving transient stability. In the in [37] study, DSSC was placed in a sample two machine power system to increase transient stability. Studies in [38] presented transient stability and power flow models of STATCOM to demonstrate that STATCOM considerably improves transient stability. FACTS devices can regulate the active and reactive power control as well as adaptive to voltage-magnitude control simultaneously because of their flexibility and fast control characteristics [39]. Power system stability enhancement of a power system by various FACTS devices is presented and discussed in [40] using TCSC. Results demonstrated the effectiveness and robustness of TCSC on transient stability improvement of the system. Analysis in [41] investigated the capability of UPFC on transient stability of a two-area power system. The analysis of generator rotor angle, voltage profile and angular frequency is done with and without UPFC at different fault clearing times, CTs. The impact of TCSC on the transient stability is studied in [42]. Line reactance and the power flow can be changed by TCSC. A general non-linear dynamical model for power systems with UPFC as a stabilizing controller is used [43] and was applied in SS. For the study in [44], STATCOM was used to improve the system by eliminating fault transients on single machine infinite bus system (SMIB); it was observed that the IPFC is better damping than STATCOM. Research study done in [45], presents the transient stability assessment of two series FACTS controllers SSSC and IPFC where it was improved transients due to faults while enhancing the Available Transfer Capacity (ATC).

The IPFC in research [46] suitably located, helps the system to remain stable by increasing critical clearing time (CCT) because of the strong multi-line control capability of integrated model of IPFC. Power Injection Model (PIM) is implemented into the modified IEEE 30-bus test system in [47] with IPFC to equalize both real and reactive power to relieve the overloaded lines. The results show the capability of IPFC utilization as an automatic generator control actuator [47, 48]. In studies done in [49], Fuzzy tuned-AVR with IPFC is used for series compensation with capability of controlling power flow. Modeling, simulation and comparison of the performance of IPFC and UPFC FACTS controllers for voltage stability enhancement and improvement of power transfer capability have been presented in [50]. From the [51] investigation, IPFC is a feasible resolution throughout the transmission lines not only to increase the transmission capacity but also improve the transient performance. The small signal studies have been carried out to investigate the performances of the IPFC and UPFC in [52]. Finding is obtained IPFC has on more series branches than the UPFC hence better series voltage compensation.

The studies in [53] reveal Hybrid Power Flow Controller (HPFC) stabilizes quickly, reduces the settling time, and thus settles out the power system transients effectively. The [54] model is adapted to IPFC and UPFC devices. On the same work, simulations done revealed the integrated IPFC model and UPFC capabilities and advantages for controlling simultaneously both active and reactive power flow hence real and reactive power coordination. This needs to extend to transient stability enhancement. For study in [55], Real power (P) and reactive power (Q) of the system is compared with and without of UPFC and IPFC in the system. It is shown that powers profiles are improved. In [56], SSSC has been applied in PSAT to improve voltage profile enhancement, power flow control is achieved and congestion is less and congestion management. Observations made in [57] shows positive improvements caused by TCSC and SSSC controllers, two of FACTS devices, in the increase of energy transmission lines capacity and amplifying voltage stability limits. When the system was examined in terms of voltage stability, improvements related to power increase were detected. It was seen on the voltage stability curves that voltage stability limits are rather favorable when same capacity load is transferred. Optimal co-ordination design of PSSs and UPFC devices in a multi-machine power system was done in [58]. The procedure was based on the use of the Angle-PSO which adjusts the parameters of the controllers to achieve system stability and maintain optimal damping as the system operating condition and/or configuration change. The simulation results proved that the power system is more stable with UPFC device provided the optimal choice of its location and parameters. Electromagnetic Transient Program (EMTP) simulation software has utilized in [59] for transient stability and power flow models of Thyristor Controlled Reactor (TCR) and Voltage Sourced Inverter (VSI) based Flexible AC Transmission System (FACTS) Controllers. Models of the SVC, TCSC, STATCOM, SSSC, and UPFC appropriate for voltage and angle stability studies have studied. Research [60] presented SSSC where its linearized power flow equations were incorporated into

Newton-Raphson algorithm in a MATLAB® written program to successfully carry out the control of active power flow and the transient stability studies. In in research work at [61], the simulation of a single-machine infinite bus power system model under different faults has been carried out in order to exemplify the superiority in the performance of damping low frequency oscillation by employing SSSC based controller with modified GA. The results clearly indicated that SSSC provided improved dynamic response and at the same time faster than other conventional controllers. Effect of SSSC and UPFC demonstrated in [62] that FACTS devices improve the power transfer capability and control the power flow. It was found out in [63] that by incorporation of SSSC, the power flow between the lines improves and the lower order harmonics are reduced. The work was implemented vide a MATLAB® code. A complete model for transient stability study of multi machine power system has been developed using MATLAB®/Simulink environment in [64]. It was deduced that Simulink model is not only well suited for an analytical study of a power system network, but it is also helpful in detailed study of load flow and parameter variations. Numerical results on the test system demonstrated in [65] that the proposed IPFC model yields fairly accurate results for bus voltages and power flows. The Available Transfer Capability (ATC) of the required transmission lines has been increased as the power transfer through the particular line has reduced. Research [66] studied that the oscillation produced in the system can be removed with SVC. From the simulation work it was clear that the power system can attain the stability in the best manner if the SVC is located optimally after fault occurrence. This way, SVC was used to improve the transient stability of system. The work was achieved using a MATLAB® program. Transient stability analysis of electrical power systems by means of LabVIEW tool based Simulation of STATCOM was done in [67]. LabVIEW helped to study the system behaviour, thus reducing its complexity. STATCOM provided better damping characteristics than the SVC, as it is able to exchange active power with the system.

2.5 Power system modeling

`Power system dynamic simulations fall in basically two groups: Electromagnetic Transients (EMT) and quasi-sinusoidal (or phasor mode) approximation. In the EMT, fast electromagnetic transients are simulated and in steady state, voltages and currents evolve sinusoidally with time at a nominal frequency. The network itself is modeled through differential equations with respect to its reactances. For the quasi-sinusoidal (or phasor mode) approximation, the network is denoted by algebraic equations corresponding to sinusoidal regime. During transients, all phasors vary with time while in steady-state they take on constant values. The dynamic model describes how the phasors evolve with time. To effectively, analyze any power system, mathematical model is used to represent the system. In this research, system has been represented in terms of Simulink blocks in a single integral model. The meriting feature of a model in Simulink is its easy interactive capacity; the display of a signal at any point is readily available; by just adding a block or, an output port. Feeding of feedback signal can be quite easily done. A block parameter can be controlled from a MATLAB® command line or *m*-file program. Thus, this is invaluable for a transient stability studies as the power system configurations are different before, during and after fault. Loading conditions and control measures can also be implemented accordingly. Power system generators on the system are considered as constant voltage sources. The largest generator is treated as the swing bus which will take care of the power mismatch in the system. All loads are treated as constant power sinks. Medium length model is considered for all transmission line sections [68]. Transformers are modelled with tertiary winding and are operating with an on-line tap changer. The Simulink environment applied in this thesis is MATLAB® PSAT, computing power system analysis simulation tool with properties for design power networks, visualize the topology and change the data stored in it, without the need of directly dealing with lists of data [70]. Matpower toolbox is a package of MATLAB® m-files for solving power flow and optimal power flow problems also utilized in this work together with PSAT is a MATLAB$^{®}$ toolbox for electric power system analysis and control a toolbox with a variety of utilities, as follows: one-line network diagram editor (Simulink library); user interfaces for settings system and routine parameters; user defined model construction and installation; GUI for plotting results; filters for converting data to and from other formats and command logs [68] [70].

2.6 Time domain simulation technique

Dynamic simulations are commonly used for checking the response of electric power systems to large disturbances. They have become indispensable for planning, design, operation, and security of power systems. Operators depend on fast and accurate dynamic simulations to train operators, analyze large sets of scenarios, assess the dynamic performance of the network in real-time. TDS require solving a large set of nonlinear, stiff, hybrid, Differential-Algebraic Equations (DAEs) that describe the physical dynamic characteristics, interactions, and control schemes of the system. A large interconnected transmission involves hundreds of thousands of such equations whose dynamics span over very different time scales and undergo many discrete transitions imposed by limiters, switching devices, etc. Consequently, dynamic simulations are challenging to execute, computationally intensive and can easily push any given computer to its limits. In this research by use of TDS tool in MATLAB$^{®}$ PSAT; two integration methods are applied forward Euler and Trapezoidal rule to evaluate the algebraic and state variable directions at each dynamic step of the algebraic and state Jacobian matrices of the system. Disturbances are fully supported in PSAT. The most common perturbations for transient stability analysis; faults and breakers are handled by function models. At TDS period, a time vector for carrying out TSA before and after the fault occurrences is created. When the faults or the fault clearances occur, the shunt admittances of the network are modified and the admittance matrix is recomputed. The responses are computed by TDS and responses given by the main graphical user interface on PSAT. Eventually in this research work, SSSC, IPFC and UPFC FACTS models are incorporated to the system and their responses for power oscillation before and after are comparatively studied using the PSAT TDS tool [69] [70].

2.7 Summary and gaps

From the foregoing literature survey, it is noted that placement various FACTS devices has been research at great depth and profundity. To realize the peak performances of the three devices; SSSC, UPFC and IPFC, the best location, based on the bus voltage magnitude has been implemented in this thesis. The review has also established that FACTS devices have been applied jointly and severally to provide voltage through active and real power control vide their voltage injection properties. Singularly, FACTS controllers like SVC, TSCS, SSSC, HPFC, and integrated model of the UPFC and IPFC have used to enhance voltage stability and transient stability. This research has gone a step further. As stated previously, other than the property of fast control of active and reactive power in power system clearly depicted in the literature exploration, the three FACTS devices also play a key part in invaluably damping power system oscillations and transient-stability enhancement hence boosting system reliability and control during disturbances. The power oscillations damping properties of single compensating series controller, SSSC, the double series-shunt compensator, UPFC and double series-series compensator, IPFC FACTS have been comparatively studied in this thesis go beyond the above survey. Further still, this research has examined the specific performances of three devices before the comparative analysis far as their damping of system oscillations, voltage support and loss reduction regimes are concerned. It has also uniquely contributed to system TS control information using FACTS through the study of the responses of double compensating and independent model of the IPFC with respect oscillations damping and loss reduction capabilities by way distinguishing their capability with respect other devices under examination. It has gone further to look at voltage stability support and loss reduction attributed to each device to enable power system planners merge and establish the trade-off among transient stability, loss reduction and voltage support characteristics of the three devices focused. Best application of FACTS needs to determined; is it voltage support or transient stability. Distinction of compensation properties of series and shunt converters in TSE is major gap in past studies.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter outlines the research procedure and approach. The most appropriate location of FACTS devices has been determined by CPF strategy by finding out the critical buses or weakest buses, for placement of the FACTS devices. The method outlines the buses with the lowest voltage magnitudes hence the best location for placing the devices. The method used is CPF via MATLAB®PSAT Toolbox. Subsequently, dynamic TSE simulations using TDS tool incorporated in power system simulation software MATLAB® PSAT Toolbox are performed with and without FACTS located based on the above criterion.PSAT is selected for its robustness and the ability of its TDS tool to analyze numerous transient stability parameters compared to other tools.

Dynamic TDS simulations to validate the effects of three FACTS controllers; SSSC, UPFC and IPFC have been realized by use of standard dynamic IEEE 14 bus model with AVR as shown in figure 3.1 below. IEEE 14 bus selected for this study as it's a multi-machine network that can be used as a basis and can be extrapolated to all network other networks including the Kenyan power network. The most critical consideration was the compensation properties of FACTS and not the size of the system. A TDS was performed for three phase fault at bus 4, see figure 3.2 for all the three FACTS controllers. The faulted bus is randomly selected since system faults can occur anywhere in the system. Other buses, generations units, substations can also be faulted.

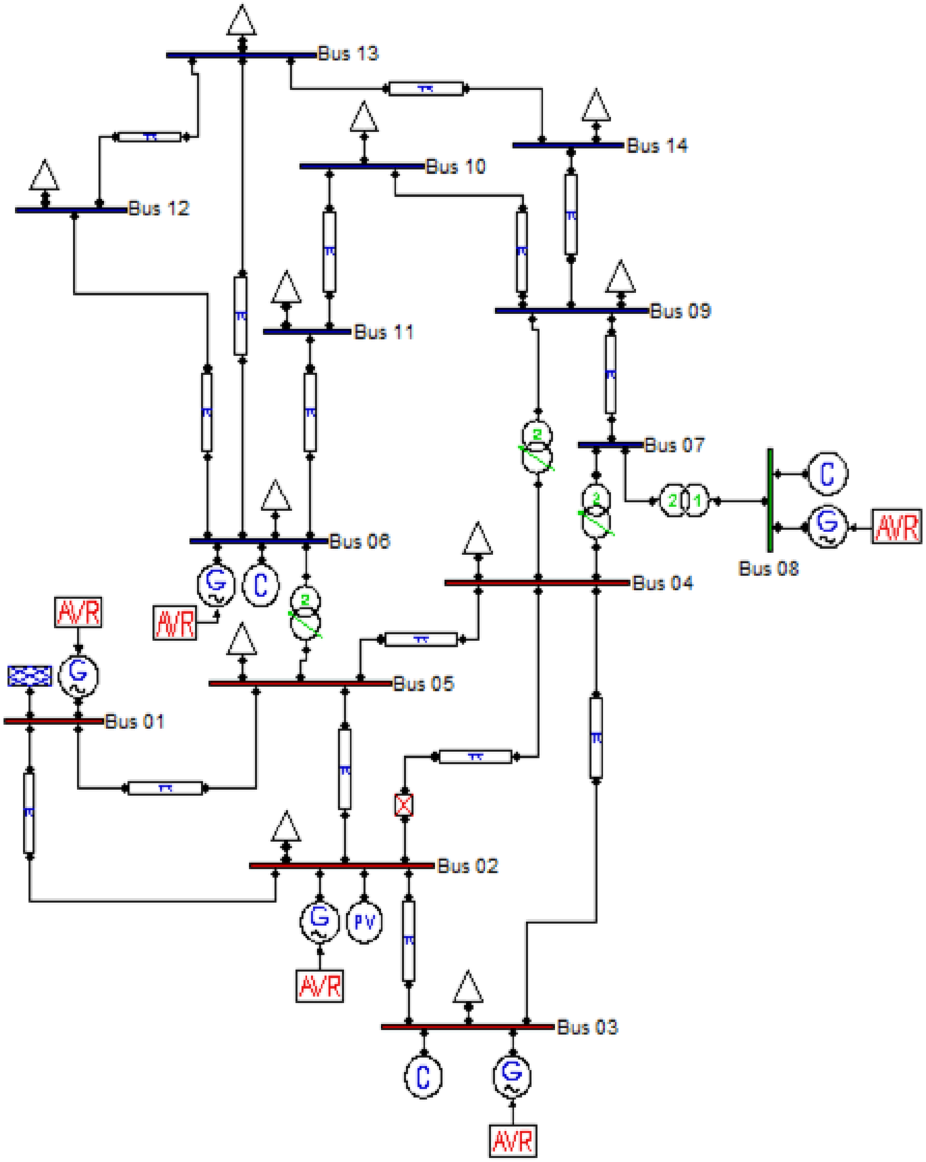

Figure 3.1: IEEE 14 test bus standard dynamic model

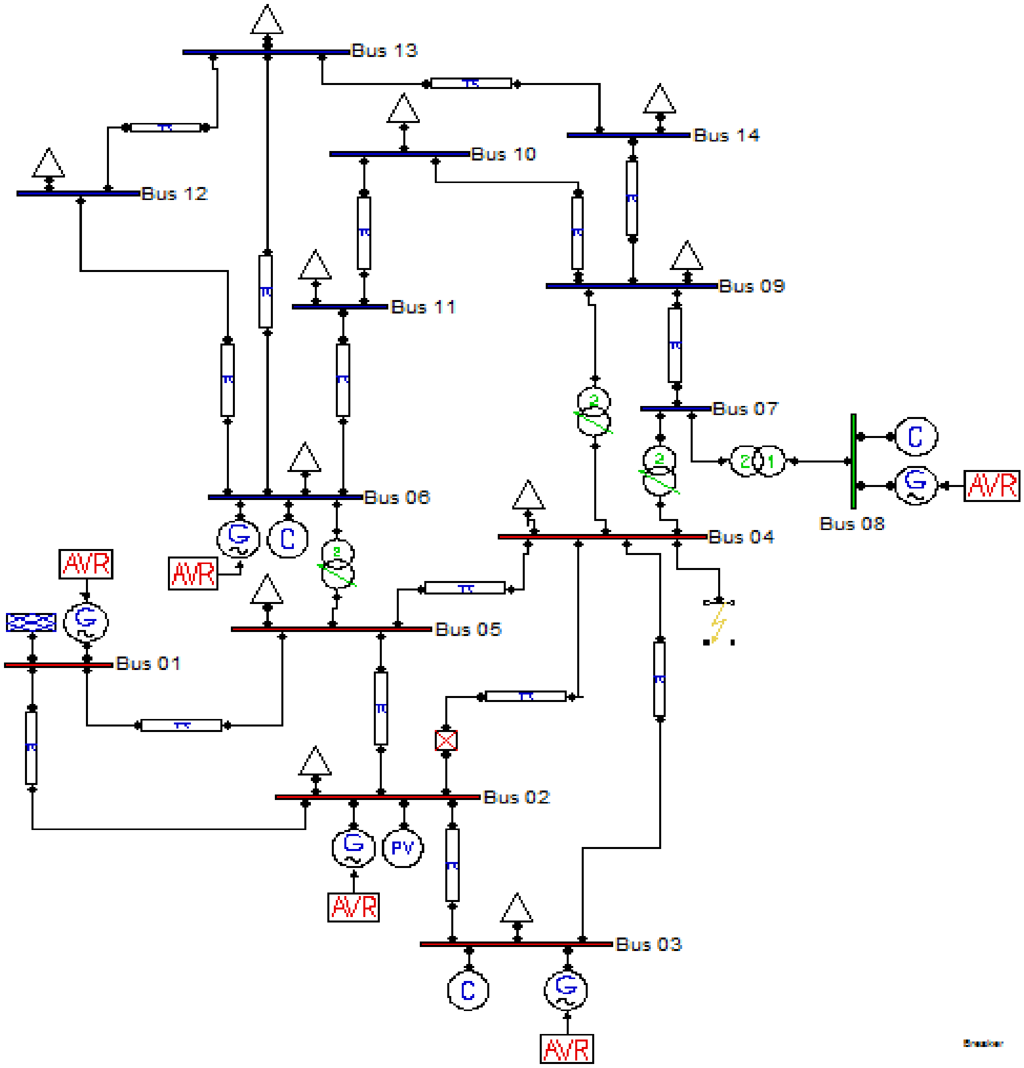

Figure 3.2: IEEE 14 Bus dynamic model with fault at bus 4

3.2 Placement of facts devices

The method employed to determine the bus with weakest voltage profile for FACTS devices location is outlined in 3.1.1 below.

3.2.1 Location of facts devices using PSAT CPF

CPF technique is used for carrying out voltage stability performance analysis of the system under study. It is used to obtain P-V curve of power system for each bus. In P-V curve Continuation power flow starting with initial operating point and increasing load to the maximum loading point as shown in figure 3.3 below.

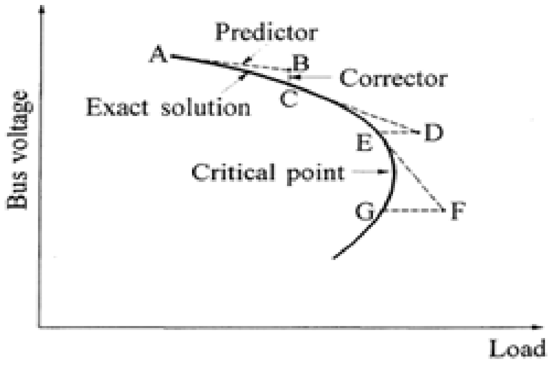

Figure 3.3 CPF Prediction step illustration

Continuation power flow analysis been done establish the bus with lowest voltage magnitude. This is the weakest bus and the best location of the FACTS device.

3.3 Dynamic model for UPFC FACTS device

The dynamic model of standard IEEE 14 Bus in PSAT toolbox with UPFC FACTS device is utilized in this thesis. UPFC FACTS device is connected to the optimal location obtained in 3.2.1 above. The best locations of the devices are the buses with lowest voltage profile. The IEEE 14 bus system consists of 14 buses, 5 generators each with AVR, 11 loads, 3 transformers and 20 branches. The bus data include the bus voltage with its phase and magnitudes. Out of five generators two generators supply real power while three generators are the reactive sources i.e. synchronous condensers to provide the reactive power supply. The system consists of total real load of 244.1 MW and reactive load of 72.4 MVAr. UPFC is a combined series-shunt controllers may have two configurations, one being two separate series (SSSC) and shunt (STATCOM) controllers that operate in a coordinated manner and the other one being interconnected series and shunt components. When these two elements are unified, a real power can be exchanged between them via the power link. The interconnected injection model has been employed in this thesis because the devices have different compensation regimes; one is shunt and the other is series. UPFC was placed close to weakest bus (Bus 14) as shown in figures 3.4 below:

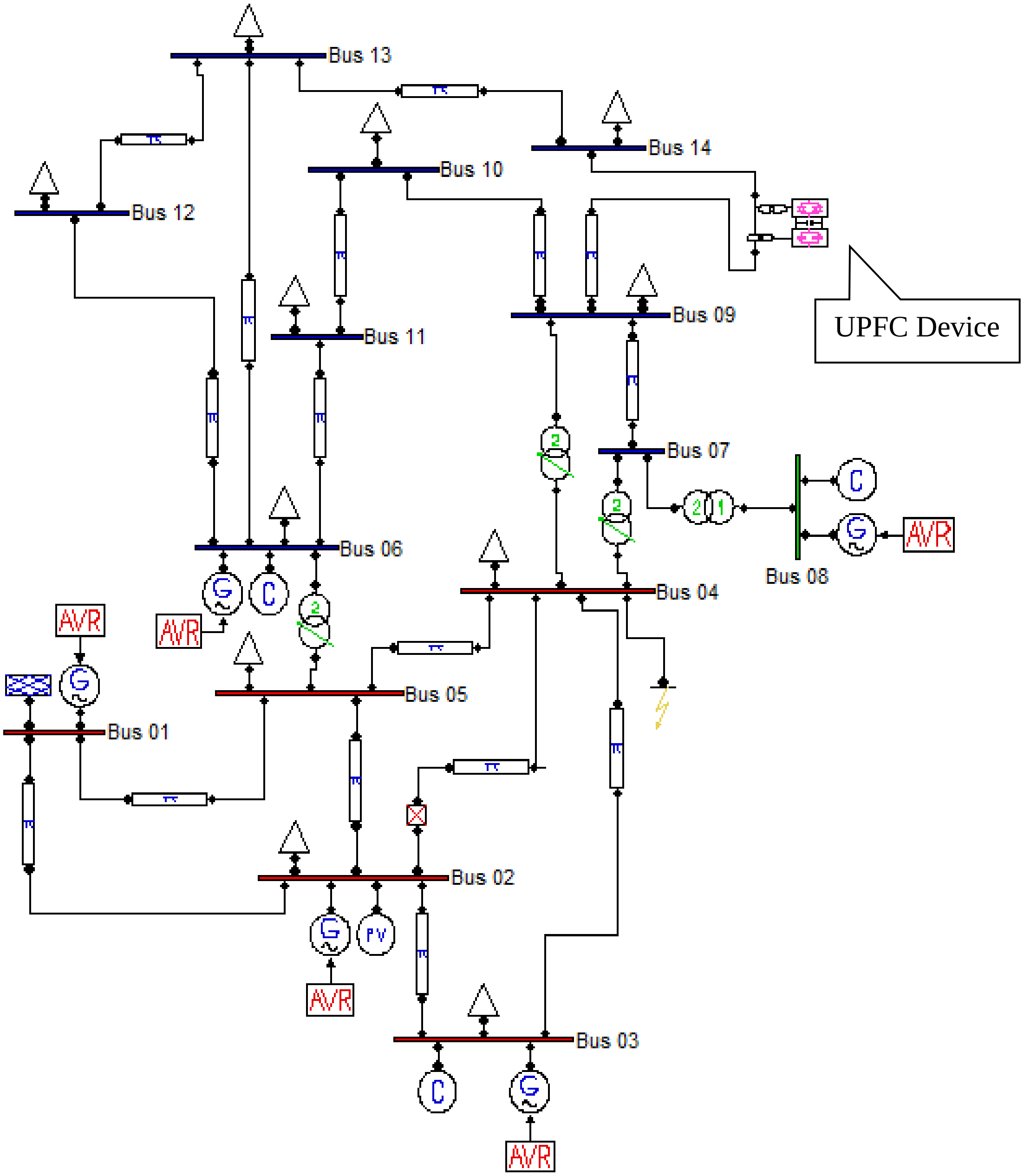

Figure 3.4: IEEE 14 Bus Dynamic Simulink Model with fault and UPFC

3.4 Dynamic model for SSSC FACTS device

The dynamic model for SSSC FACTS device was developed to check the effectiveness of SSSC for TSE. The IEEE 14 bus dynamic model for SSSC placed close to 14 is shown in figures 3.5 below:

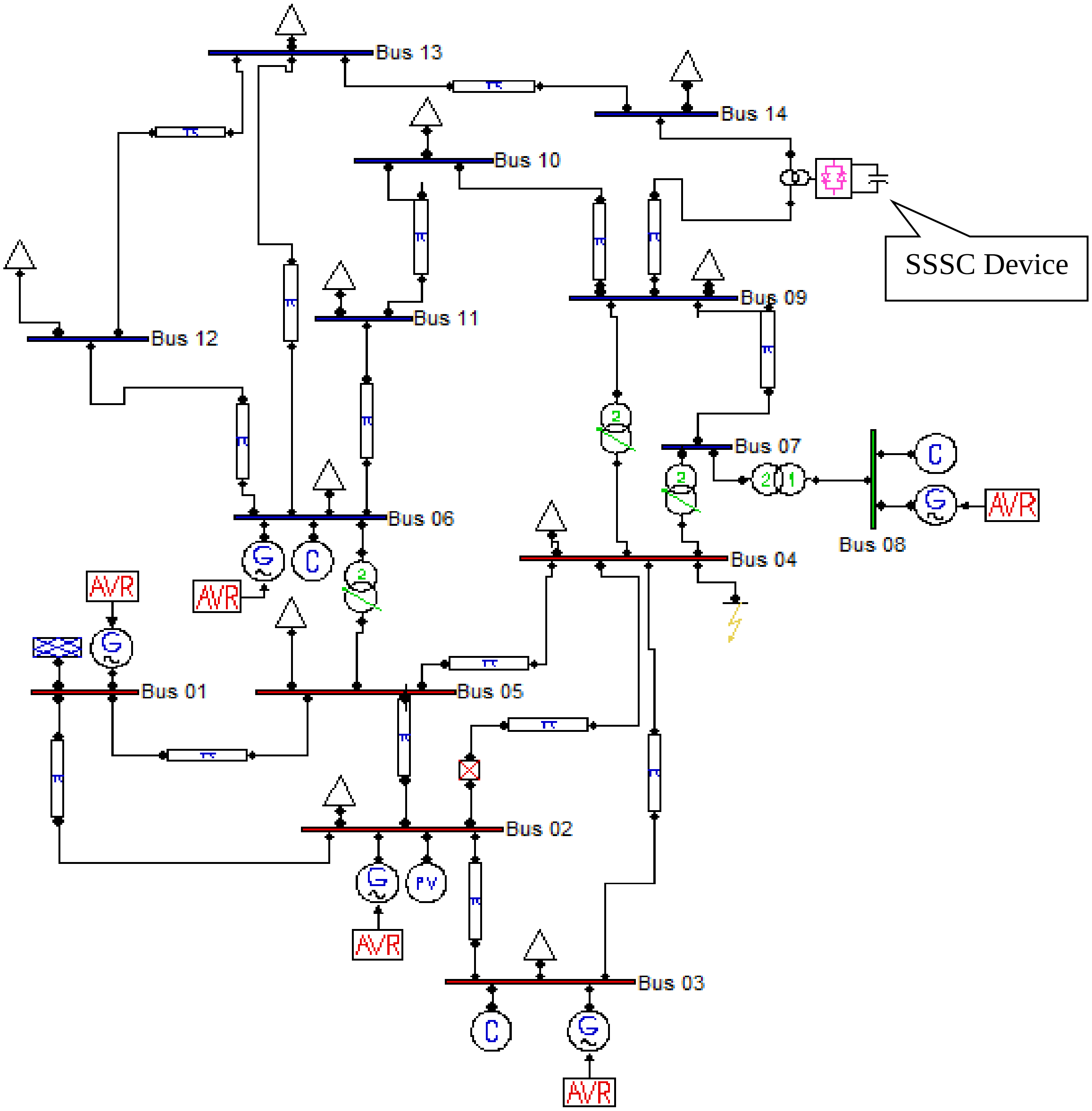

Figure 3.5: IEEE 14 Bus Dynamic Simulink Model with fault and SSSC

3.5 Dynamic model for IPFC FACTS device

The dynamic model with independent configuration of IPFC FACTS device was also utilized to check the effectiveness of IPFC for TSE. The Simulink arrangement is shown in figure 3.6 below.

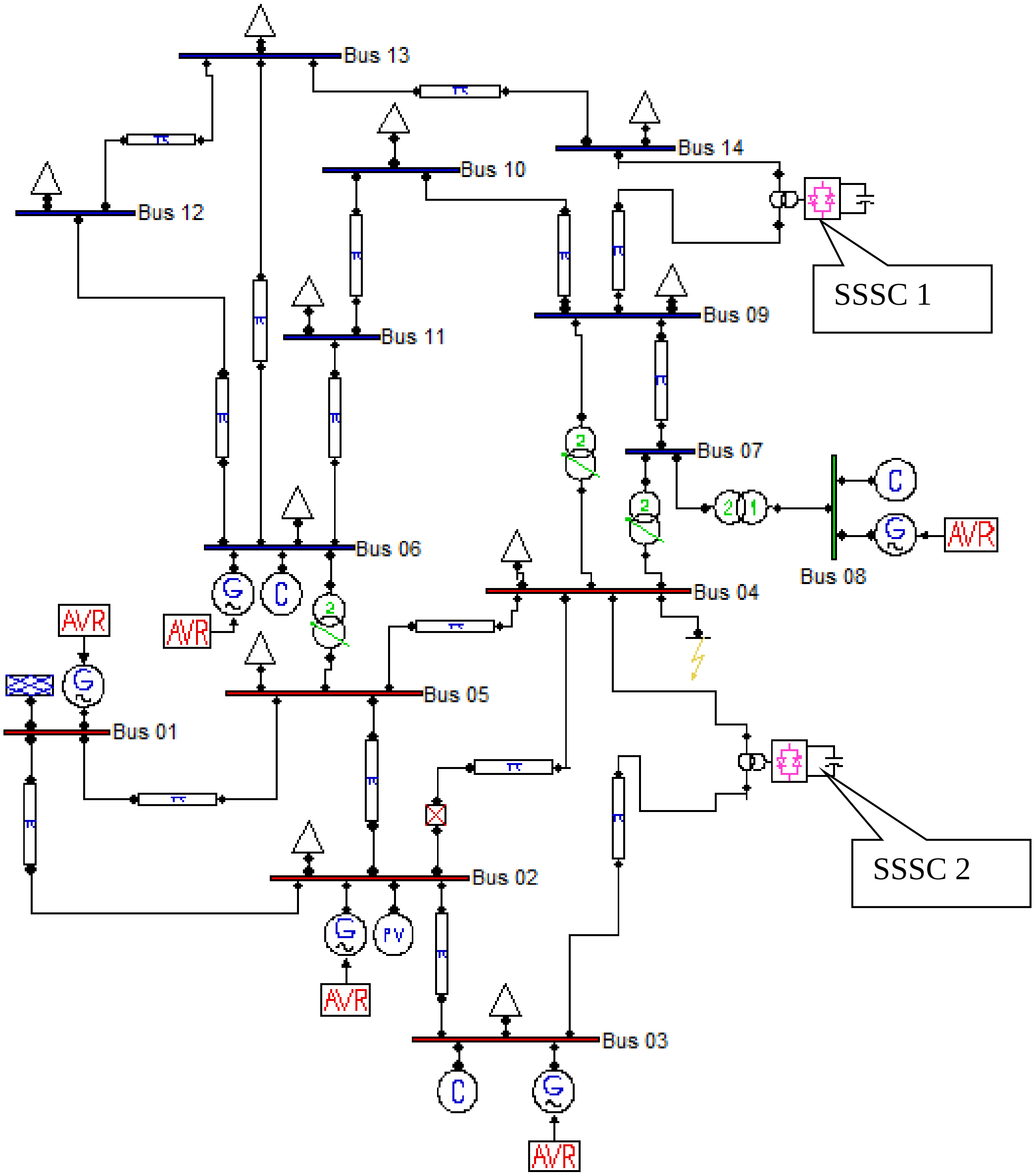

Figure 3.6: Dynamic Simulink Model with fault and IPFC device

3.6 **Simulation and analysis of transient stability**

PSAT is used to assess the effectiveness of the three FACTS device models developed in this thesis. 3-Phase fault is has been simulation to provide the source of disturbance with fault time occurring at 1.000 second cleared time at 1.250 seconds. The following cases are considered:

Case I:

TDS is carried out with 3-Phase fault with no FACTS device connected.

Case II:

TDS is carried out with 3-Phase fault with the three FACTS devices connected to the system.

The TSE responses were obtained from the above TDS for comparative analysis alongside the effects of the three devices in voltage profile improvement and loss reduction. Appendices A1-A8 outlines the details of IEEE 14 bus test system, system bus/line data and FACTS controllers' data.

CHAPTER FOUR

RESULTS, DISCUSSIONS AND ANALYSIS

4.1 Introduction

This chapter deals analysis of the results. The results of the FACTS controllers' location are initially outlined. Thereafter, the TSE simulation results with and without the controllers, in time domain, were subsequently obtained. The results of determination of suitable location of FACTS devices have been obtained by use of CPF method in the PSAT platform. Accordingly, dynamic TSE simulations using TDS tool incorporated in power system simulation software PSAT Toolbox are performed for the three devices. TS parameters including rotor speed, settling time and angle have been simulated and analysed. Initially, Transient Stability Enhancement (TSE) analysis for single parameters was dealt with before multiple parameters machines were considered.

4.2 Placement of facts devices

4.2.1 Location of facts devices using PSAT CPF

Continuation power flow simulation was done using PSAT software and the results were obtained as displayed in table 4.1. The power flow results revealed that the buses with lowest voltage magnitudes are 04 and 14. The P-V nose curves for the weakest buses are illustrated in figure 4.1. It was deduced from the curves for the 14-bus test system, that bus 14 was the weakest bus for IEEE 14 bus system. Continuation power flow technique has been used to successfully identify weakest bus in the system to locate the devices.

Table 4.1: Continuation Power Flow results for IEEE 14 bus system

POWER FLOW RESULTS (Voltage and Angle)		
Bus	V[p.u.]	Phase[rad]
Bus 01	1.060	0
Bus 02	1.045	-0.136
Bus 03	1.010	-0.332
Bus 04	0.998	-0.263
Bus 05	1.002	-0.227
Bus 06	1.070	-0.380
Bus 07	1.035	-0.354
Bus 08	1.090	-0.354
Bus 09	1.011	-0.402
Bus 10	1.0105	-0.405
Bus 11	1.034	-0.395
Bus 12	1.046	-0.401
Bus 13	1.036	-0.403
Bus 14	0.996	-0.429

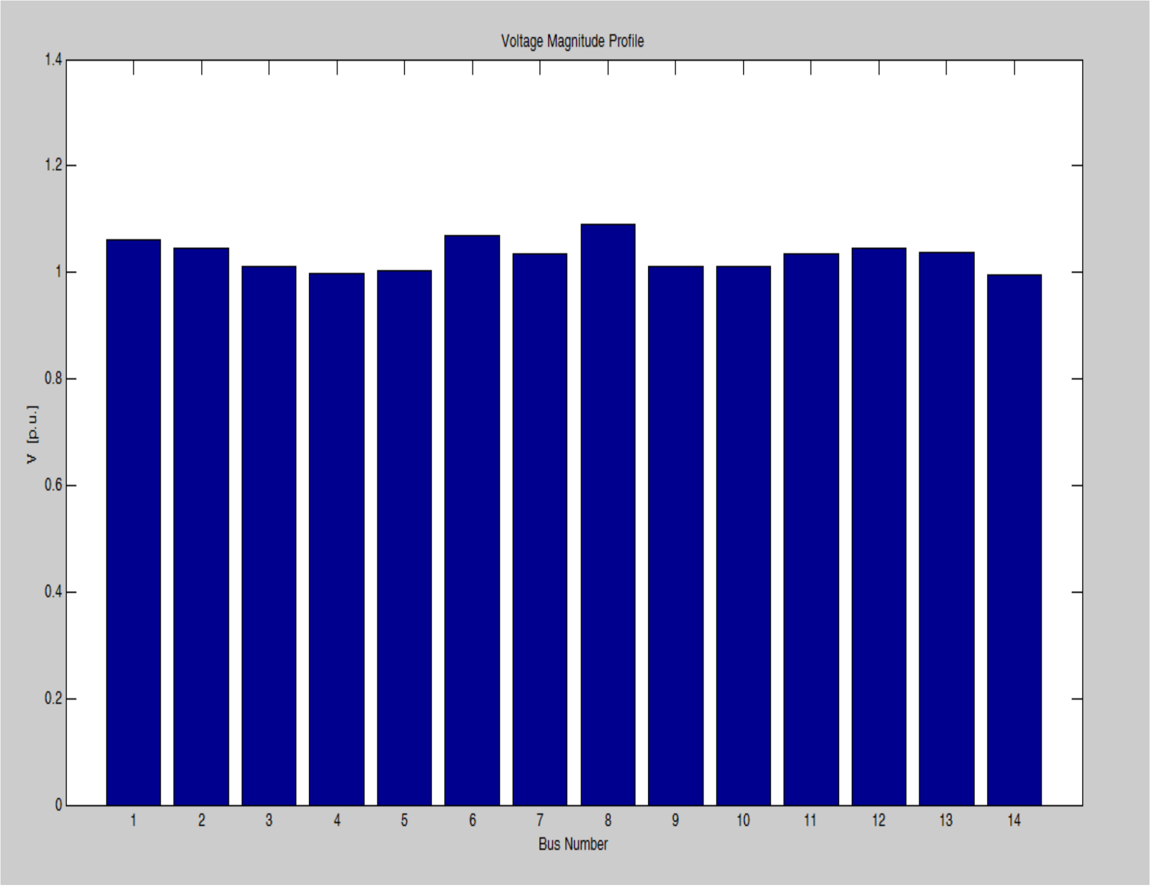

Figure 4.1: Voltage profile magnitude

From the above outcome, buses 04 and 14 possess the lowest voltage magnitudes of 0.998 p.u and 0.996p.u, respectively. Thus, the weakest bus is 14. The next step was to generate and plot the P-V curves for the lowest voltage buses. It was performed and curves generated effectively. The curves are illustrated in figure 4.2.

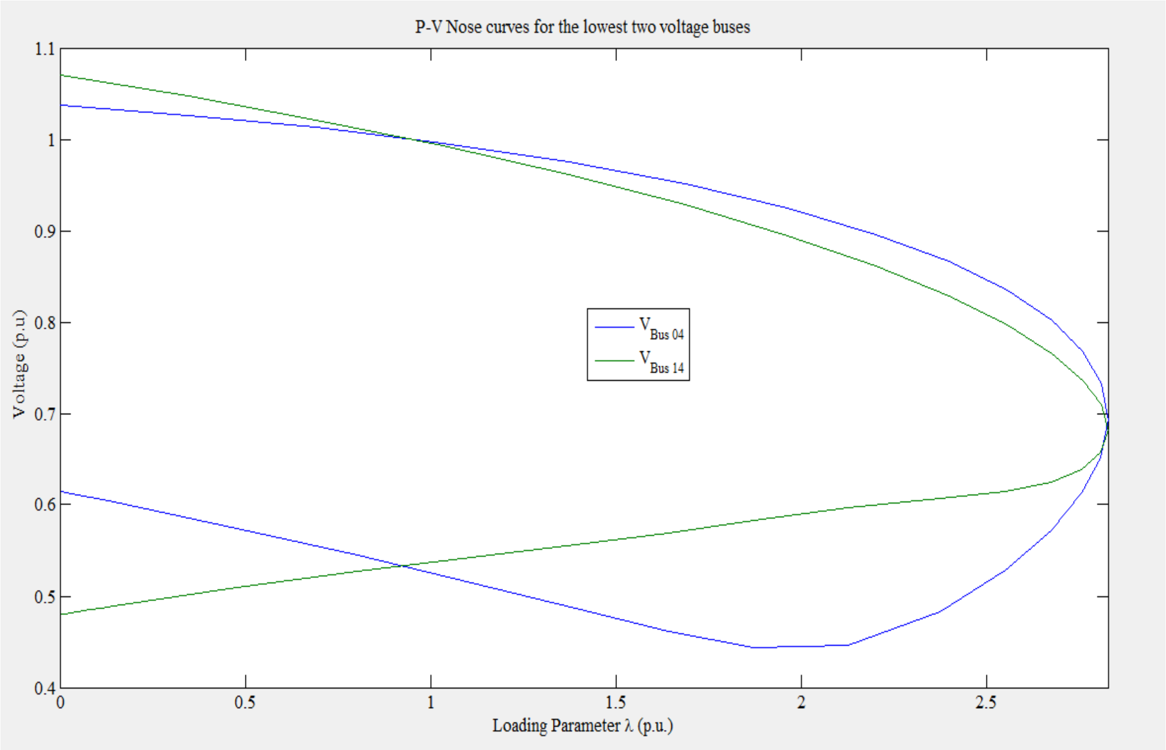

Figure 4.2: Voltage P-V nose curves for two low voltage buses in IEEE 14 bus system

The figure above shows the changes of bus voltage with the loading factor lambda (λ) for IEEE 14 bus test system. From the plots of buses 04 and 14, it is deduced that bus number 14 is the most insecure bus as the voltage at each reactive load of bus 14 is minimum. Thus, this is the best location for the three FACTS devices for TDS. The P-V is plot of variation of bus voltage with the loading factor.

4.3 Analysis for a single synchronous generator

TSE simulations were carried in TDS tool embedded in MATLAB® PSAT toolbox. The simulations were carried out initially without FACTS controllers. Later, simulations with three FACTS controllers were also done and the results recorded. Though there are numerous TSE variables were done in the development of this work, the thesis can have very many plots. For purposes of this work, rotor speed, q-axis voltage component behind transient reactance, generator power and rotor angle and speed parameters were selected for time domain simulations (TDS) and analysis. TDS have been carried out to evaluate the effectiveness of the three FACTS device models in this work. Three-phase fault is has been applied to provide the source of disturbance with fault time occurring at 1.00 second cleared time at 1.25 seconds with and without FACTS. Single parameter-responses for singular machines were obtained and studied initially before consideration of multiple machines.

4.3.1 Analysis with UPFC

1. Rotor speed responses

a. Rotor Speed Response of Generator 1

Without UPFC, the oscillations of the rotor speed (angular frequency) of synchronous generator 1 settle to steady state condition after 40 seconds as observed in figure 4.3. The damping to steady state operating condition of post fault oscillations is significantly enhanced by UPFC FACTS device. The UPFC damps the oscillations at a time of about 25 seconds as shown in figure 4.4.

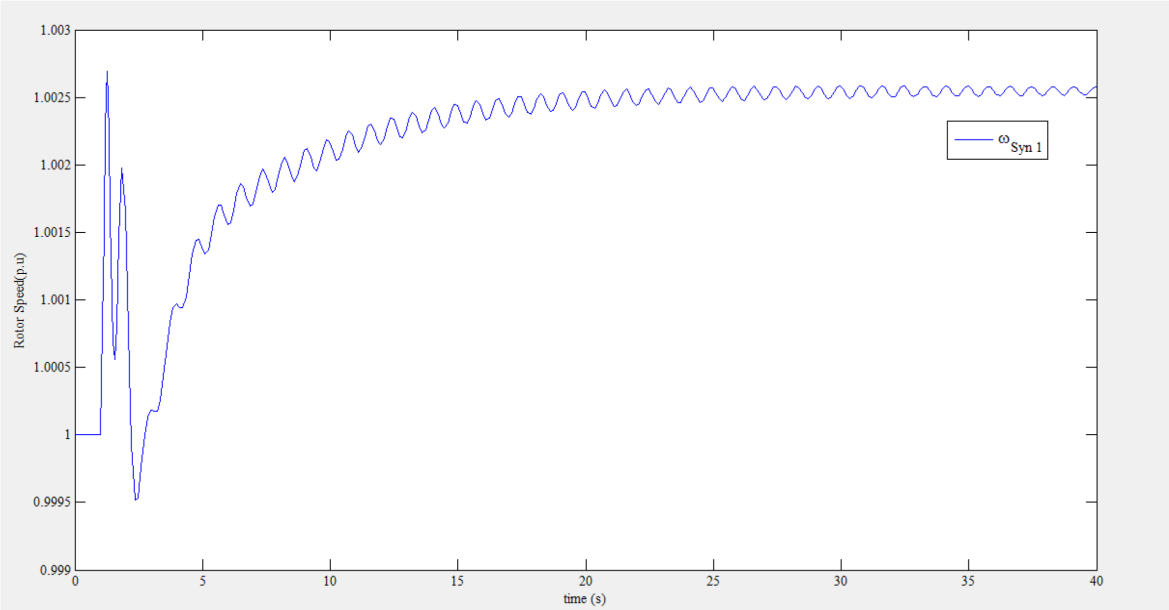

Figure 4.3: Generator 1 rotor speed with fault applied at bus 4

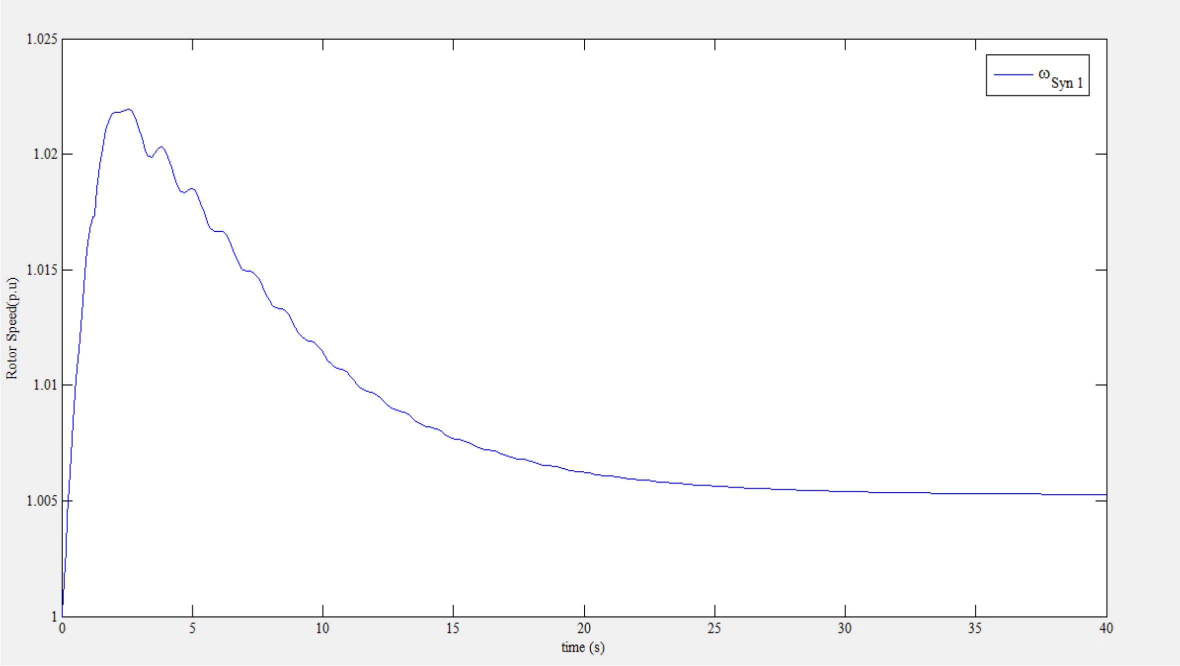

Figure 4.4: Generator 1 rotor speed with fault applied at bus 4 and UPFC close to 14.

b. Rotor Speed Response of Generator 5

For synchronous generator number 5, UPFC damps the oscillations of the rotor speed (angular frequency) of synchronous generator 5 after about 25 seconds. The damping of post fault oscillations to steady state operating condition is significantly achieved faster with UPFC FACTS device. The oscillations phenomena with and without UPFC are shown below, in figures 4.5 and 4.6 respectively.

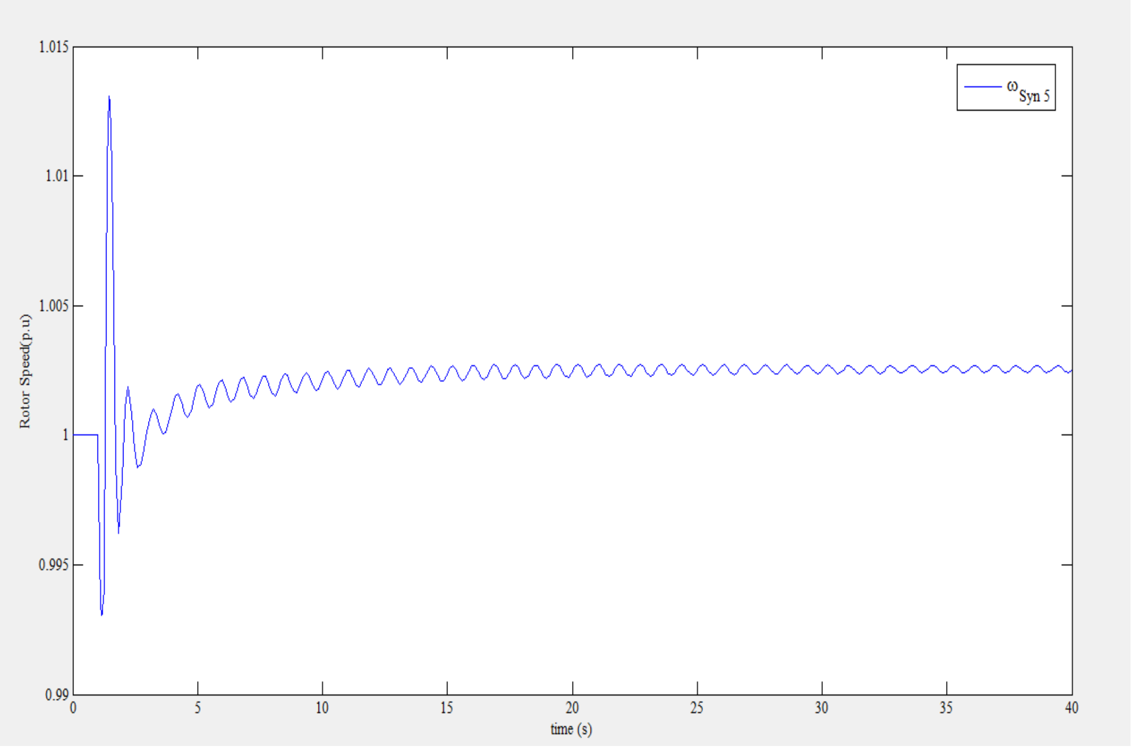

Figure 4.5: Generator 5 rotor speeds with fault applied at bus 4

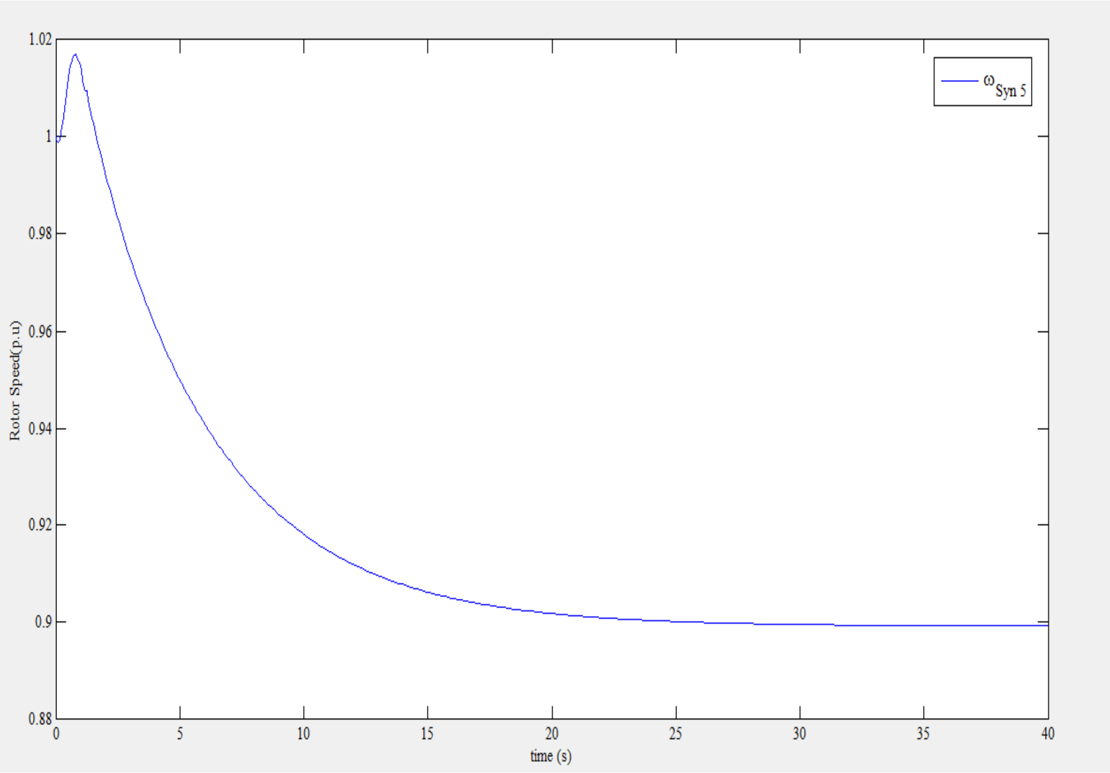

Figure 4.6: Generator 5 rotor speed with fault at bus 4 and UPFC at Bus 14

2. Generator 3 real power response

Real power, P, response of synchronous generator 3 without UPFC is shown in figure 4.7. Figure 4.8 below displays the response with UPFC. Oscillations after fault clearance at 1.25 seconds remain unstable and go beyond the simulations ending time set at 40 seconds. However, with UPFC the swings are damped to steady sate operating condition at about 15 seconds at real power magnitude of about 0.4 p.u.

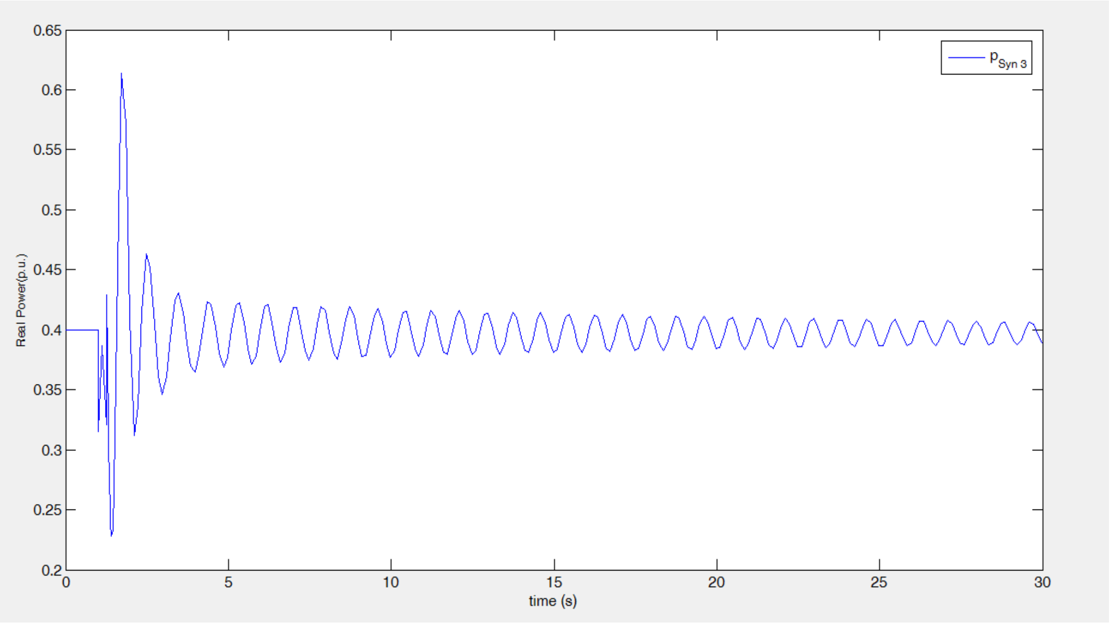

Figure 4.7: Generator 3 real power response with fault applied at bus 4

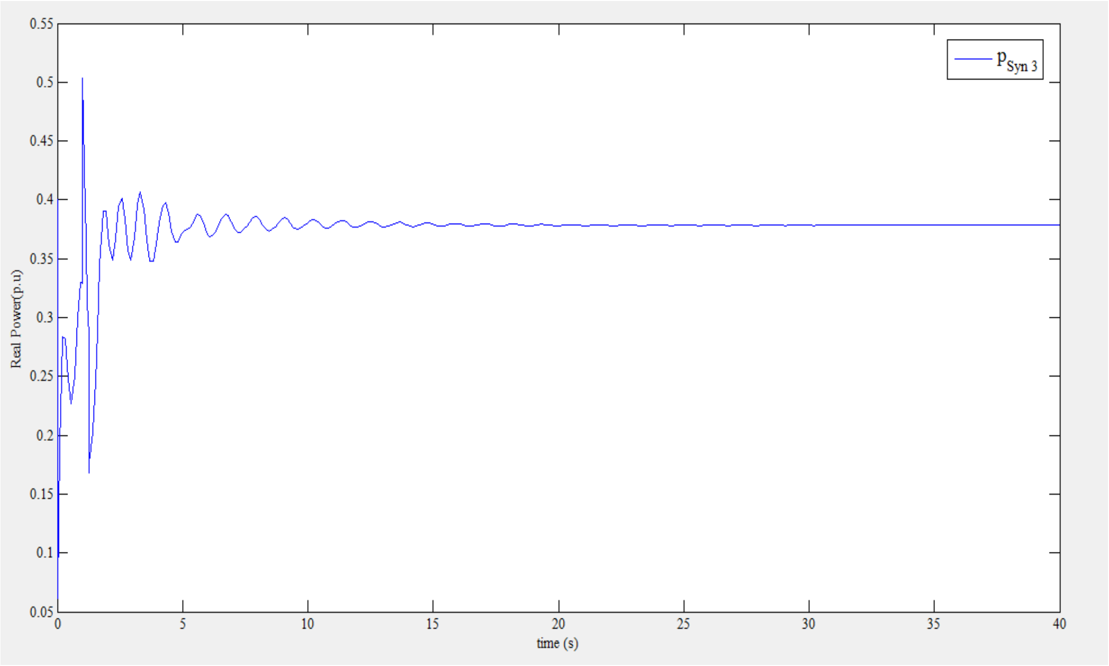

Figure 4.8: Generator 3 real power response, fault at bus 4 with UPFC at Bus 14

4.3.2 Analysis with SSSC

1) Rotor speed response

A. Rotor Speed Response of Generator 1

When the SSSC FACTS was not connected, the oscillations of the rotor speed, also referred to as angular frequency, of synchronous generator 1 are remain un-damped for the simulation time set at 40 seconds as observed in figure 4.9. The damping of post fault oscillations is improved considerably by SSSC FACTS device. The device damps the oscillations in about 25 seconds as shown in figure 4.10 shown below.

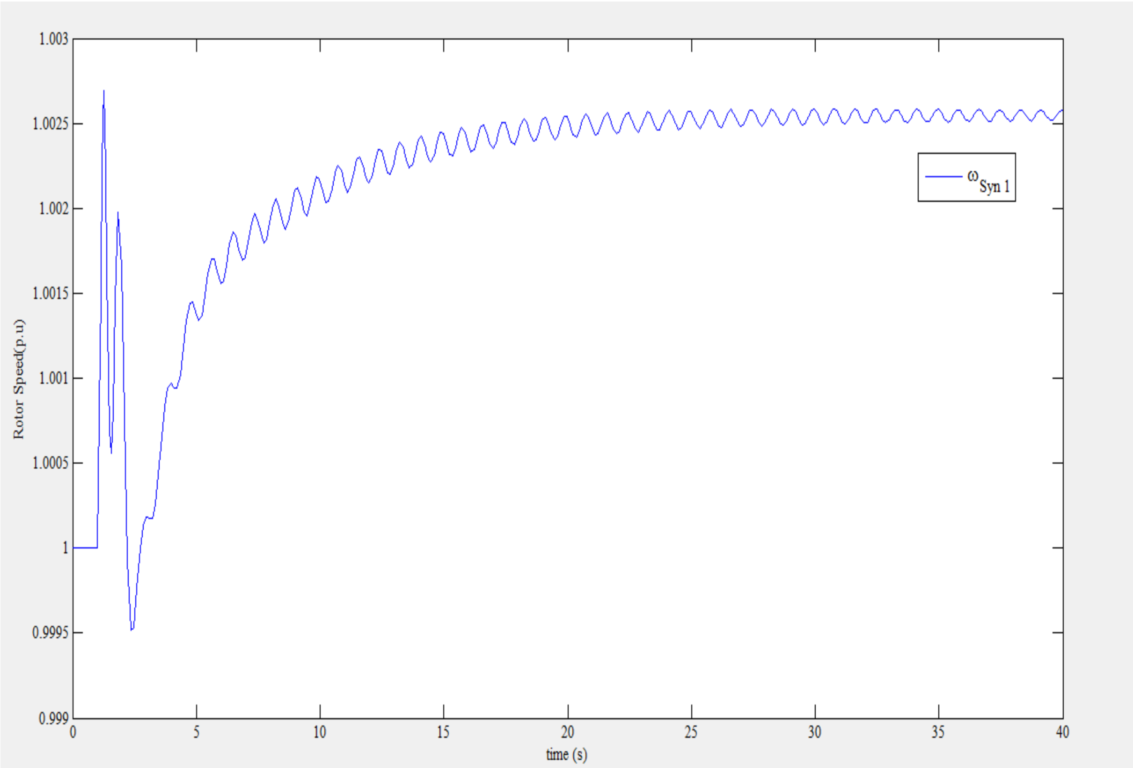

Figure 4.9: Generator 1 rotor speed with fault applied at bus 4

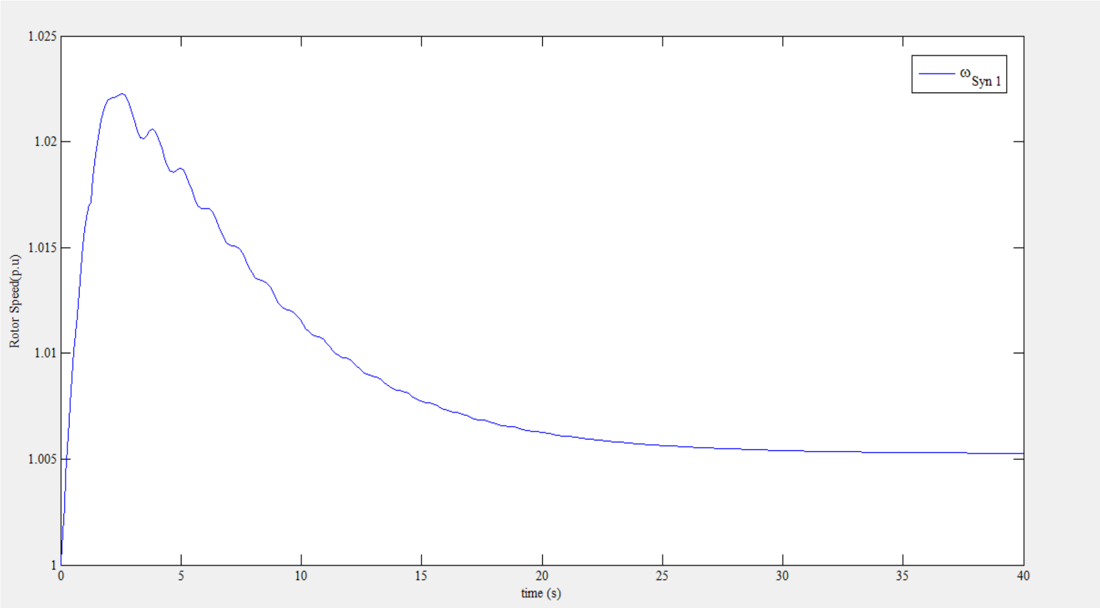

Figure 4.10: Generator 1 rotor speed, fault at bus 4 and SSSC at bus 14

B. Generator 3 real power response

Real power, P, response of synchronous generator 3 without UPFC is shown in figure 4.11. Figure 4.12 displays the response with SSSC. Oscillations after fault clearance at 1.25 seconds continue unsettled and go beyond the simulations ending time set at 40 seconds. However, with SSSC the swings settle to steady state operating condition at about 22 seconds at real power magnitude of about 0.4 p.u.

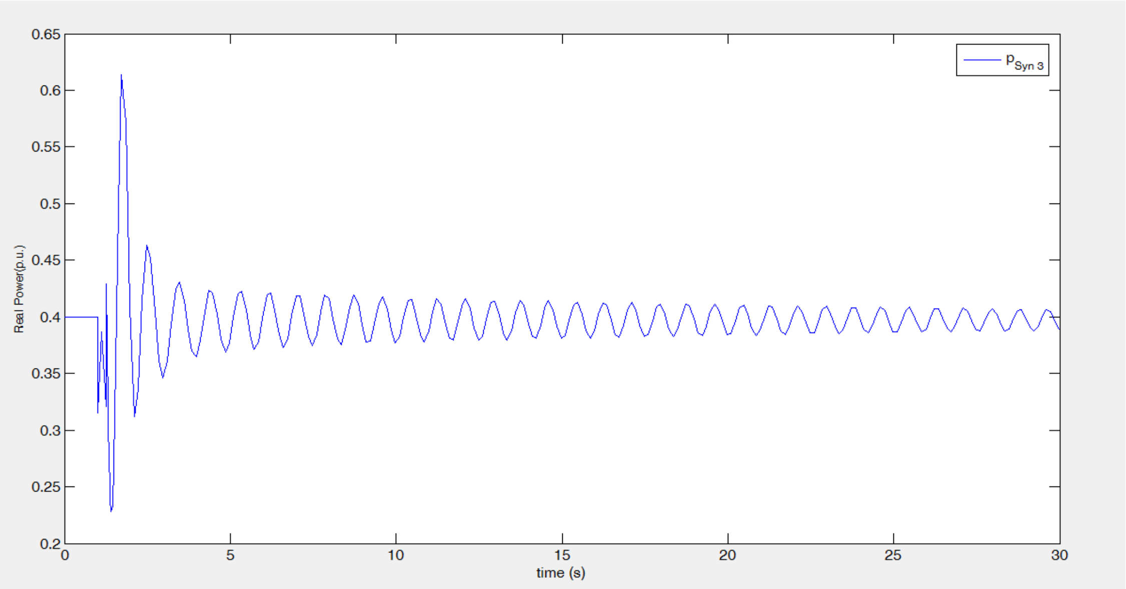

Figure 4.11: Generator 3 real power response, fault applied at bus 4

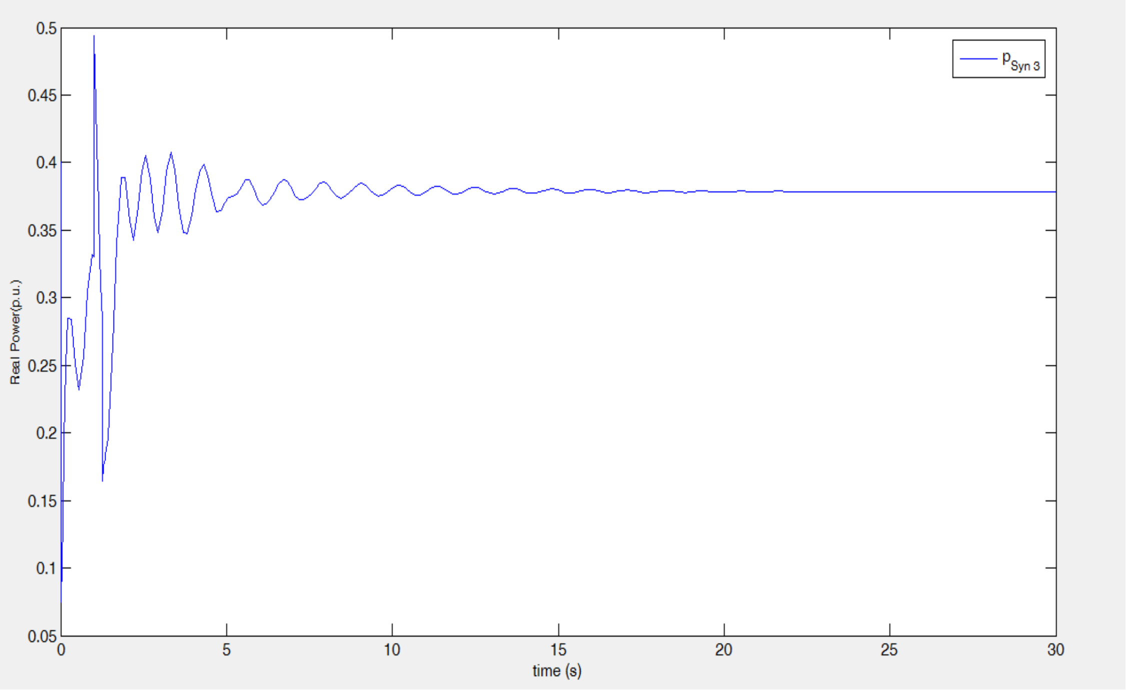

Figure 4.12: Generator 3 real power, fault applied at bus 4 and SSSC at Bus 14

4.3.3 Analysis with IPFC

C. Rotor speed responses

I. Rotor Speed Response of Generator 1

When the IPFC FACTS device is not connected at the weakest buses, the response of the rotor speed of synchronous generator 1 oscillate beyond the simulation time of 40 seconds as observed in figure 4.13. The damping of post fault oscillations is improved significantly by placing independent IPFC FACTS device at bus 04 and 14. The device damps the oscillations giving rotor speed settling time of about 25 seconds as shown in figure 4.14 shown below.

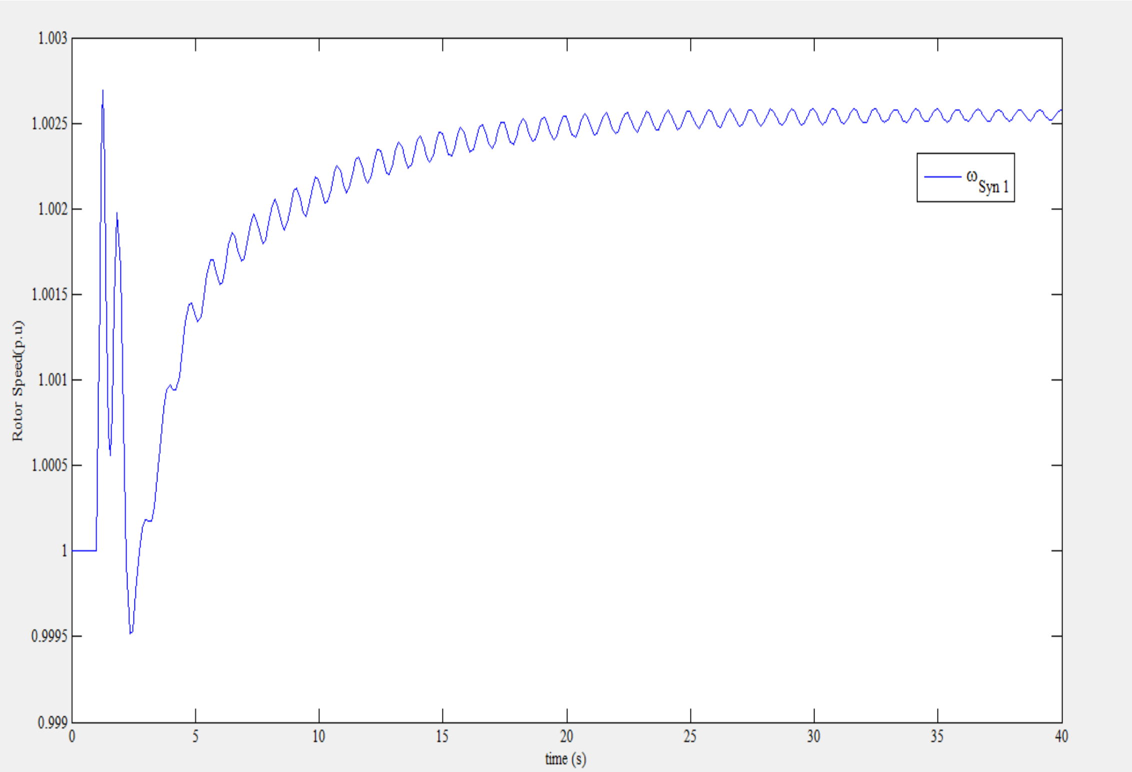

Figure 4.13: Generator 1 rotor speed for IEEE-14-bus system with fault at bus 4

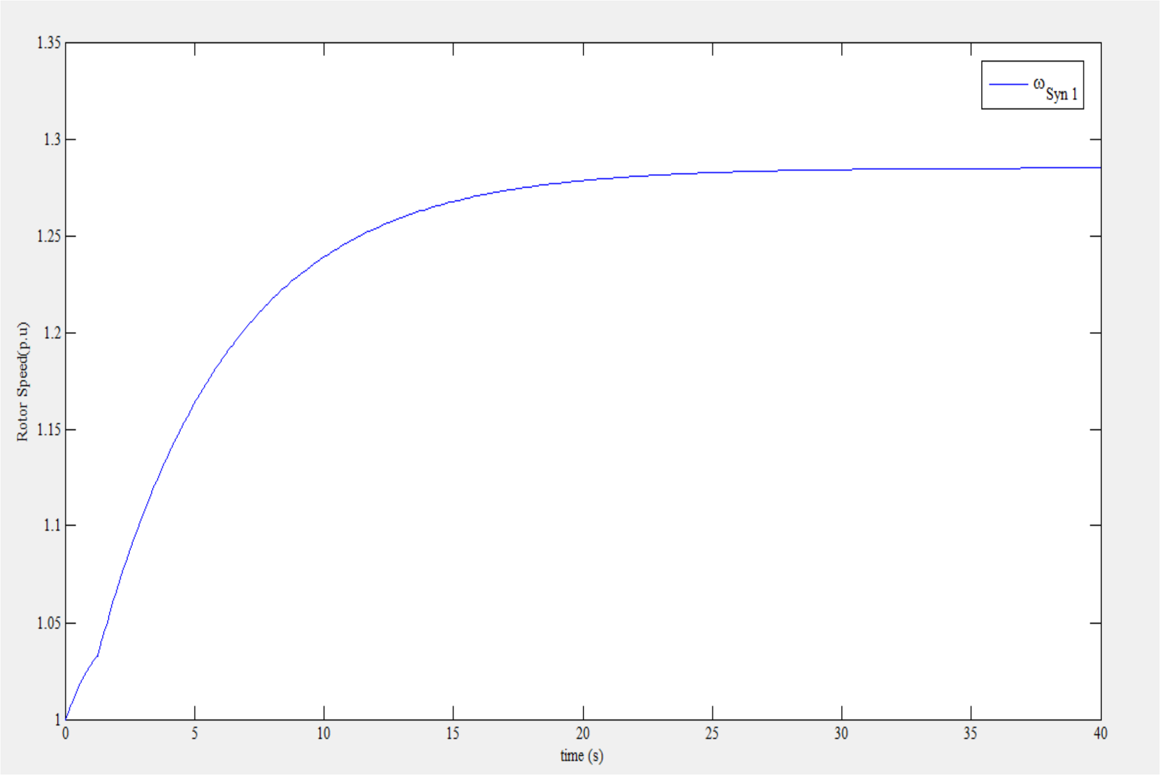

Figure 4.14: Generator 1 rotor speed with fault applied at bus 4 and IPFC

D. Generator 4 reactive power response

A similar arrangement for reactive power response of synchronous generator 4 without IPFC is shown in figure 4.15. Figure 4.16 is an illustration of Q response with IPFC. Oscillations after fault clearance at 1.25 seconds swung unstably beyond the simulations ending time set at 30 seconds. However, with IPFC of independent configuration (dual SSSC) the swings are damped steady state operating condition at about 5 second as shown in figure 4.16. It can be observed that after fault clearance, oscillations of rose to a peak of about 0.75p.u. IPFC has been utilized to damp power transients efficiently as shown in figure 4.16.

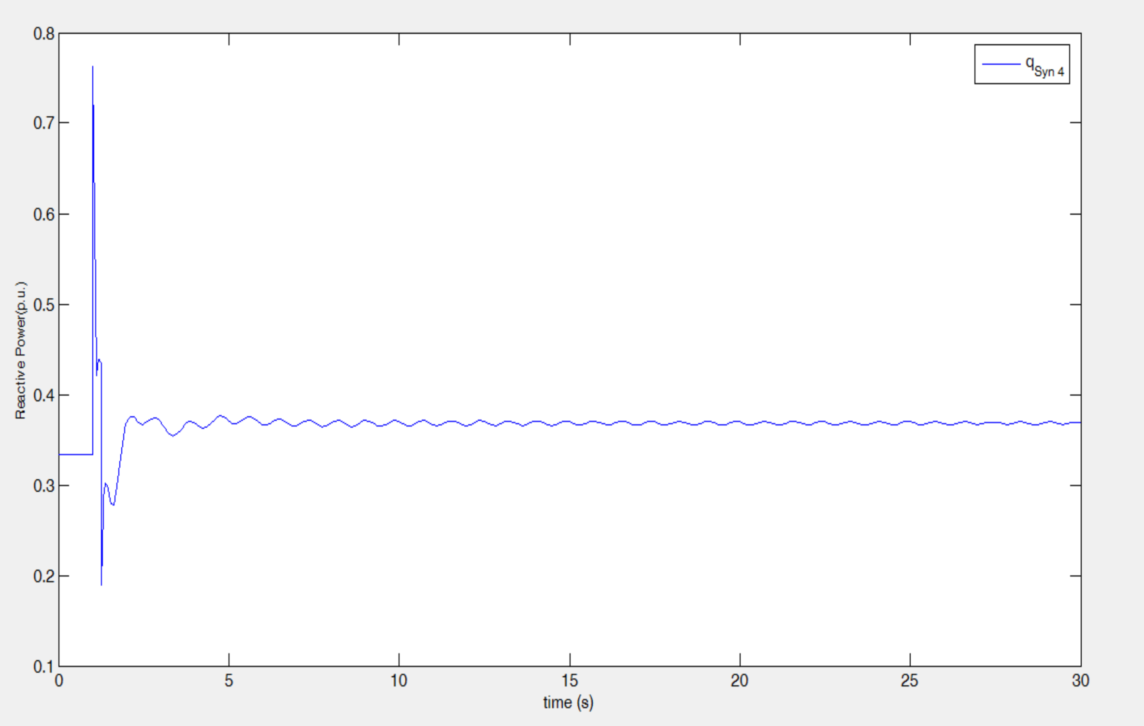

Figure 4.15: Generator 4 reactive power response with fault applied at bus 4

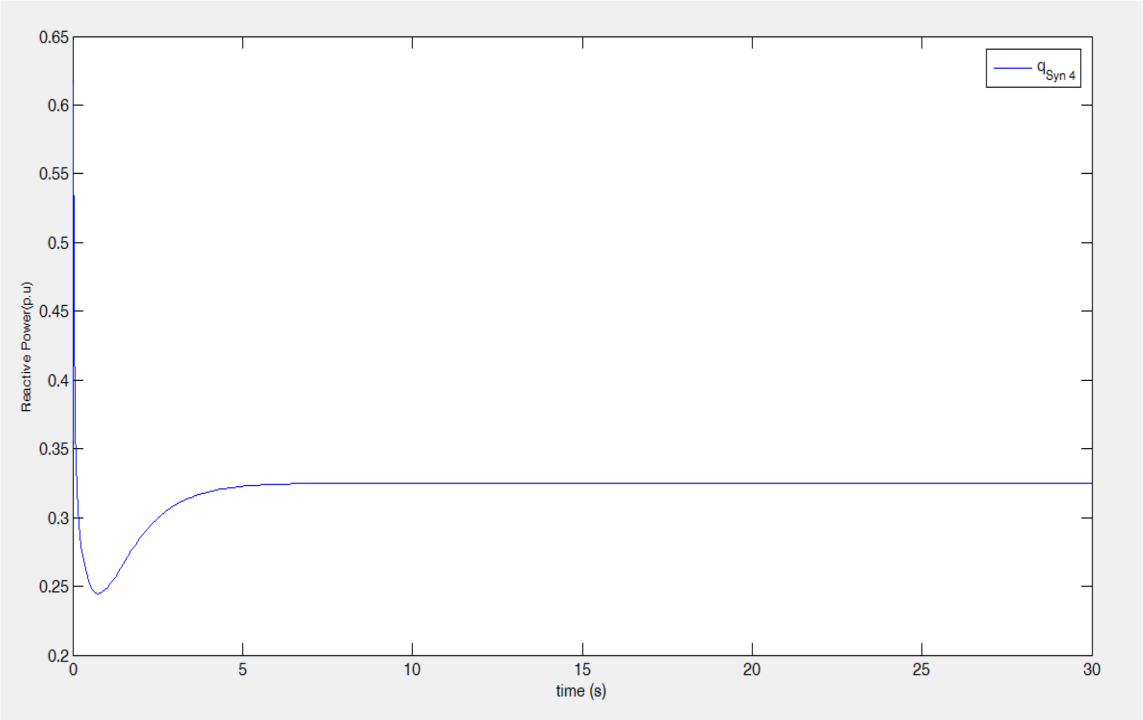

Figure 4.16: Generator 4 reactive power response with fault and IPFC at bus 14

4.4 Analysis for more than one synchronous generator

While considering thee three generators, Time Domain Simulations are carried out to assess the effectiveness of the three FACTS device models developed in this work. Three-phase fault is has been simulated to provide the source of disturbance with fault time occurring at 1.00 second cleared time at 1.25 seconds with and without FACTS.

4.4.1 Generator rotor angle behaviour

Figures 4.17 to 4.20 illustrate the rotor angle behavior for three synchronous generators 2, 4 and 5. They show the simulation results of rotor angle responses. Without using the FACTS devices, the rotor angles keeps accelerating and go out of synchronism as shown in figure 4.17. When the dynamic model with the FACTS is simulated, the responses start decreasing. Generally, for the three generators, the three FACTS decrease the acceleration of the rotor angles. For all of the three cases, the rotor angle of generator 5 decreases the most followed by angle of generator 4 and the least decreasing rotor angle is that of the generator 2. The decrease is as a result of damping characteristics of FACTS devices connected. It is more pronounced with IPFC than SSSC and UPFC.

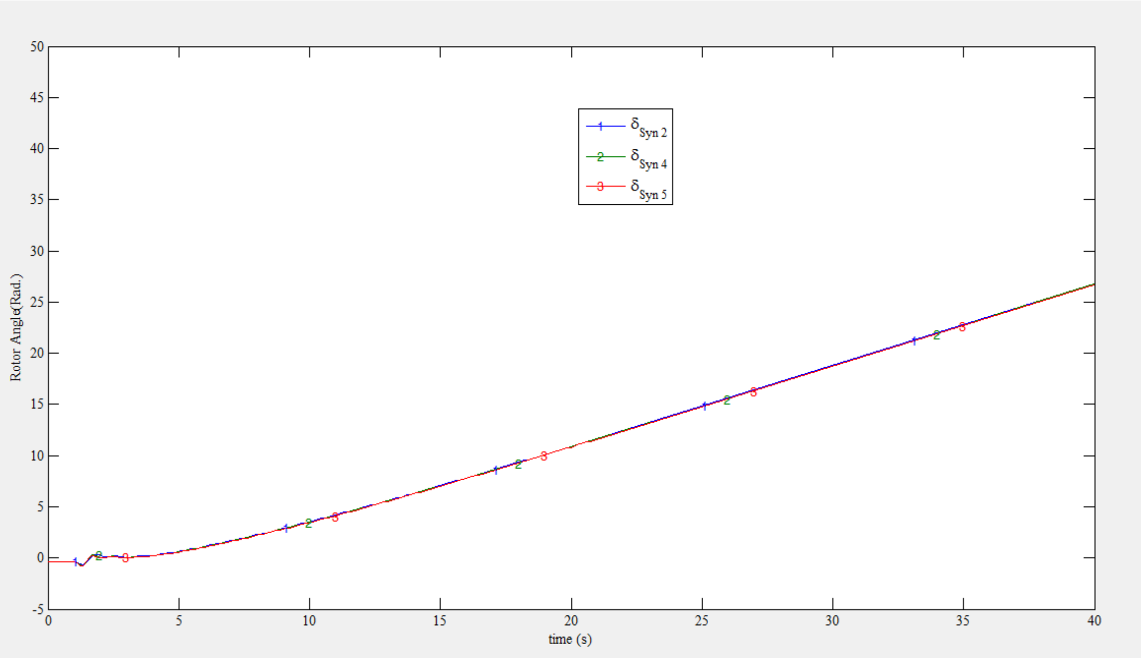

Figure 4.17: Rotor angle responses without FACTS, fault at bus 04

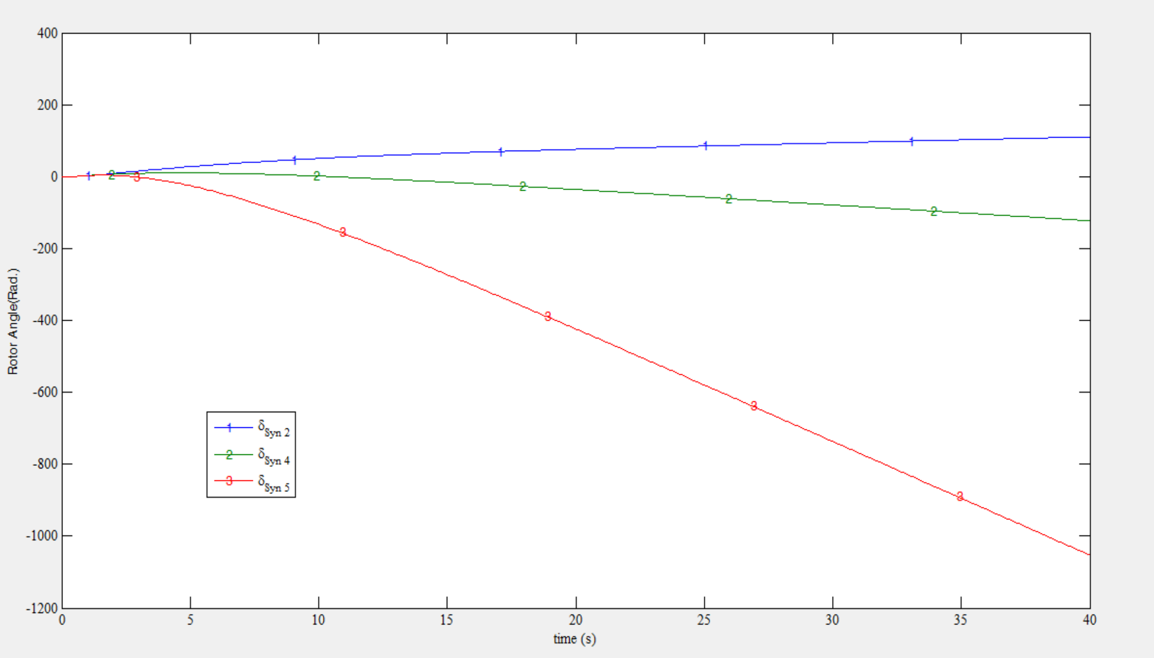

Figure 4.18: Rotor angle responses UPFC FACTS device, fault applied at bus 04

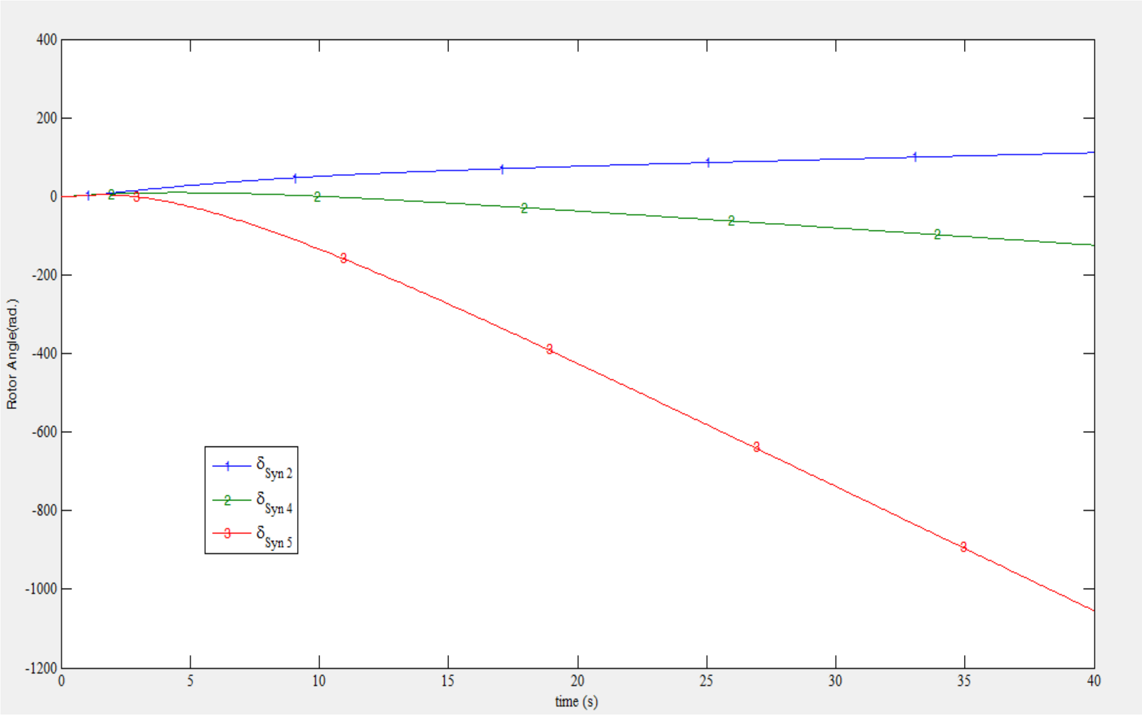

Figure 4.19: Rotor angle responses for SSSC, fault applied at bus 4

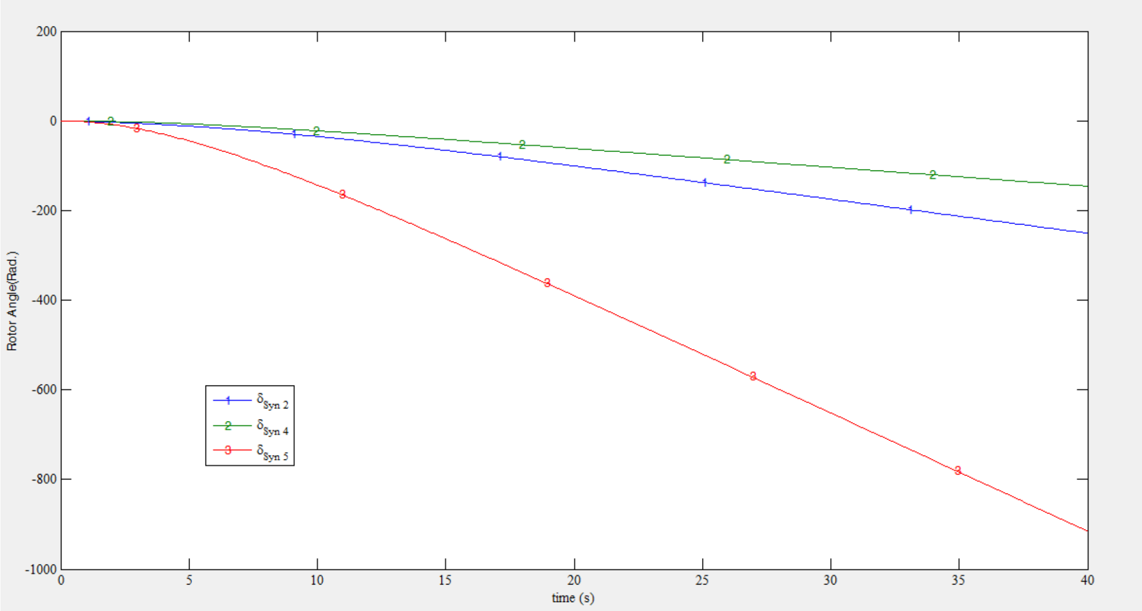

Figure 4.20: Rotor angle responses with IPFC, fault applied at bus 4

4.4.2 Q-axis component of voltage behind transient reactance responses

Responses of quadrature axis component of voltage behind transient reactance for the three synchronous generators with and without FACTS are displayed in figure 4.22 to figure 4.25 below. With FACTS, the post fault oscillations are damped. Overall, for the three generators, without facts the responses oscillate beyond the simulation time. With FACTS, the oscillation is damped as follows, for UPFC and SSSC, generator two and four at about 4 seconds and generator 5 at about 12 seconds. For IPFC devices, the oscillations are damped as follows; generators 2 and 4 at about 4 seconds and generator 5 at about 8 seconds. As observed, IPFC provides overall better damping characteristics.

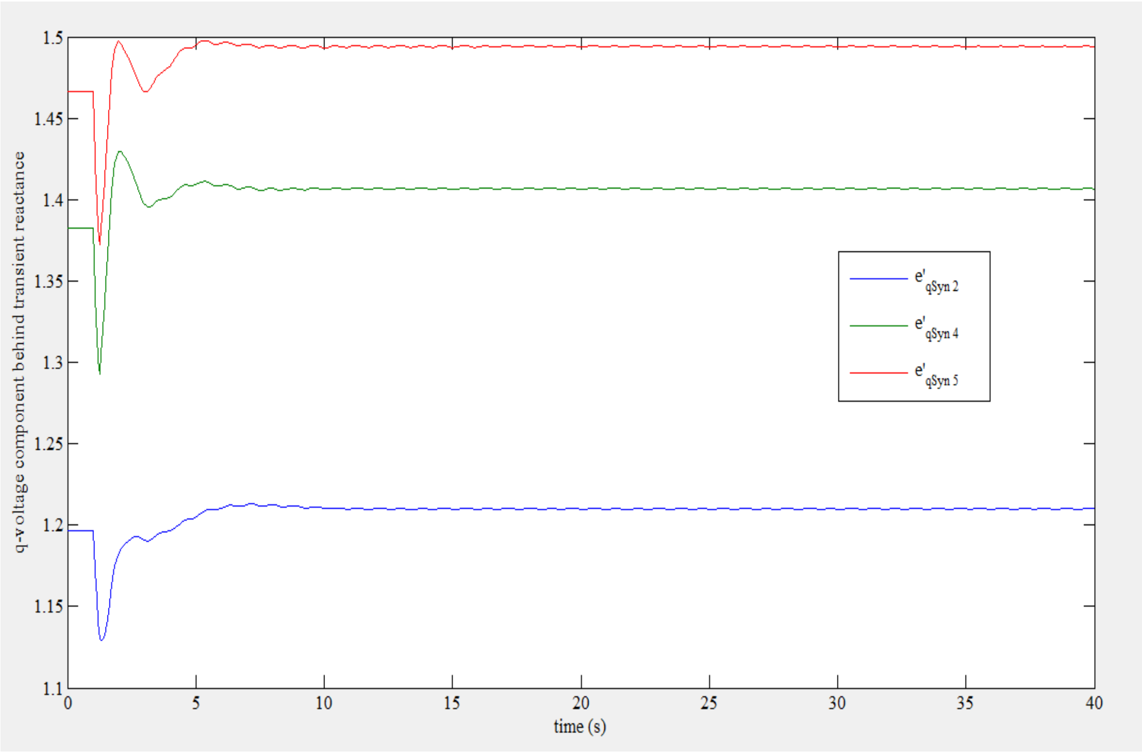

Figure 4.21: q-axis voltage component behind transient reactance responses without FACTS

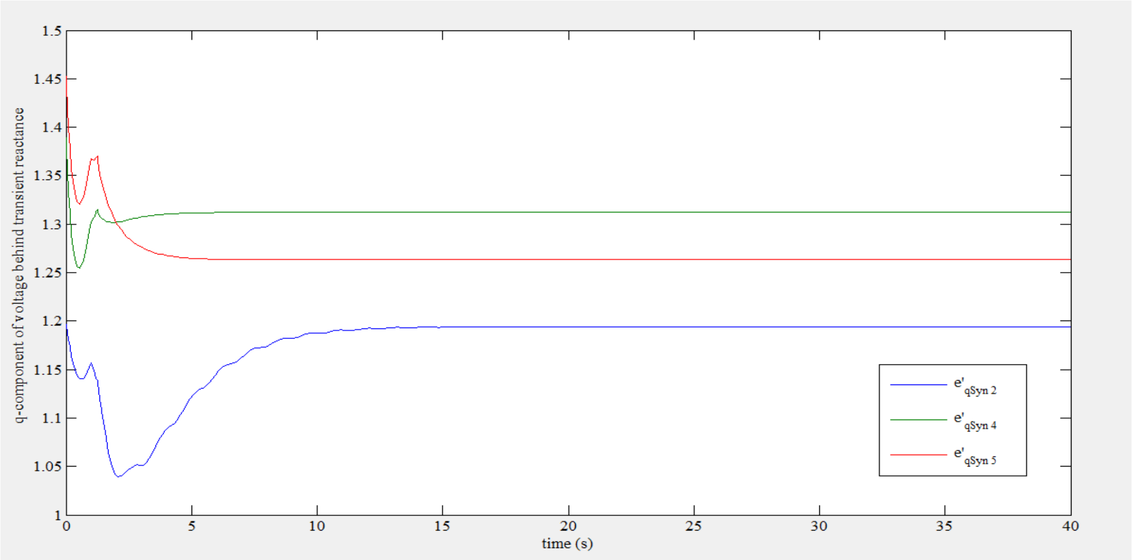

Figure 4.22: q-axis voltage component behind transient reactance responses with UPFC

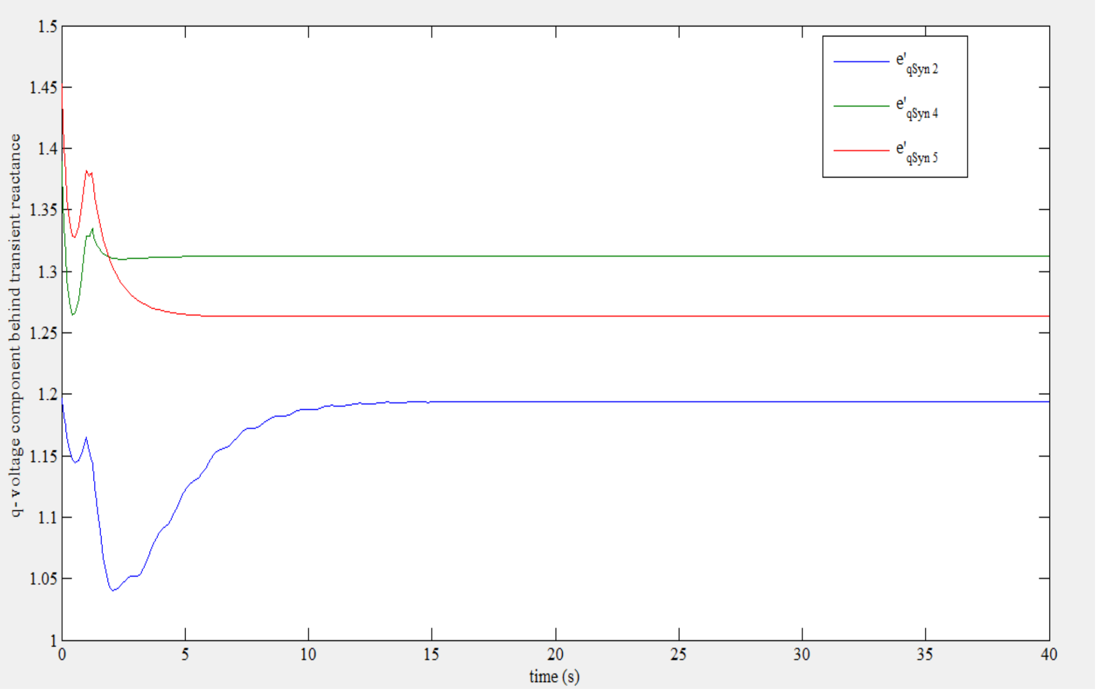

Figure 4.23: q-axis voltage component behind transient reactance responses with SSSC

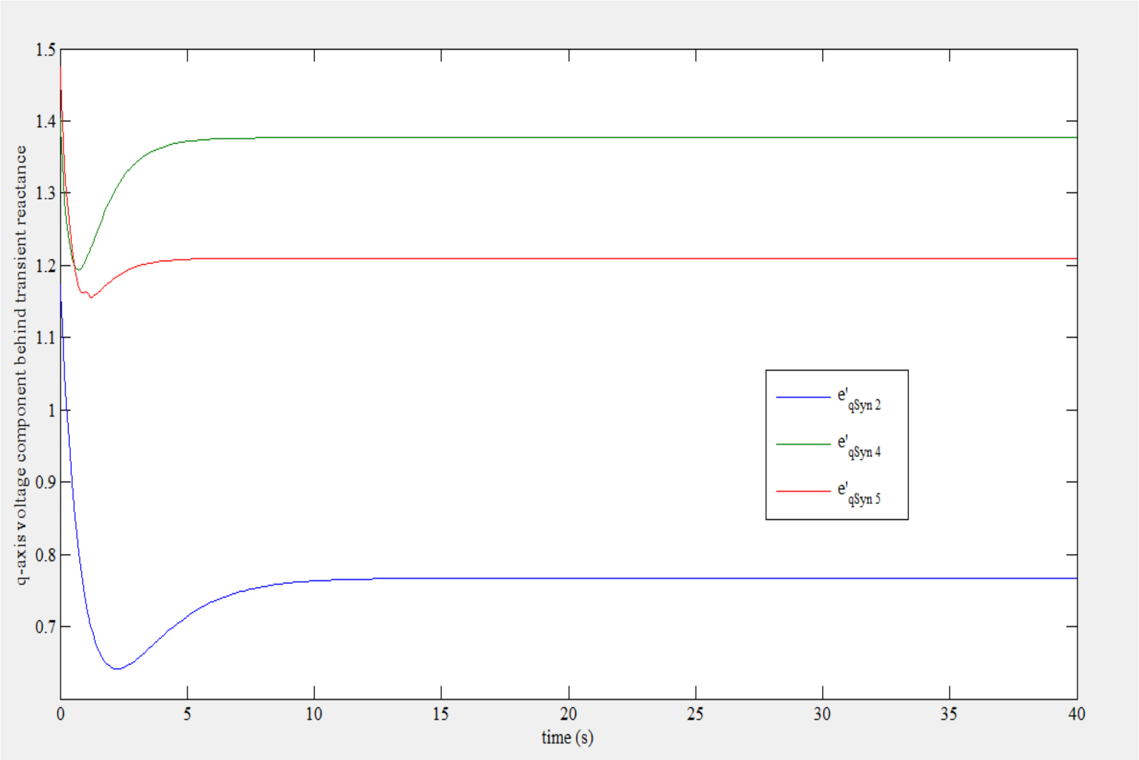

Figure 4.24: q-axis voltage component behind transient reactance responses with IPFC

4.5 Voltage stability and loss reduction with FACTS

FACTS controllers: SSSC, IPFC and UPFC significantly enhance voltage stability. It is evident that IPFC provides better voltage support than UPFC and SSSC as shown in table 4.2 and figure 4.25 below. All the three FACTS reduce power losses in poor networks with SSSC and UPFC by 0.03 p.u and IPFC by 0.14p.u hence IPFC is best suited for loss reduction applications among the three devices.

Table 4.2: Voltage magnitude and real power losses

VOLTAGE MAGNITUDE AND REAL POWER LOSSES FROM PF REPORT					
Bus	Without fault and Device	Fault at Bus 4 Without Device	Fault at Bus 4 With SSSC	Fault at Bus 4 With UFPC	Fault at Bus 4 With IPFC
	[p.u.]	[p.u.]	[p.u.]	[p.u.]	[p.u.]
Bus 4	0.978	0.975	0.992	0.992	0.992
Bus 5	0.987	0.984	0.999	0.999	0.999
Bus 14	0.986	0.983	0.995	0.995	1.005
Real Power Losses		0.294	0.291	0.291	0.280

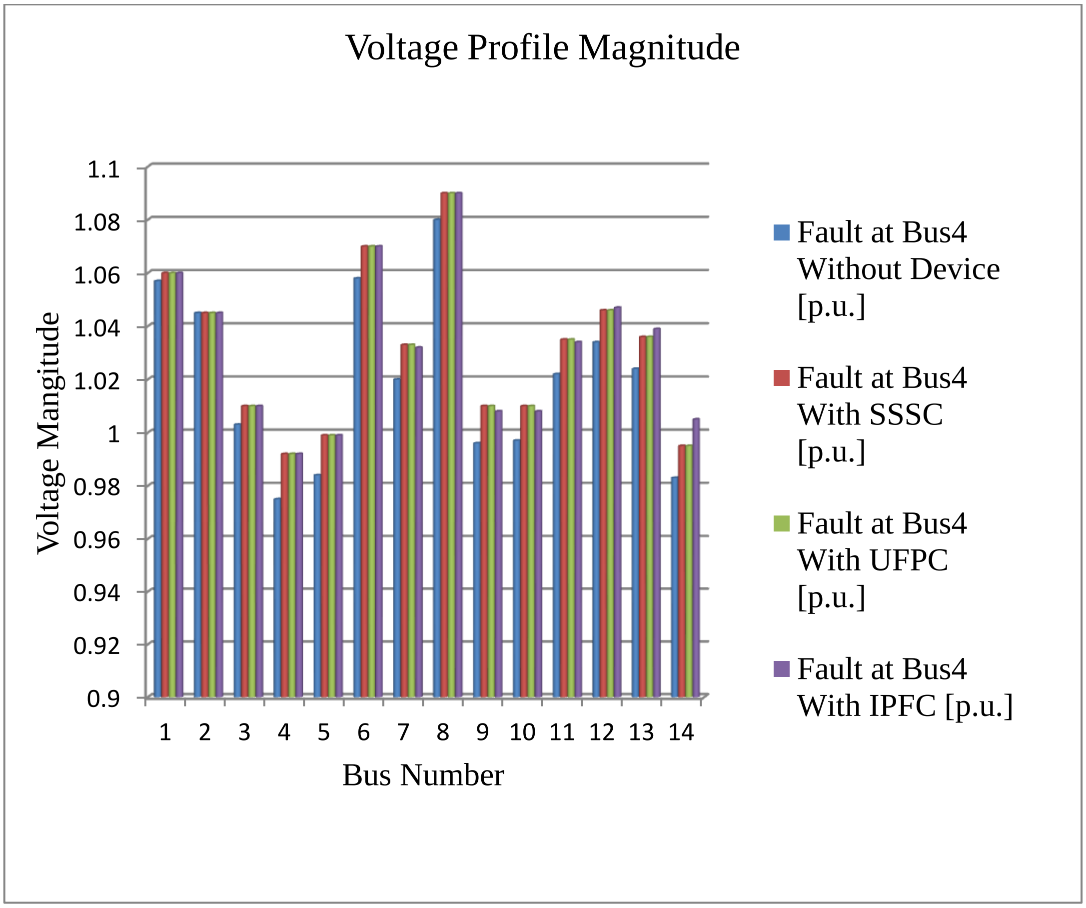

Figure 4.25: Voltage magnitude profiles with and without FACTS controllers

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The best location was determined using bus voltage magnitude profiles. The bus with the least voltage profile or magnitude is best location. The standard IEEE 14 bus test system was used in this work. The suitable location/placement has been effectively implemented through CPF P-V curves. FACTS devices best location in IEEE 14 bus system was found to be bus 14 for placement of the three FACTS controllers (UPFC, SSSC and IPFC). Time domain simulations were performed on dynamic IEEE-14 bus system model. The analysis was done through specific and comparative study with and without the three devices. It was observed that when three phase fault occurs at bus 4 near the generator, synchronous machine oscillations generated do not settle to steady state condition and makes the system unstable for the simulation time under consideration.

Although individual compensations differ, all the three FACTS devices not only damp the system oscillations of the multimachine system but also reduce the oscillations transient periods accordingly. The transient state period of rotor speed responses is longer than those of voltage responses hence FACTS provide better support to system voltages compared to other parameters like rotor angle. To achieve steady state operating condition after disturbances, UPFC and SSSC exhibited similar oscillations damping characteristics for the variables studied. SSSC and UPFC have better damping features for reactive power response, while IPFC provide better damping for generator sub transient voltages, rotor angle and real power oscillations compared than UPFC and SSSC. It’s evident that the damping characteristics of the IPFC are comparatively superior to those of SSSC and IPFC.

It is unequivocal from this work that FACTS controllers play two key roles in power networks. Firstly, FACTS have the merits of power flow control through injection and/or absorption of voltage real and reactive power. Secondly, they enhance transient stability. Thus, FACTS can be used to complement conventional power system stabilizers since they have the extra advantage of damping oscillations after occurrence of a fault. Thus, the simulations studies revealed that oscillations present after occurrence of fault greatly reduces after the best placement of UPFC, SSSC and IPFC. It is deduced that series compensators have superior damping of oscillations' properties compared to shunt ones.

It's further construed that for the three FACTS controllers, IPFC provides comparatively better voltage stability enhancement than UPFC and SSSC. All the three FACTS reduce power losses in poor networks with SSSC and UPFC by 0.03p.u and IPFC by 0.14p.u hence IPFC is best placed for loss reduction applications than the other three FACTS controllers. The results of this analysis confirm the consistency of application and versatility of FACTS in transient stability using other methods outlined in the literature review and goes further to bring out the comparative advantages of the three FACTS (SSSC, UPFC and IPFC) using PSAT TDS module.

5.2 Recommendations

The work developed throughout this thesis is a contribution to power system stability research in the foreseeable future aiming at expanding research studies in the dynamic analysis of power systems with FACTS devices. Suggestions are hereby presented to develop new work undertakings taking this work as a starting point. The future work should include introduction of the of renewable energy technologies generator models like wind and solar for transient stability with these devices. The use of integrated IPFC model and contrast its performance of the independent model used in this work is also proposed. This is also feasible and foreseeable.

PSAT technique and other power system simulation softwares like DigSilent Power Factory and ETAP (Electrical Transient Analyzer Program), EuroStag and PSS/E need to be compared for effectiveness of modeling power systems with these controllers for the benefit of design, planning, and implementation of FACTS devices compensation regimes. The comparative performance of integrated and independent models of IPFC needs to be explored. Another task which is opined for the future is superiority of series compensators to the shunt ones.

The economic analysis for application of the three FACTS controllers are also recommended for impending future work.

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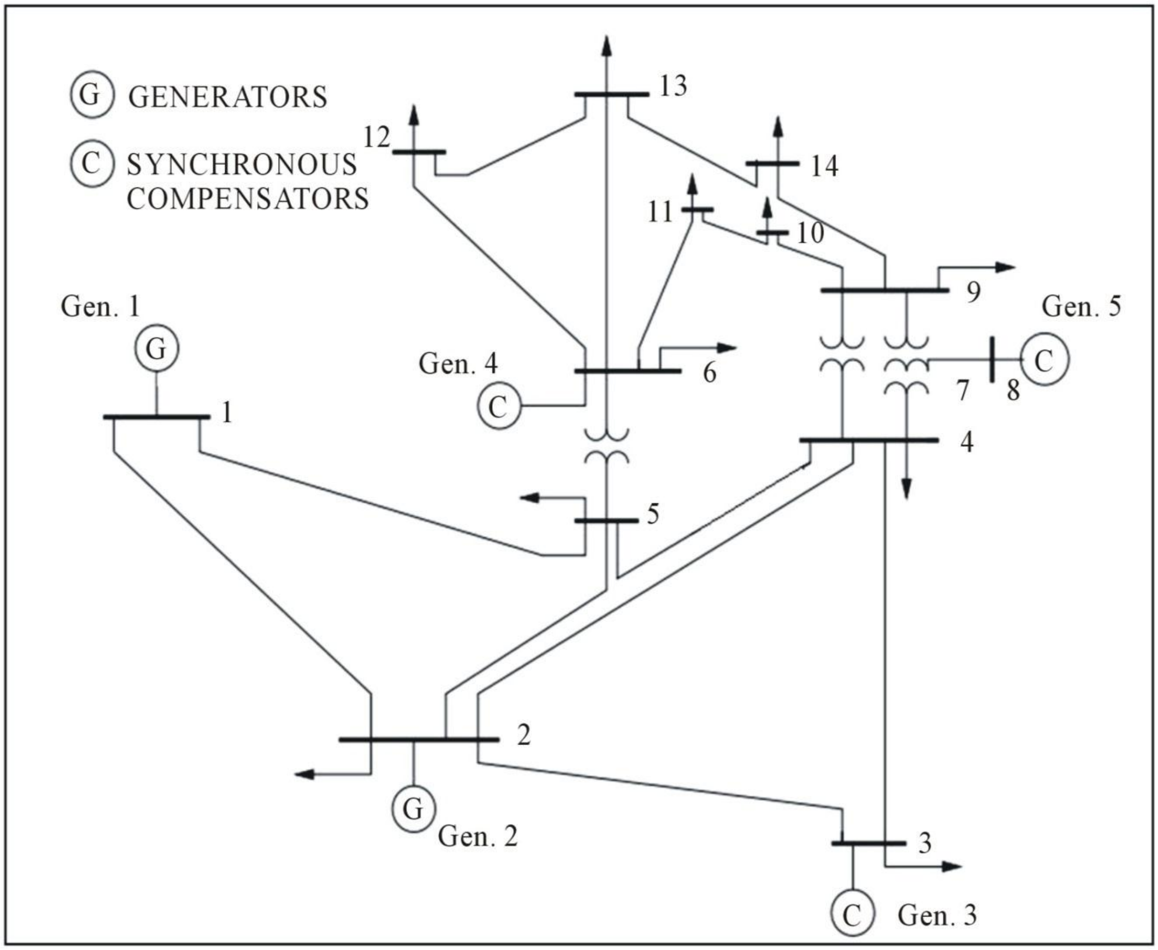
APPENDICES

Appendix 1: Single line diagram of static IEEE 14-bus system



Appendix 2: Bus data of IEEE 14-bus system

Bus No	Vm	PG	PL	QL	PGmin	PGmax	QGmin	QGmax
1	1.06	0	0	0	0.5	2	-0.45	1
2	1.045	0.4	0.217	0.127	0.2	1	-0.4	0.5
3	1.07	0.1	0.112	0.075	0.2	1	-0.06	0.24
4	1.01	0	0.942	0.19	0	0	0	0.4
5	1.09	0	0	0	0	0	-0.06	0.24
6	1	0	0	0	0	0	0	0
7	1	0	0.295	0.166	0	0	0	0
8	1	0	0.076	0.016	0	0	0	0
9	1	0	0.478	-0.039	0	0	0	0
10	1	0	0.09	0.058	0	0	0	0
11	1	0	0.035	0.018	0	0	0	0
12	1	0	0.061	0.016	0	0	0	0
14	1	0	0.149	0.05	0	0	0	0

Appendix 3: Line data of IEEE 14-bus system

Line No	From	To	R	X	B_{sh}	Tap (full charging)
1	8	3	0	0.25202	0	0.962
2	9	6	0	0.20912	0	0.978
3	9	7	0	0.55618	0	0.969
4	1	8	0.05403	0.22304	0.0492	1
5	2	8	0.05695	0.17388	0.034	1
6	4	9	0.06701	0.17103	0.0346	1
7	9	8	0.01335	0.04211	0.0128	1
8	1	2	0.01938	0.05917	0.0528	1
9	2	4	0.04699	0.19797	0.0438	1
10	6	5	0	0.17615	0	1
11	2	9	0.05811	0.17632	0.0374	1
12	6	7	0	0.11001	0	1
13	7	10	0.03181	0.0845	0	1
14	3	11	0.09498	0.1989	0	1
15	3	12	0.12291	0.25581	0	1
16	3	13	0.06615	0.13027	0	1
17	7	14	0.12711	0.27038	0	1
18	10	11	0.08205	0.19207	0	1
19	12	13	0.22092	0.19988	0	1
20	13	14	0.17093	0.34802	0	1

Appendix 4: IEEE 14 bus generator data

GENERATOR	G1	G2	G3	G4	G5
Power (MVA)	615	60	60	25	25
Voltage(kV)	69	69	69	18	13.8
Frequency (Hz)	60	60	60	60	60
Resistance,(r_a)	0.00	0.0031	0.0031	0.0014	0.0014
Leakage (x_l)	0.2396	0.00	0.00	0.134	0.134
d-axis reactances(X_d)	0.8979	1.05	1.05	1.25	1.25
d-axis reactances (X'_d)	0.6	0.1850	0.1850	0.232	0.232
d-axis reactances (X''_d)	0.23	0.13	0.13	0.12	0.12
d-axis constants(T'_{d0})	7.4	6.1	6.1	4.75	4.75
d-axis constants(T''_{d0})	0.03	0.04	0.04	0.06	0.06
q-axis reactances (X_q)	0.646	0.98	0.98	1.22	1.22
q-axis reactances (X'_q)	0.646	.036	0.36	0.75	0.75
q-axis reactances (X''_q)	0.4	0.13	0.13	0.12	0.12
q-axis constants(T'_{q0})	0.00	0.3	0.3	1.5	1.5
q-axis constants(T''_{q0})	0.033	0.099	0.099	0.21	0.21
Inertia(M = 2H)	2*5.148	2*6.54	2*6.54	2*5.06	2*5.06
Damping(s)	2.00	2.00	2.00	2.00	2.00
Speed(K_w)	0.00	0.00	0.00	0.00	0.00
Power signals(K_p)	0.00	0.00	0.00	0.00	0.00
Percentage of active(p.u)	1.00	1.00	1.00	1.00	1.00
Reactive powers(p.u)	1.00	1.00	1.00	1.00	1.00
d-axis additional circuit leakage time constant(T_{aa})	0.00	0.00	0.00	0.00	0.00
Saturation coefficients(s)	0	0	0	0	0
Saturation coefficients(s)	0	0	0	0	0
Number of input signals	1	1	1	1	1

Appendix 5: IEEE 14 bus system AVR data

AVR	AVR 1	AVR 2	AVR 3	AVR 4	AVR 5
Automatic Voltage Regulator Type	2	2	2	2	2
Max. Regulator Voltage(p.u)	4.38	4.38	6.81	6.81	7.32
Min. Regulator Voltage(p.u)	0	0	1.395	1395	0
Amplifier Gain(k_a)	20	20	20	20	200
Amplifier Time Constant (T_a)	0.02	0.02	0.02	0.02	0.02
Stabilizer Gain(K_f)	0.001	0.001	0.001	0.001	0.002
Stabilizer Time(T_f)	1.0	1.0	1.0	1.0	1.0
Integral deviation(K_e)	1	1	1	1	1
Time Constant of the Field Circuit(T_d)	1.98	1.98	0.7	0.7	0.2
Time Delay of the Measurement System(T_r)	0.001	0.001	0.001	0.001	0.001
Coefficient of the Ceiling Function (A B)	0.0006 0.9	0.0006 0.9	0.0006 0.9	0.0006 0.9	0.0006 0.9

Appendix 6: IEEE 14 bus compensator data

COMPENSATOR	COMPENSATOR 1	COMPENSATOR 2	COMPENSATOR 3
Power(MVA)	100	100	100
Voltage(kV)	69	18	13.8
Voltage magnitude(p.u)	1.01	1.09	1.07
Qmax(p.u)	0.4	0.24	0.24
Qmin(p.u)	0.0	-0.06	-0.06
Vmax(p.u)	1.2	1.2	1.2
Vmin(p.u)	0.8	0.8	0.8
Loss Participation Coefficients	1	1	1

Appendix 7: UPFC data

Power(MVA)	100
Voltage(kV)	230
Frequency Ratings(H_z)	60
Percentage of Series Compensation(Cp)	25
Gain(K_r)	50
Time constant(T_r)	0.1
Max (V_p)	1.15
Min(V_p)	0.85
Max(V_q)	1.15
Min(V_q)	0.85
Max(I_q)	1.1
Min(I_q)	0.9

Appendix 8: SSSC data

Power(MVA)	100
Voltage(kV)	230
Frequency Ratings(H_z)	60
Percentage of Series Compensation(C_p)	25
Regulator time constant(T_r)	0.1
Max. Voltage(p.u)	1.15
Min. Voltage(p.u)	0.85
Proportional Gains(K_p)	10
Integral gains(K_i)	50

Appendix 9: Equations for Modeling Synchronous machine

The dynamics of the stator winding, field winding, and damper windings are included in the model. All stator and rotor quantities are expressed in the two-axis reference frame (two-axis *d–q* frame). All rotor parameters and electrical quantities are referred to stator and are represented by primed variables.

The mathematical equations are given by

$V_d = R_S i_d + \frac{d}{dt}\varphi_d - \omega_R \varphi_q$ V_d=RSid+ddtφd-ωRφq (1)

$V_q = R_S i_q + \frac{d}{dt}\varphi_q + \omega_R \varphi_d$ Vq=RSiq+ddtφq+ωRφd (2)

$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt}\varphi'_{fd}$ Vfd′=Rfd′ifd′+ddtφfd′ (3)

$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt}\varphi'_{kd}$ Vkd′=Rkd′ikd′+ddtφkd′ (4)

$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d}{dt}\varphi'_{kq1}$ Vkq1′=Rkq1′ikq1′+ddtφkq (5)

$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d}{dt}\varphi'_{kq2}$ Vkq2′=Rkq2′ikq2′+ddtφkq (6)

Where $\varphi_d = L_d i_d + L_{md}(i'_{fd} + i'_{kd})$ φd=Ldid+Lmd (ifd′+ikd′), $\varphi_q = L_q i_q + L_{mq} + i'_{kq}$ φq=Lqiq+Lmq+ikq′, $\varphi'_{fd} = L'_{fd} i'_{fd} + L_{md}(i_d + i'_{kd})$ φfd′=Lfd′ifd′+Lmd (id+ikd′),

$\varphi'_{kd} = L'_{kd} i'_{kd} + L_{md}(i_d + i'_{fd})$φkd′=Lkd′ikd′+Lmd (id+ifd′), $\varphi'_{kq1} = L'_{kq1} i'_{kq1} + L_{mq} i_q$ φkq1′=Lkq1′ikq1′+Lmqiq, $\varphi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q$φkq2′=Lkq2′ikq2′+Lmqiq.

In the above equations, the subscripts

d and *q* represent *d*-axis and *q*-axis quantities.

R and *S* represent rotor and stator quantities.

f and *k* represent field and damper windings.

l and *m* represent leakage and magnetizing inductances.

The mechanical equations are given by

$$\frac{d}{dt}\omega_r = \frac{1}{J}(P_e - F_r\omega_r - P_m) \qquad (7)$$

ddtωr=1J(Pe-Frωr-Pm)

$$\frac{d}{dt}\theta = \omega_r \qquad (8)$$

ddtθ=ω

Where ω_r and θ are the angular velocity and angular position of the rotor respectively, P_e and P_m represent electrical and mechanical power respectively, and J and F_r represent inertia and friction of rotor respectively.

Appendix 10: Power flow Equations of FACTS devices

The power flow equations with FACTS is given by,

$$P_{ij} = V_i^2 b_{ij} - V_i V_j \left(g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij} \right) - V_i V_{se} \left(g_{ij} \sin\left(\theta_i - \theta_{se}\right) - b_{ij} \cos\left(\theta_i - \theta_{se}\right) \right) \quad (1)$$

$$Q_{ij} = V_i^2 b_{ij} - V_i V_j \left(g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij} \right) - V_i V_{se} \left(g_{ij} \sin\left(\theta_i - \theta_{se}\right) - b_{ij} \cos\left(\theta_i - \theta_{se}\right) \right) \quad (2)$$

Appendix 11: Time domain report in PSAT

POWER FLOW RESULTS						
Bus	V	phase	P gen	Q gen	P load	Q load
	[p.u.]	[rad]	[p.u.]	[p.u.]	[p.u.]	[p.u.]
Bus 01	1.05803	27.16298	3.520304	-0.28197	0	0
Bus 02	1.045723	27.03928	0.4	0.948602	0.3038	0.1778
Bus 03	1.003696	26.79922	8.88E-16	0.59736	1.3188	0.266
Bus 04	0.975418	26.83136	1.23E-14	1.62E-15	0.6692	0.056
Bus 05	0.984594	26.89136	-4.4E-15	2.29E-14	0.1064	0.0224
Bus 06	1.058936	26.73961	3.86E-15	0.444329	0.1568	0.105
Bus 07	1.020443	26.75938	1.84E-15	5.21E-15	0	0
Bus 08	1.080607	26.7588	-1.1E-16	0.334022	0	0
Bus 09	0.99707	26.72193	-8.2E-15	-8.9E-16	0.413	0.2324
Bus 10	0.997244	26.71808	1.53E-15	-5.7E-16	0.126	0.0812
Bus 11	1.022553	26.72609	7.49E-16	-1.2E-15	0.049	0.0252

Bus 12	1.03503	26.718	1.11E-15	9.75E-16	0.0854	0.0224
Bus 13	1.02504	26.71665	6.94E-16	-4.7E-16	0.189	0.0812
Bus 14	0.983328	26.6936	6.66E-16	-4.6E-16	0.2086	0.07
STATE VARIABLES						
delta_Syn_1			27.48554			
omega_Syn_1			1.002577			
e1q_Syn_1			1.087798			
e2q_Syn_1			1.035646			
e2d_Syn_1			0.127655			
delta_Syn_2			26.79565			
omega_Syn_2			1.002431			
e1q_Syn_2			1.209946			
e1d_Syn_2			0.000506			
e2q_Syn_2			1.145613			
e2d_Syn_2			0.000727			
delta_Syn_3			27.28045			
omega_Syn_3			1.002492			

e1q_Syn_3		1.314976			
e1d_Syn_3		0.142449			
e2q_Syn_3		1.221713			
e2d_Syn_3		0.221598			
delta_Syn_4		26.75479			
omega_Syn_4		1.002473			
e1q_Syn_4		1.406525			
e1d_Syn_4		-0.00046			
e2q_Syn_4		1.244536			
e2d_Syn_4		-0.00145			
delta_Syn_5		26.73549			
omega_Syn_5		1.002499			
e1q_Syn_5		1.493844			
e1d_Syn_5		-0.00018			
e2q_Syn_5		1.277668			
e2d_Syn_5		-0.00104			
vm_Exc_1		1.058022			
vr1_Exc_1		1.475705			

vr2_Exc_1			-0.00224			
vf_Exc_1			1.297724			
vm_Exc_2			1.045721			
vr1_Exc_2			2.722767			
vr2_Exc_2			-0.00267			
vf_Exc_2			2.670958			
vm_Exc_3			1.003697			
vr1_Exc_3			2.177744			
vr2_Exc_3			-0.00214			
vf_Exc_3			2.143683			
vm_Exc_4			1.080607			
vr1_Exc_4			2.825933			
vr2_Exc_4			-0.00278			
vf_Exc_4			2.783478			
vm_Exc_5			1.058936			
vr1_Exc_5			3.398965			
vr2_Exc_5			-0.00333			
vf_Exc_5			3.332129			

OTHER ALGEBRAIC VARIABLES						
vf_Syn_1			1.297724			
pm_Syn_1			3.520304			
p_Syn_1			3.493545			
q_Syn_1			-0.20772			
vf_Syn_2			2.143683			
pm_Syn_2			0.001807			
p_Syn_2			-0.00667			
q_Syn_2			0.657535			
vf_Syn_3			2.670958			
pm_Syn_3			0.405014			
p_Syn_3			0.391799			
q_Syn_3			0.92485			
vf_Syn_4			2.783478			
pm_Syn_4			0.000526			
p_Syn_4			-0.00366			
q_Syn_4			0.369081			
vf_Syn_5			3.332129			

pm_Syn_5		0.000966			
p_Syn_5		-0.00367			
q_Syn_5		0.482578			
vref_Exc_1		1.065623			
vref_Exc_2		1.181848			
vref_Exc_3		1.112638			
vref_Exc_4		1.221944			
vref_Exc_5		1.228917			