JULY 2018

M.Sc. in Electrical and Electronics Engineering

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**UNIVERSITY OF GAZIANTEP**

**GRADUATE SCHOOL OF**

**NATURAL & APPLIED SCIENCES**

# COMPARISON OF DYNAMIC PERFORMANCES OF TCSC, SSSC AND STATCOM ON INTER-AREA OSCILLATION DAMPING

**M. Sc. THESIS**

**IN**

**ELECTRICAL AND ELECTRONICS ENGINEERING**

**BY**

**SAIF TAHER FADHIL**

**JULY 2018**

**Comparison of Dynamic Performances of**

**TCSC, SSSC and STATCOM on Inter-Area**

**Oscillation Damping**

**M.Sc. Thesis**

**in**

**Electrical and Electronics Engineering**

**University of Gaziantep**

**Supervisor**

**Assoc. Prof. Dr. Ahmet Mete VURAL**

**by**

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**July 2018**

**REPUBLIC OF TURKEY**
**UNIVERSITY OF GAZIANTEP**
**GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES**
**ELECTRICAL AND ELECTRONICS ENGINEERING**

Name of the thesis : Comparison of Dynamic Performances Of TCSC, SSSC and STATCOM On Inter-Area Oscillation Damping.

Exam Date : July 27, 2018

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This is to certify that we have read this thesis and that in our consensus opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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**Saif FADHIL**

# ABSTRACT

## COMPARISON OF DYNAMIC PERFORMANCES OF TCSC, SSSC AND STATCOM ON INTER-AREA OSCILLATIONS

**FADHIL, Saif Taher**
**M.Sc. in Electrical and Electronics Engineering**
**Supervisor: Assoc. Prof. Dr. Ahmet Mete VURAL**
**July 2018**
**55 pages**

In power systems, the effective control of the power flows on transmission lines is very important. This control capability aids to transfer the power in full capacity and reduces power losses to minimum values. There is a necessity of studying the problems that effect on power system stability for ensuring optimum operation conditions. One of these problems is the oscillations of low frequency. Inter-area oscillations are one type of these low frequency oscillations which are critical and should be detected and damped efficiently before not to cause a blackout in the power systems. With this respect, it is of great importance to deal with inter-area oscillations so that power quality of the power systems is continuously supplied by the power system operators. The objective of this thesis is to investigate the inter-area oscillations and damp these oscillations effectively. In this thesis, three different “Flexible Alternating Current Transmission (FACTS) devices” are used to damp inter-area oscillations in an example power system which is called “Kundur System”. Kundur System has two separate generation areas which is very suitable to research about inter-area oscillations. These FACTS devices are Thyristor-Controlled Series Compensator (TCSC), Static Synchronous Series Compensator (SSSC), and Static Synchronous Compensator (STATCOM). Aforementioned FACTS devices are allocated to a selected bus/transmission line of Kundur System in simulation environment and their capabilities on inter-area oscillation damping are observed and compared to each other. The simulation results are presented and the conclusions are given at the end of the work.



**Keywords**: FACTS, TCSC, STATCOM, SSSC, Inter-area oscillations, Kundur.

# ÖZET

**BÖLGELER-ARASI SALINIMLARIN SÖNÜMLENDİRİLMESİNDE TCSC, SSSC VE STATCOM DİNAMİK PERFORMANSLARININ KARŞILAŞTIRILMASI**

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**Tez Yöneticisi : Doç. Dr. Ahmet Mete VURAL**
**Temmuz 2018**
**55 sayfa**

Güç sistemlerinde, iletim hatları üzerindeki güç akışlarının efektif denetimleri oldukça önemlidir. Bu kontrol yeteneği gücü tam kapasitede transfer etmeye yardımcı olur ve güç kayıplarını minimum değerlere indirir. Optimum işletim şartlarının sağlanması için güç sistemi kararlılığını etkileyen problemlerin çalışılması gerekmektedir. Bu problemlerin bir tanesi düşük frekanslı salınımlardır. Bölgeler-arası salınımlar bu tip düşük frekanslı salınımların bir türü olup, kritiklerdir ve güç sistemlerinde bir elektrik kesintisine yol açmadan önce verimli bir şekilde tespit edilmeli ve sönümlendirilmelidirler. Bu bağlamda, bölgeler-arası salınımlarla uğraşmak güç sistemlerinin güç kalitesinin güç sistemi operatörleri tarafından sürekli sağlanması bakımından önem arz etmektedir. Bu tezin amacı bölgeler-arası salınımları araştırmak ve bu salınımları etkin bir şekilde sönümlendirmektir. Bu tezde, üç farklı "Esnek Alternatif Akım İletim (FACTS) cihazı" "Kundur Sistemi" olarak adlandırılan örnek bir güç sistemindeki bölgeler-arası salınımları sönümlendirmek için kullanılmıştır. Kundur Sistemi bölgeler-arası salınımlar hakkında araştırma yapmaya son derece uygun iki ayrı üretim bölgesine sahiptir. Bu FACTS cihazları, Tristör-Denetimli Seri Kompanzatör (TCSC), Statik Senkron Seri Kompanzatör (SSSC) ve Static Senkron Kompanzatör (STATCOM)' dür. Adı geçen FACTS cihazları benzetim ortamında Kundur Sistemi'nin seçilmiş bir bara/iletim hattına yerleştirilmiş ve bölgeler-arası salınımları sönümlendirmedeki yetenekleri gözlemlenmiş ve birbirleriyle karşılaştırılmıştır. Benzetim sonuçları sunulmuş ve sonuçlar çalışmanın sonunda verilmiştir.



**Anahtar Kelimeler**: FACTS, TCSC, STATCOM, SSSC, Bölgeler-Arası, Kundur.

This thesis is dedicated to my family (father, mother, brothers, sisters) for their endless love, encouragement and support.

**ACKNOWLEDGEMENT**

In the name of Allah, the Most Gracious, the most Merciful.

Foremost, I would like to express my sincere gratitude to my advisor Assoc. Prof. Dr. Ahmet Mete VURAL for the continuous support of my Msc. study, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time and writing of this thesis.

I would like to express my gratitude to the staff individuals from the Electrical and Electronics Department Engineering at the University of Gaziantep and my gratitude to every single other companion for their helping me in setting up this exploration.

At last but not least, I would like to express my deepest gratitude and thanks to my family and friends especially my parents for their patience and continued support and their advice to me at all stages of my studies and life.

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## LIST OF SYMBOLS

| | |
|---|---|
| FACTS | Flexible Alternating Current Transmission System |
| LFO | Low Frequency Oscillation |
| PSS | Power System Stabilizer |
| DC | Direct Current |
| AC | Alternative Current |
| IGBT | Insulated Gate Bipolar Transistor |
| GTO | Gate Turn-Off Thyristor |
| VSC | Voltage-Source Converter |
| PWM | Pulse Width Modulation |
| Vdc | DC Link Voltage |
| P | Active Power |
| Q | Reactive Power |
| V | Voltage |
| I | Current |
| f | Frequency |
| TCSC | Thyristor Controlled Series Capacitor |
| STATCOM | Static Synchronous Compensator |
| SSSC | Static Synchronous Series Compensator |
| SDC | Supplementary Damping Controllers |
| LMI | Linear Matrix Inequalities |
| D-Q | Direct-Quadrature axis |
| SVC | Static Var Compensator |

| | |
|---|---|
| SMIB | Single Machine Infinite Bus |
| MMIB | Multi Machine Infinite Bus |
| POD | Power Oscillation Damping |
| TCPS | Thyristor Controlled Phase Shifting Transformer |
| DPFC | Dynamic Power Flow Controller |
| IPFC | Interline Power Flow Controller |
| UPFC | Unified Power Flow Controller |
| TSC | Thyristor Switched Capacitor |
| TCR | Thyristor Controlled Reactor |
| $V_s$ | Sending Voltage |
| $V_r$ | Receiving Voltage |
| XL | Transmission Line Reactance |
| XTCSC | TCSC Reactance |
| $\delta$ | Phase Angle |
| PCC | Point of Common Coupling |
| XL | Inductive Reactance |
| PI | Proportional Integral |
| PLL | Phase Looked Loop |
| $\boldsymbol{\sigma}$ | Damping Factor |

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Due to evolution on various sides of life, additional energy is required from power stations to meet the mounting demands of power to exploit it in various fields. The mounting demand reveals an urgent requirement to construct either new power stations or improving the existing transmission networks to reduce losses and enhance system operation. The existing power system contains thousands of bus bars, involving generating units, numerous transmission lines and loads. There are many difficulties facing the idea of establishing new power stations and lines, including of economic and environmental limits. Furthermore, the existing power system does not follow by a sufficient development of the infrastructures that make the power system susceptible and more vulnerable to widespread faults and failures. Thence, the complexity of these systems is increasing in an unsafe way leads to a minimum security. Operating conditions, traditional planning also operating modes which might pose threats to the stability of the system [1].

The stability of power system can be described as a system's capability in a specific initial operating status to retrieve a status of equilibrium operational in the wake of subjecting it to these conditions to dynamical trouble. Because most variables of the system still steady, therefore the whole systems stay intact practically [2].

On the other hand, the instability problems are latent because of the oscillations of low frequency. The value of these oscillations is small but stay for long duration. Occasionally, they keep on rising to lead to adversely impact and constraints the abilities of power transferring [3].

This phenomenon posed a menace in the designing/operating of interconnected power grids that are the oscillations of low frequencies. The dynamical interactions among a set of generators that creates these oscillations. There are two types of low-frequency oscillations.

Local area oscillations that observed when swinging one generator versus the entire remaining system. It has frequencies that are ranging (0.7-2.0) Hz. The other type is known as Inter-area. This term refers to the oscillations that can be observed when a set of generators oscillating with another group or plant. This usually results in fluctuations between two groups of generators separated through mileage. It can also occur when long transmission lines interconnect two remote generation sites. The frequencies of these oscillations are between (0.1-0.8) Hz [4]. This type of oscillation adversely influences the amount of power transferred on the lines between the regions of the interconnected groups of generators that cause damage to the reliability and stability of the power system.

However, power system stabilizer PSS have been effective in providing damping for low-frequency oscillations in power systems. Yet, it suffers a drawback of being liable for the variation of voltage profile that may have an effect in leading power factor. In addition, it may not be able to suppress oscillations resulting from rigorous disturbances, particularly those three-phase faults that may happen at the generator terminals and inter-area oscillations [5].

The system's operation when an inter-area mode is existing is difficult. Therefore, it is necessary to put out these injurious oscillations effectively. Generally, PSS is successful to damp out local oscillations effectively due to using of local signal measurement to produce control action because PSS have the limit of capability for damping oscillations. Furthermore, PSS may also cause huge variations in the voltage profile of power system with disturbances. That might lead to loss of stability [6]. Practically, the effectiveness of PSSs for damping the oscillations of the local area is clear without doubts, however, they cannot prove its effectiveness for damping of inter-area oscillation. This fundamentally happened because of the troubles regarding tuning and coordination of multiples PSSs which operate in various areas of power systems [7].

The detection of inter-area oscillation is very difficult when this detection is a concern to the measurement of local signal because it is affected by global states. The other option can be by using Flexible Alternating Current Transmission Systems (FACTS). The latent concept of FACTS based on the high static power converter, allowing it to act on oscillations of inter-area successfully in relatively short response times. The process of raising the power transferred through the current network transmission lines is a prerequisite. Various electrical power systems problem can be solved using FACTS devices. Access to high-quality electricity is a major source of concern in the present era [8].

Many variables in a power system can be controlled when using FACTS, for example, line impedance, terminals voltage, and voltage angle for providing high-quality regulation to control power system disturbances [9]. The main benefit of using the FACTS is to improve the system dynamics so as to ensure better stability of the electrical energy and positively reflect on the reliability of the system [10]. The complementary damping controllers are providing by FACTS devices, which are supple to be compacted at the main corridors of the network. Can consequently be getting damped, which is much better than PSS [11].

FACTS is referred to the acronym of "*Flexible alternating current transmission system*", proposed originally by Narain G. Hingorani in 1988's in the Electric Power Research Institute [12]. FACTS indeed is an appliance composed of power electronic types of equipment with a single function or multifunctional. It is used to control and regulate many electrical parameters in order to ensure the proper operating of the electrical system such as transmission line's voltage, current, impedance, phase angle and oscillation damping. That can lead to causing a fast change in the essential system of the parameters above mentioned [13].

The first generation of FACTS utilizes thyristors as the switching semiconductor device together with bulky capacitor/reactor banks to produce/consume reactive power to/from the power system [14]. Whilst, second generation FACTS utilize IGBT or GTO as the switching semiconductor device together with relatively smaller capacitors. Four quadrant converters are used in the second generation FACTS device and this arrangement makes it possible to produce/consume reactive power in an efficient manner, yielding a faster response and smaller device size when compared to the first generation FACTS devices [15]. TCSC is a member of the first generation, while SSSC and STATCOM are two members of the second-generation FACTs. FACTs can also be described as an optimal solution for damping out inter-area oscillation and transfer of maximum power without losing synchronism.

## 1.2 The Aim of Thesis

The purpose of the thesis is to compare dynamic performances of TCSC, SSSC, and STATCOM on inter-area oscillations in a simulation environment. First, how inter-area oscillations occur and grow easily to be studied and simulated with an interconnected small example of a power system. Then a suitable damping controller for each FACTS device to be chosen and completion of the literature survey. Extensive simulation studies will be performed to conduct generalized results obtained from this study.

## 1.3 Structure of the Thesis

A brief review of the contents and organization of this thesis in six chapters.

The six chapters are as follows: -

Chapter one: This chapter provides an overview of the research topic, the introduction concerning a comprehensive study summarized, and the chapter includes the composition of the thesis and the basic purpose of it.

Chapter two: A brief history of this study and similar research and its location are presented in detail in this chapter.

Chapter three: An overview of the FACTS with a summary of the most prominent devices.

Chapter four: General information about each device used for comparison through the thesis (research orbit) with the model and control in addition to the principle of work

Chapter five: This chapter includes the results obtained during the study and the simulations.

Chapter six: Presented during the discussion for the study and future work.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 General

Many kinds of research have focused on damping inter-area oscillation in the power system by utilizing different types of controllers. This chapter establishes a comprehensive, up to date literature survey by employing various kinds of controllers. This section builds up.

Roman Kuiava, (2009) success to enhance the damping ratio of inter-area modes. With a placement of TCSC in a New England/New York benchmark system are validated to obtain the result. It is designed Supplementary Damping Controllers (SDC) by using linear matrix inequalities (LMIs) [7].

M.W. Mustafa, (2009) developed the performance of TCSC by using eigenvalue methods. Designing of two areas four machines have laid with an appropriate controller for damping oscillation in a residue method [16].

H. Taheri, (2009) Develop solutions to the problems facing the flow of power in transmission lines by conducting analytical studies for detailed. In addition, manipulating control variables in an innovative way as an alternative to the traditional DQ-type method. The results obtained indicate the possibility of mitigating power oscillations and improving voltage for transmission lines when using SSSC. The comparison of this device in terms of the principle of working and operating conditions with other devices to determine the benefits of SSSC. The study included comparisons between the two control methods of the above strategies and the benefits and disadvantages of each [17].

F. Gharedaghi, (2011) Showed the purpose of using STATCOM and depicted the effects of it and principle work for regulating of the voltage at a midpoint. Meanwhile, it has made a comparison between STATCOM and SVC, which was considered as a conventional FACTS device by subjecting the network to a specific fault situation.

The results proved the effectiveness of STATCOM to the achievement of regulating transmission line voltage at midpoint. It is clarified that the reliability of STATCOM device for compensating of power system more than VSC [18].

Hossein Nasir Aghdam, (2011) manipulated the issues that faced transmission line by using the SSSC FACTS device. The principle operation of SSSC is illustrated by placing this device in the power system grids and observe the results. It is showing the advantages of utilizing SSSC in the network to reduce congestion and increased power flow [19].

S. Sahu, (2012) the design of SMIB and MMIB with the implementation of STATCOM are carried out. Two-area 11-bus system is considered as a test study and subjected it under 3-phase fault to observing the dynamical performance. STATCOM can success to rise power system stability and contribute to compensation of reactive power [20].

Arthit Sode-Yome, (2013) presented a comparison of some of FACTS devices by investigating the different function of each device at normal and disturbance conditions and shows the convenient for choosing the FACTS devices to improve voltage stability and loading margin. The discussion of various features and drawbacks of each device in the network validated of improving loading margin for FACTS devices [21].

Prashant Dhoble, (2013) The SSSC was investigated for the purpose of adjusting the system voltage. A comparison of the results was also made for both the SSCC system, which is classified as the series FACTS device and the shunt FACTS device STATCOM. Through simulation to find out how much compensation can be obtained from the device SSSC. The process of extrapolation and collection of values of the power system such as line current and line voltage, both P and Q power of the line in both cases (when the SSC and STATCOM are integrated separately into the power grid). The proposed system for examination, study and modelling consists of 11 buses and two areas. What has been proven by the results is that the SSCC with an appropriate controller has successfully processed high damping of oscillations and is remarkably effective when compared with the STATCOM [22].

Shervin Samimian Tehrani, (2014) monitors the influence of STATCOM to enhance voltage stability. The installation of STATCOM in a system of 14- bus and subject the whole system to the fault [23].

Shyam B. Ghodke, (2014) Discuss an active mechanism for the development of the SSSC, a device that contains a VSC for the purpose of providing series line compensation. The method that follows for obtaining this compensation is either injecting or generating a voltage in the quadrature phase with the current line. The SSSC will operate in two capacitive or induced reactance modes, which will subsequently affect the power flow of the transmission lines. When applying this device to the simulation system, a simplified system model was used with two machines to prove that SSSC gives the acceptable damping for the oscillations associated with the operation of the power system and compensate active and reactive power flow control [24].

Shashi Gandhar, (2014) search of the utilization of SSSC for study and took advantages of the dynamic compensation that can be obtained. It has been proposed a studied system comprised of diesel generating system connect with a wind turbine generator system in what was considered as a merger between two different systems. When the device is connected in the middle between the two systems, it is observed that reactive power has improved. Moreover, the real power has not been affected significantly. The results of the study, the extent of the impact of SSSC on both ends of the generating systems and the stability of the voltage in the different loads also contributed to clarifying the effectiveness of SSSC on the P, Q in the system used [25].

Thaw Tar Tun, (2016) discussed the problems of inter-area oscillation damping. The analysis of these problems based on eigenvalue and simulation of the time domain by using a Myanmar National network as a test system. The system has checked with the installing of FACTS devices (STATCOM, TCSC) then compared the result to show the best performance in power system damping and voltage support. The obtained rating clarifies the effective damping it can occur by implementing STATCOM to the studied system [26].

Agus Tiyono, (2017) STATCOM control with a POD to mitigate power system oscillations, this approach Proved effective to reduce the oscillations of inter-area. The system used is based on Kundur system. The results obtained of the simulation indicate a noticeable development in damping. That led to enhance the stability of the transmission line effectively. STATCOM characteristics are discussed and validated the proper location of this device in the studied system [27].

# CHAPTER 3

# FACTS DEVICES

## 3.1 Introduction

The rapid growth of power electronic based solid-state equipment has led to the introduction and development of FACTS devices. FACTS refers to the acronym of “Flexible alternating current transmission system”, proposed originally by Narain G. Hingorani in 1988's in the Electric Power Research Institute [12]. FACTS has been proposed as a new solution to alleviate numerous power system troubles for the enhancement of stability and controllability of power systems together with increasing the capability of power transfer [17].

The performance in the steady state of the power system is enhanced by proposing of FACTS devices. For example, increasing the capacity in the transmission line, controlling a flow of both active and reactive power flow, controlling a loop-flow, voltage regulation, congestion management, and getting an optimal power flow for economic operation of power system. FACTS indeed is an appliance composed of power electronic equipment with single function or multifunctional. It is used to control and regulate many electrical parameters in order to ensure the proper operation of the electrical system such as transmission line's voltage, current, impedance, phase angle and oscillations damping that can lead to causing fast changes in the essential system of the parameters above-mentioned [13].

The first generation of FACTS utilizes thyristors as the switching semiconductor device together with bulky capacitor/reactor banks to produce/consume reactive power to/from the power system. Whilst, second-generation FACTS utilize IGBT or GTO as the switching semiconductor device together with relatively smaller capacitors. Four quadrant converters are used in the second-generation FACTS device and this arrangement makes it possible to produce/consume reactive power in an efficient manner, yielding a faster response and smaller device size when compared to the first - generation FACTS devices.

## 3.2 Facts Classifications

FACTS generally can be divided into four main groups. They are,

- ❖ The shunt connected FACTS.
- ❖ Serial-connected FACTS.
- ❖ Combined series and shunt connected FACTS.
- ❖ Voltage regulators are other FACTS [18].

*The shunt connected FACTS:* This connection is somewhat similar to series type; the only difference is that it injects current to the line instead of the voltages. Which enhances the controllability of both P and Q power flow. Several devices fall under this type such as the STATCOM, TSR, TCR and TCS [19]. Figure 3.1 Show simple depict of this type.

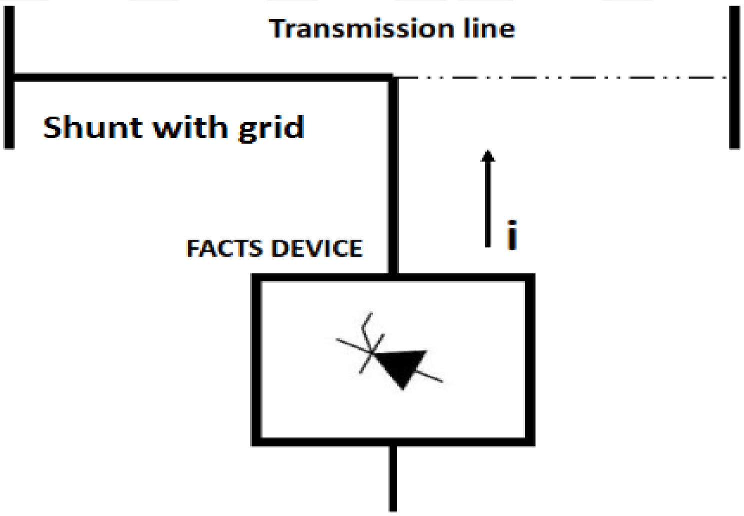


**Figure 3.1** Shunt FACTS device.

Series connected FACTS controllers: As evidenced by the label, this section consists of devices connected in series through transmission lines. This connection is equipped with a voltage that is injected in a series through of the line, contributing to control of the flow of power and the suppression of oscillations that occur during the disturbances, and thus better transfer of energy through the lines. Among the devices that make up this type are the SSC, TCSC, and TCSR. SSC is the most widely used and widespread in this group because of its enormous potential to benefit from various uses [20]. Figure 3.2 Shows simple series of FACTS device.

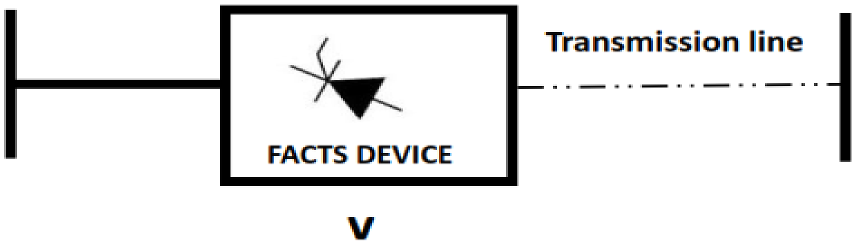


**Figure 3.2** Series FACTS device.

Combined Series-Series Connected: The use of two separate units of FACTS devices that are series connecting and combined with some other device which is a series too as shown in Figure 3.3. The main objective of this type is to balance active and reactive power through a transmission line. IPFC is a member of this type [20].

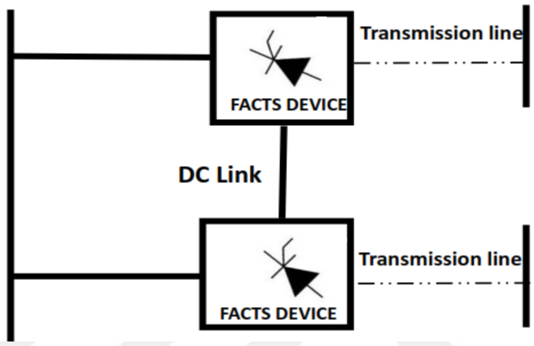


**Figure 3.3** Combined series-series FACTS device.

Combined Series -Shunt Connected: It combines two different connections, one of which is a series connected and another one is shunt to configure this type which is depicted in Figure 3.4. As an example of UPFC device.

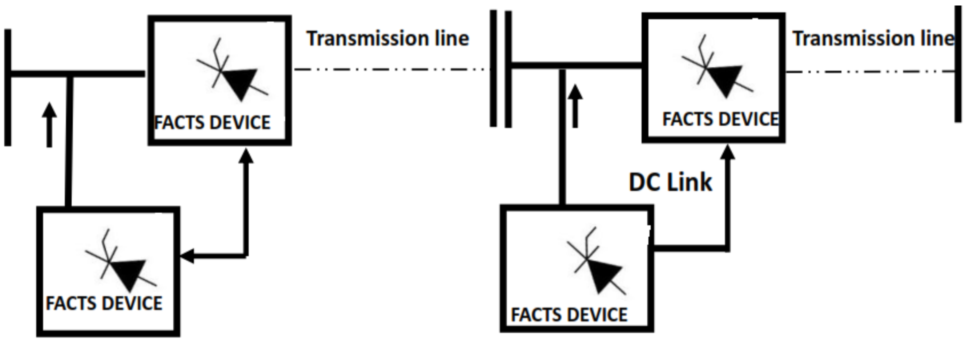


**Figure 3.4** Series-shunt FACTS devices.

Over time, researchers have added new classifications to FACTS based on several factors and some will be listed.

The type of the main device used can divide the FACTS into the following branches: -

1. FACTS device with thyristor

In this type of devices, the thyristor is relied upon mainly in its basic configuration. Which have the following elements [21].

- Static Var Compensator SVC.
- Thyristor Controlled Series Compensator or Capacitor TCSC.
- Thyristor Controlled Phase Shifting Transformer TCPS.
- Dynamic Power Flow Controller DPFC.

2. FACTS device with Voltage Source Converter VSC

In this type of devices, the converter is relied upon mainly in its basic configuration. Which have the following elements [33].

- Synchronous Static Series Compensator SSSC.
- Interline Power Flow Controller IPFC.
- Unified Power Flow Controller UPFC.
- Synchronous Static Compensator STATCOM.

Figure 3.5 Clarifies the classification of FACTS depending on thyristor or the converter.

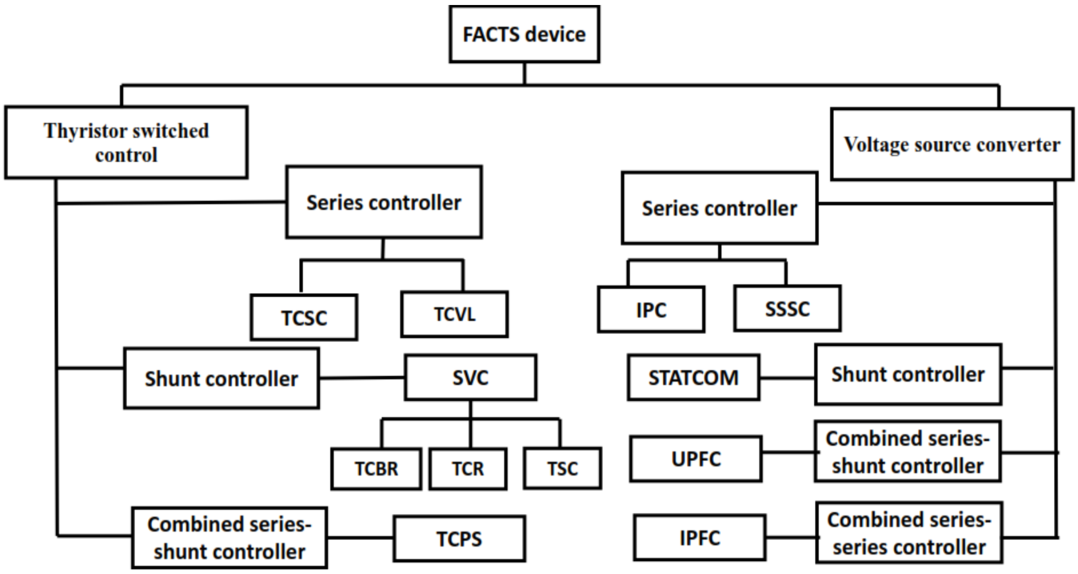


**Figure 3.5** Clarifies the classification of FACT converting on thyristor or converter.

## 3.3 Simple View of Some FACTS Devices

### 3.3.1 SVC

It belongs to shunt family of FACTS devices. SVC uses power electronics including the thyristor mainly to work. The main purpose of SVC is to improve control voltages. The component parts of the device are a parallel capacitor and a reactor in addition to the controlled thyristor [23]. Therefore, it works as a generator or load, depending on special situations, to produce a current that is either inductive or capacitive and then exploit it to perpetuate the power system transactions in the network. It equips the network with the necessary support for instantaneous control of disturbances at the weak lines of the network. All this is done by supplying or retrieving reactive power from the transmission line [24]. Figure 3.6 Shows a simple of SVC. the SVC is classified into three sections by depending on the method of SVC's parts are connected [25]:-

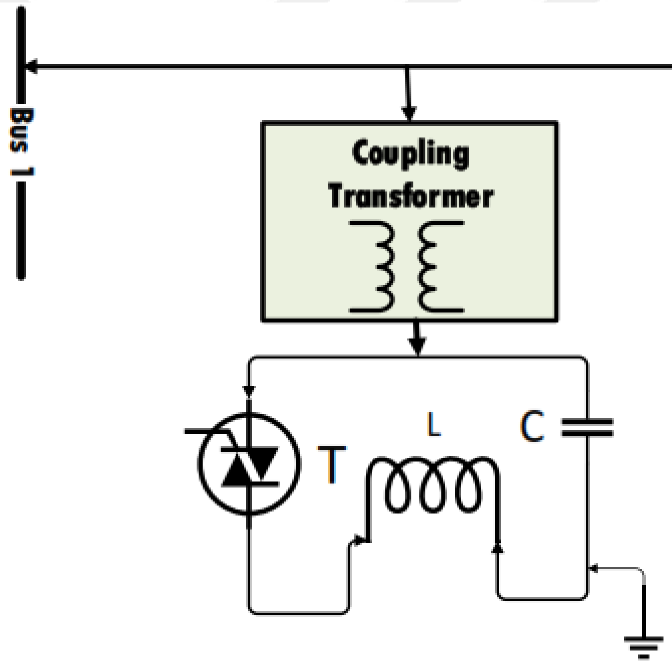


**Figure 3.6** FACTS device.

a) Thyristor switched capacitor TSC: a series connection of thyristor and reactor connected in series also with a transformer.

b) Thyristor controlled reactor TCR: the series connection of thyristor and reactor that Constitutes the essence of this type adding to a parallel capacitor. Making use of the valve is controlled thyristor to changes the reactance incessantly. It should be noted that one of its disadvantages is harmonics in low orders.

c) TSC: anti-parallel thyristors are connected series with the capacitor. The thyristor switched the capacitors that are compensated switched their conduction mode zero- full.

### 3.3.2 TCSC

TCSC is the latest one first-generation member of the FACTS device. It uses silicon-controlled rectifiers to manage a capacitor connected in series to a line. The world's first three-phase TCSC was developed and installed by ABB in Arizona Kayenta transformer in 1992 [26]. TCSC comprises of a thyristor-controlled reactor TCR, two opposite connected thyristor pair, a reactor connected to thyristor pair in series, and a capacitor C connected in series with the line as in Figure 3.7. TCSC is based on the variable series reactance concept. The purpose of the series reactance is to allow the determined value of active power flow through the series compensated line. TCSC behaves as an inductive compensator or a capacitive compensator by varying the line reactance. TCSC is significantly more efficient than some of the others contending FACTS devices due to no interfacing equipment necessary, like high voltage transformers.

Using TCSC natural commutated thyristor has advantages and switching of low frequency. This reduces cost, complexity and power loss [27]. Employing of TCSC has beneficial features such as rising the stability of the grid, line current control, load flow balancing and damping oscillations.

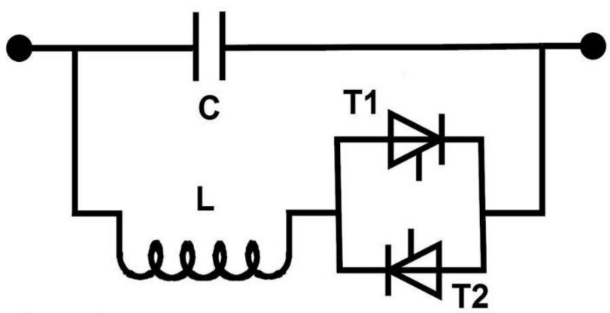


**Figure 3.7** Simple configuration of TCSC.

### 3.3.3 STATCOM

STATCOM is a FACTS device shunted to the transmission line belong to FACTS generation two. The STATCOM consists of the simplest form of the source voltage converter, a DC capacitor and transformer that is coupled with line. VSC is utilized largely to acquire a 3-phase after output voltage converting from an input voltage. The purpose of a transformer is tying VSC with the system. The inductance of the transformer guarantees that the DC capacitor is not short-circuited and quickly discharged, the high voltage system may be causing a damage to the STATCOM. The capacitor acting as a power source in DC. STATCOM equips support, which is a shunt compensation for the network that tied to it [28]. The control of the local bus voltage to which STATCOM is tied is the most familiar control function. Which lead to better damping in the release and to achieve improvement in stability level [29]. STATCOM's operation can be diversified between an inductive region and capacitive region. The bus voltage which has a relatively changing according to the output voltage that leads to an inductive or capacitive operation. Figure 3.8 Depicts the simple configuration of STATCOM.

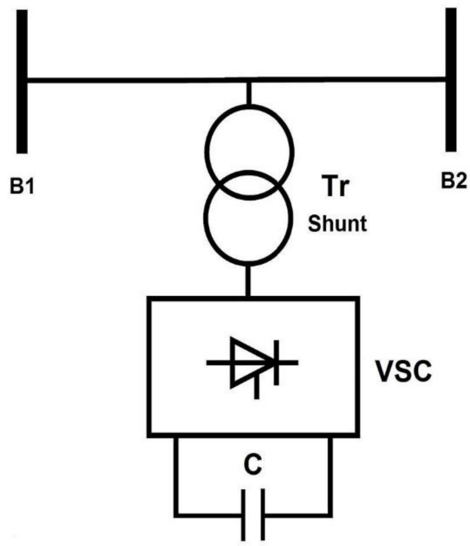


**Figure 3.8** The simple configuration of STATCOM.

### 3.3.4 SSSC

Static synchronous series compensator SSSC is a series connected FACTS devices consisting of a VSC, a DC capacitor, and a series coupling transformer. The basic scheme of SSSC is illustrated in Figure 3.9 SSSC has more capabilities when compared to the conventional series compensation based on variable reactance. The SSSC is very efficient to regulate bus voltage and controlling power flow in the transmission line and it has the ability to equip inductive or capacitive series compensation by varying the reactance [30]. Thereby SSSC has been considered to be an alternative and effective solution to the conventional series line compensation. The VSC produces a controllable sinusoidal voltage in series with the transmission line. To provide series compensation and DC link voltage regulation, the series injected voltage should be in quadrature with the current line. The transmission line can be modified by regulating the magnitude of the series injected voltage, the reactance of, therefore power flow or bus voltage can be controlled [31]. The phase angle of the series injected voltage, DC link voltage can be regulated at the reference value [32].

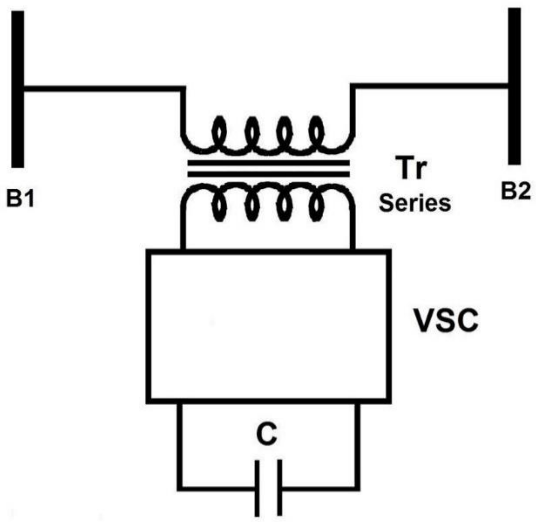


**Figure 3.9** Simple configuration of SSSC.

### 3.3.5 UPFC

This device has a multifaceted utility of FACTS devices. UPFC is characterized by multi-faceted performance, all based on various variables that affect the regulation of voltage, active power and reactive power etc. [33]. This flexible control provides a high response to any changes on the network and the processing duration is the shortest. UPFC consists of two devices STATCOM, SSSC connected to a way cross-link DC joint. Thus, the active power will flow in both directions through the ends of these devices. This will contribute to high control and instantaneously compensate for both active and reactive power in the network, without the need for an external power source. Figure 3.10 Illustrates a simple of UPFC.

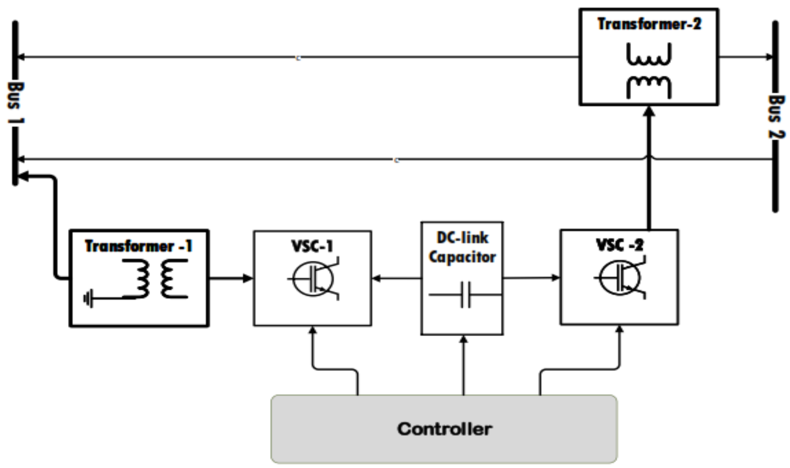


**Figure 3.10** Simple of UPFC.

### 3.3.6 IPFC

One of the FACTS devices that are connected in series. The main contribution is direct compensation for both real and reactive power through the network of the power system. IPFC consists of the combining of two SSSC devices of FACTS. Which greatly affects the damping of oscillations and thus improves power and reduce losses [34]. The Figure 3.11 Clarifying IPFC device.

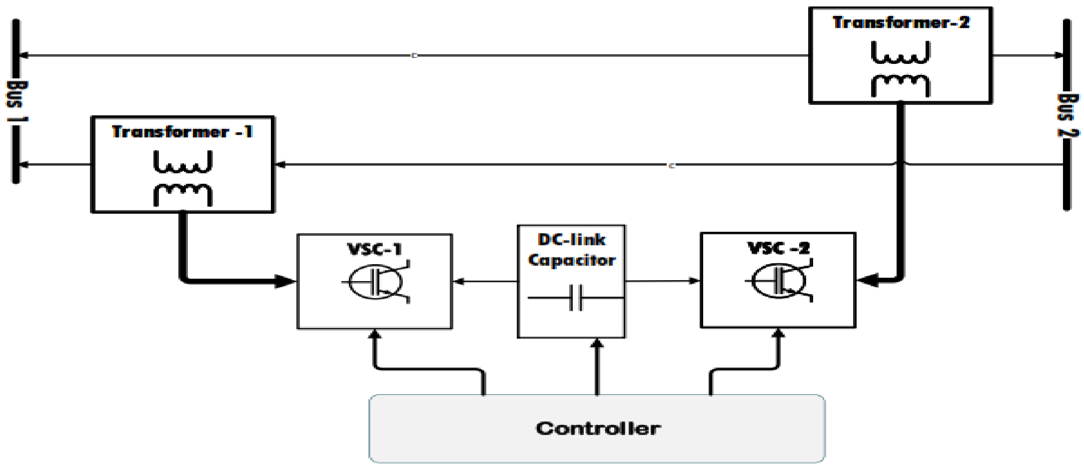


**Figure 3.11** IPFC simple scheme.

# CHAPTER 4

# MODELLING OF TCSC, STATCOM AND SSSC

## 4.1 Introduction

In recent years, electrical networks have become very large and complex. Thus, if there are problems, such as transmission lines going down or a sudden load change, fluctuations and damage to the system can result. Therefore, there is a need for an effective solution to eliminate or suppress these fluctuations. The modelling of FACTS devices and the use of different control methodologies for them are crucial in improving the stability of the electrical systems by damping the oscillations. This chapter provides a detailed investigation of the selected FACTS devices used in the thesis, namely TCSC, STATCOM and SSSC. Each section in this chapter includes the definition of the device, working principle, the circuit used for modelling and control.

Pulse width modulation (PWM) is a technology commonly used for controlling both the magnitude and angle of the injecting voltage and has been obtained by this technique. Several internal processing operations are in this device for both voltage and current. This is because the voltage control path produces an injected voltage and maintains the angle whereas the current control path produces the injected voltage and maintains its value [17].

## 4.2 TCSC

The thyristor-controlled series compensator (TCSC) is a well-known device with the ability to quickly modify the transmission line's impedance. Since 1993 in Oregon, the series compensation by TCSC has been accomplished [36]. Consequently, the advantages of this device are line current control, fault current limiting, voltage stability enhancement, transient and dynamic stability improvement and damping oscillations [33]. It is significantly more efficient than some of the other contending FACTS devices, such as STATCOM and SSSC, due to its lower cost and complexity as it does not need a coupling transformer [37]. It is used to improve both steady state and dynamic performance of the transmission system. The basic configuration of a TCSC is shown in Figure 4.1. The TCSC is comprised of a thyristor-controlled reactor (TCR), two opposite connected thyristor pairs, a reactor connected to thyristor pair in series and a capacitor connected in series with the line. The TCSC is based on the variable series reactance concept. The purpose of the series reactance is to allow a determined value of active power flow through the series compensated line. The TCSC behaves as an inductive or a capacitive compensator by varying the line reactance [27].

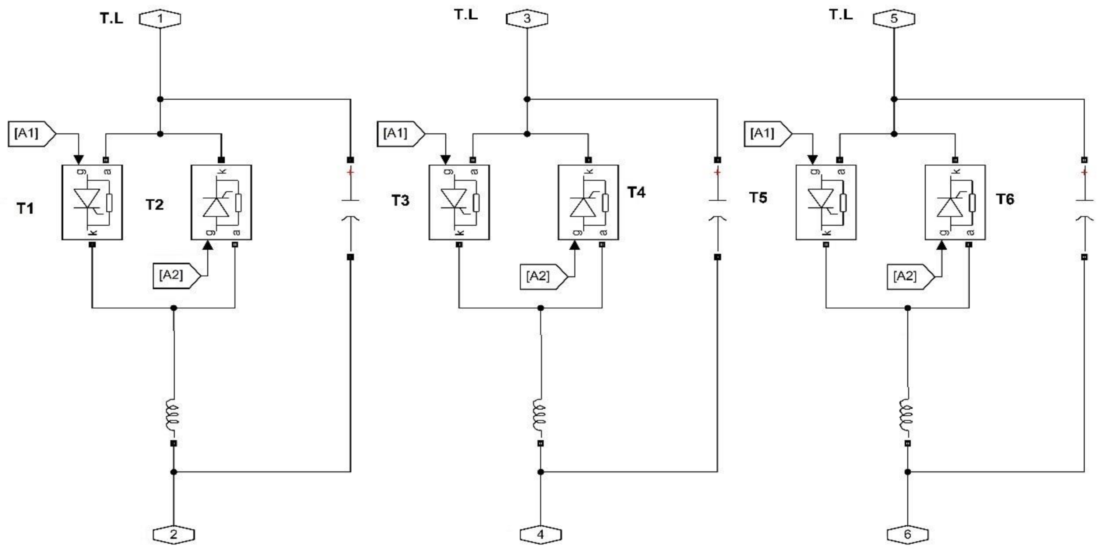


**Figure 4.1** Simple diagram of 3-Ø TCSC.

The power flow through the transmission line, p, is compensated by the TCSC per Equation (4.1) [12].

$$p = \frac{V_S \, . \, V_R}{X_L + X_{TCSC}(\alpha)} \sin \delta \tag{4.1}$$

Where Vs and Vr are the sending and receiving voltages, respectively; $X_L$ is the reactance of the transmission line; the impedance of TCSC due to $X_{TCSC}$ losses is ignored; and δ is the power angle in this derivation where loss of the TCSC is ignored [38].

The TCSC operation modes can be explained as follows:

- Bypass: The bi-directional controlled switches turn on ±180°. The nature of current flow through the reactor is continuous with a sinusoidal waveform. The flow of current is mostly through the line that consists of the thyristor and reactor valves. This approach has been utilized to obtain sufficient protection for the capacitor from the overvoltage conditions [39]. Figure 4.2 illustrates the TCSC bypass mode.

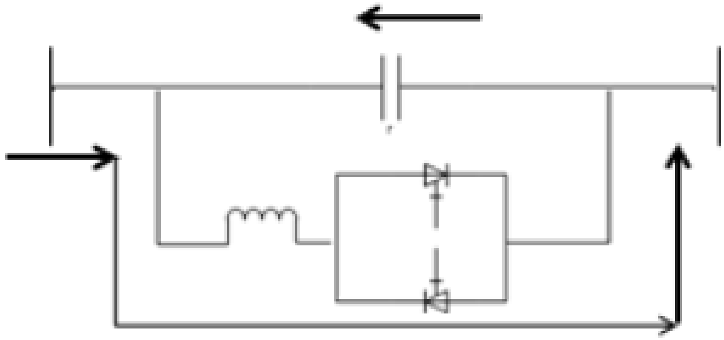

**Figure 4.2** Bypass mode of TCSC.

- Block mode: No current flows through thyristor valves because pulses in the gate block it. This mode performs similar that of a fixed capacitor. Therefore, it is undesired in practical applications [40]. Figure 4.3 illustrating block mode.

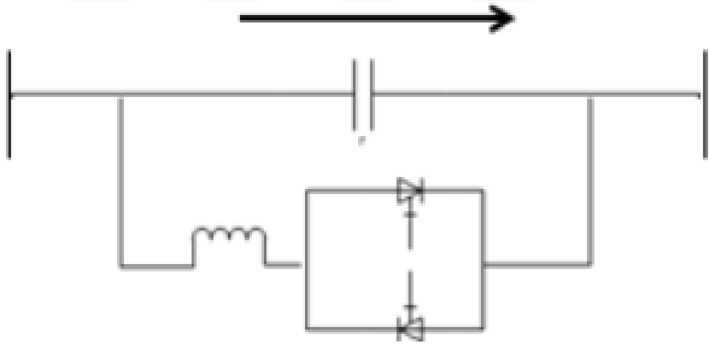

**Figure 4.3** Block mode of TCSC.

- Vernier control: In this mode, the valves of thyristor are gated from a minimum firing angle to 90 degrees. The conduction occurs during part of a cycle. Whenever the angle of conduction increases to more than the zero, the valve of TCSC reactance increases (capacitive region). Moreover, in the inductive region, the valve increases whenever the angle of conduction decreases below $180^{o}$ [41]. Figure 4.4 illustrates the capacitive and inductive modes.

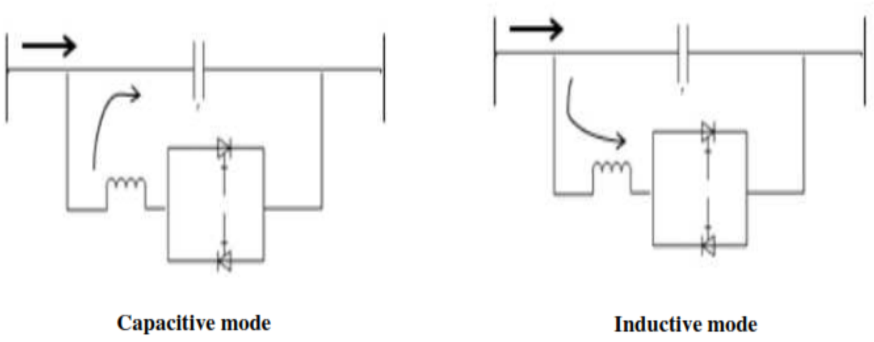


**Figure 4.4** Capacitive and inductive cases of TCSC mode.

### 4.2.1 Control of TCSC

The sensing voltage and current from the transmission line return as feedback in order to calculate the impedance of the TCSC. The reference impedance is the direct and primary determinant of the power level. The loops included in each controller have functions to enhance the processing and control of the wide operation range. When the TCSC operates in a mode of constant impedance, the current feedback is utilized to compute the TCSC impedance. The power level is limited indirectly by the impedance, so it is possible to present an automatic power control mode. It can be determined whether it is inductive or capacitive by comparing the reference impedance with the measured impedance, $Z_m$. The outside part of it controls whether the TCSC mode is inductive or capacitive.

The line current is fundamentally used to obtain synchronization, and it is applied instead of voltage because the TCSC voltage that can vary more during operation. The output of the current control deals with firing angle to the bus. Each mode of operation has a separate controller [42] that has an adaptive controlling loop to ensure a better operation in a various ranges, as clarified in Figure 4.5.

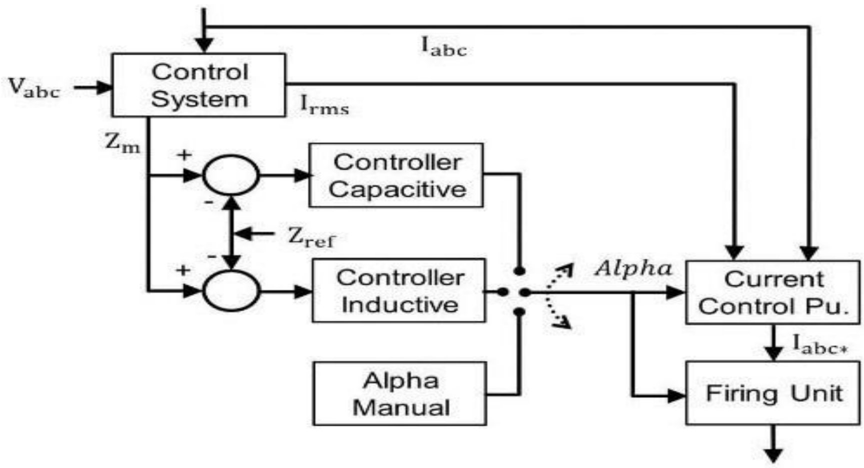


**Figure 4. 5** TCSC control scheme [52].

### 4.2.2 STATCOM

A static synchronous compensator (STATCOM) is a second-generation shunt connected to FACTS devices. A STATCOM system can change the flow of reactive power by absorbing Q from the system or supply. The configuration of STATCOM is shown in Figure 4.6. It is comprised of a VSC and a capacitor that is connected through a 3-∅ coupling transformer with the power system. The STATCOM system is basically used to damp oscillations and enhance the stability of the system [43]. The main purpose of the transformer is to connect the bus system with the VSC. Moreover, the transformer's inductance prevents a rapid discharge or short circuit from occurring in the DC link of the capacitor.

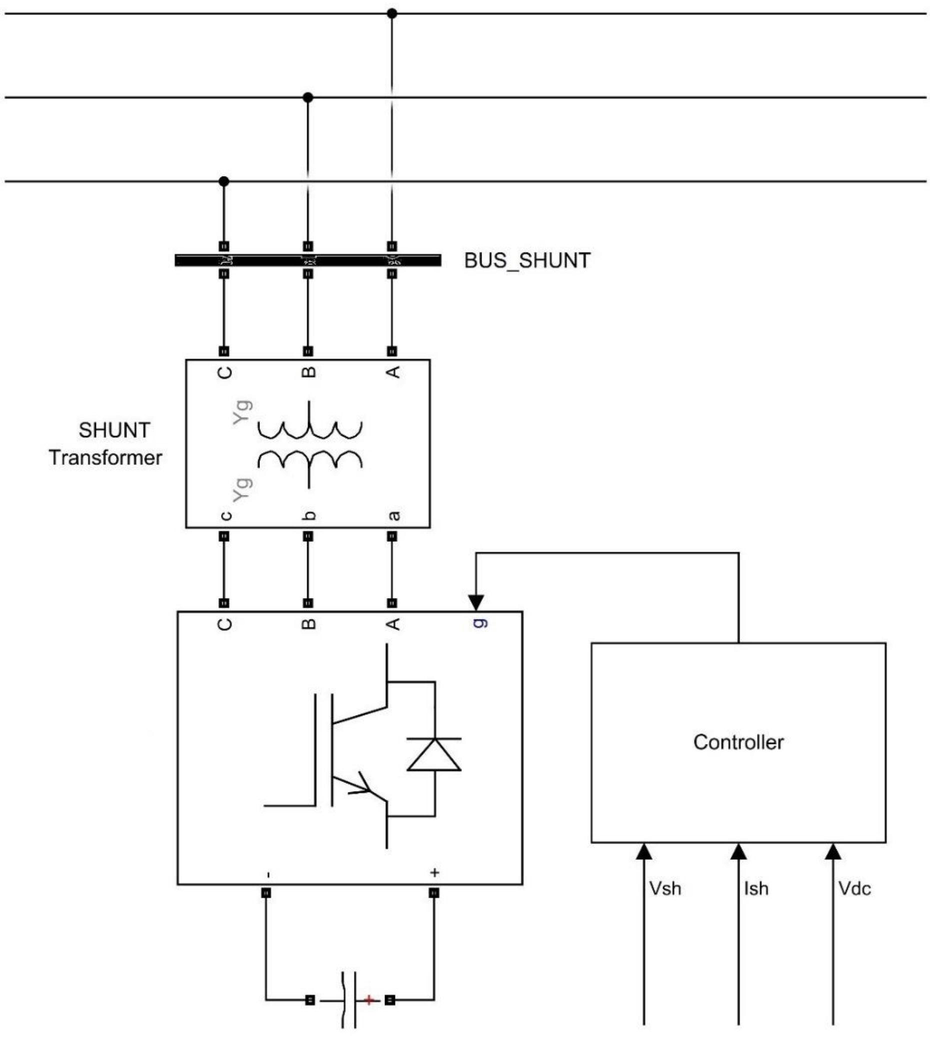


**Figure 4.6** Simple diagram of 3-∅ STATCOM.

The basic concept of using a VSC is to generate an AC voltage that is controllable and can be converted from a DC link capacitor then stepped up through a coupling transformer. The voltage at the output of the VSC is kept lower or higher compared to the voltage on the line [44]. Moreover, the reactive power is exchanged within the network and that can occur by two sides of the converter with a controllable AC voltage [45]. When the AC voltage of $V_{VSC}$ is higher than the voltage of point common coupling (PCC), the $V_S$ will supply real power in a capacitive mode to the system. Conversely, if $V_{VSC}$ is smaller than $V_S$ the STATCOM will intake reactive power in an inductive mode from the system. If $V_S$ and $V_{VSC}$ are equal in magnitude, the STATCOM will remain in standby mode in which zero reactive power transfer [56].

The active and reactive power can be expressed in Equations (4.2) and (4.3):

$$p = \frac{V_{bus} * \quad V_{VSC}}{X_L} \sin\delta \qquad (4.2)$$

$$Q = \frac{V_{bus}^2 - V_{bus} \; V_{VSC} \; \cos\alpha}{X_L} \qquad (4.3)$$

where $X_l$ is the normalized inductive reactance of the coupling transformer (per-unit), and δ is the phase angle [47].

When both the magnitude and phase angle of $V_{VSC}$ are controlled, the exchanging of both the real and the active power through the power grid has been achieved. The output voltage of the converter is used for computing the orientation of both active and reactive power.

### 4.2.3 Control of STATCOM

Obtaining the compensation for reactive power bidirectionally has been achieved by the output voltage of STATCOM varying in accordance with the requirements of this compensation.

Figure 4.7 illustrates the comparison of the shunt value for $Q_{sh}$ and $V_{sh}$ with reference to values verified as $Q_{ref}$ and $V_{ref}$. This comparison is important to provide the system with reactive power. There are two types of controllers, namely reactive and voltage. The voltage of a DC link returns feedback to compare with reference values and vary the output to provide the system with the desired compensation.

The outputs of the controllers, which are in d-q direct and quadrature axis frames, generate a pulse block sinusoidal pulse width modulation (SPWM) or space vector PWM in order to control the converter switches [48]. The main objective of PWM is to keep the voltage values constant at the terminals of the converter by changing the modulation index according to d-q frame value address in [49].

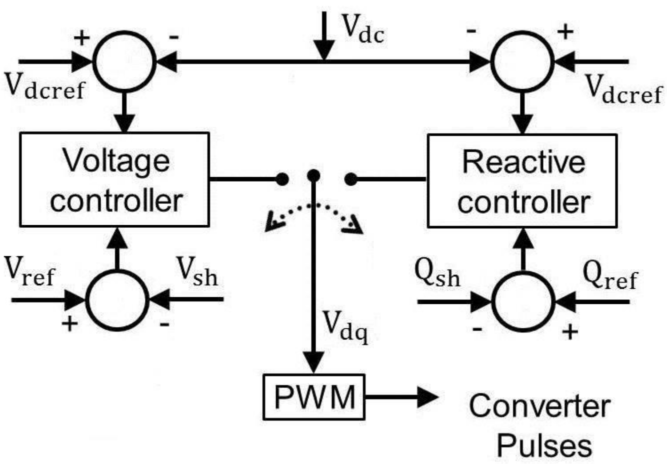


**Figure 4.7** Control of STATCOM [48].

## 4.3 SSSC

A static synchronous series compensator (SSSC) is a series connected FACTS. It uses the techniques of PWM in the converter in a controlled manner to achieve control of the voltage value and amount. The SSSC is comprised of a VSC, a DC link, that is a capacitor.

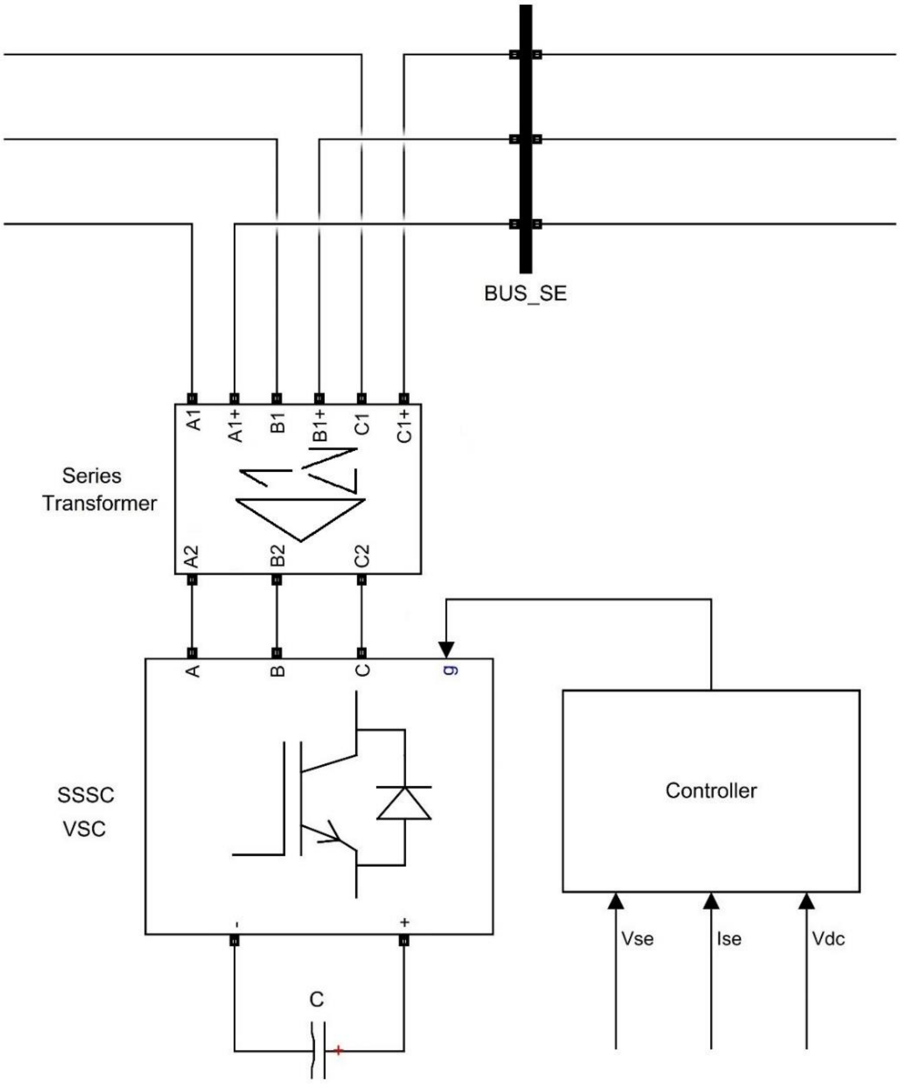


**Figure 4.8** Diagram of Three-phase SSSC.

Figure 4.8 shows the three-phase connection of the SSSC to a transmission line. Note that the SSSC is connected serially with the line and the VSC produces a controllable sinusoidal voltage in series with the transmission line. To provide series compensation and DC link voltage regulation, the series injected voltage should be in quadrature with the line current. the transmission line can be modified by regulating the magnitude of the series injected voltage, the reactance of; therefore, power flow or bus voltage can be controlled [51].

The phase angle of the series injected voltage and DC link voltage can be regulated at the reference value [52]. The power that flows across the transmission line can be represented by Equation (4.4):

$$P = \frac{V_R V_S}{X_l} \sin(\delta_R - \delta_S) \quad (4.4)$$

Where $V_R$, $V_S$ are the voltages at both sides of VSC terminals, $\delta_R$, $\delta_S$ are the phase angles for these terminals and $X_l$ is the reactance of line.

If $V_R, V_S$ are equal, the assumption of $V_R = V_S = V$, $\delta = (\delta_R - \delta_S)$ that leads the equations to be: -

$$P = \frac{V^2}{X_l} \sin\delta \quad s \quad (4.5)$$

$$Q = \frac{V_R V_S}{X_l} (1 - \cos(\delta_R - \delta_S)) \quad (4.6)$$

Nonetheless, there are two modes that control transmission line impedance, namely capacitive and inductive modes. This may lead to a variable impedance of the transmission line. The total line reactance is diversified according to the injected voltage. If the injected voltage leads the current of the line by 90 degrees, the SSSC acts in an inductive mode and improves the power flow. On the other hand, if the injected voltage lags the current of the line by 90 degrees, the SSSC acts in a capacitive mode and improves the power flow [53] [54].

### 4.3.1 Control of SSSC

The strategy of SSSC control is analogous to controlled series compensation tentatively. the design of VSC and pulse techniques of converter in SSSC play a crucial role in the controlling strategy. Figure 4.9 describes control of SSSC. The control block diagram of SSSC composed many components has fundamental operations in the controlling according to a function of each component. The principle is based on comparing the input signals to the references values to produce a variation used after treated through voltage and current controls to getting the sinusoidal form of these signals. Furthermore, the voltage of DC link is varied with a reference DC voltage then the controller is treated the product to modify or remove the error in signal [55]

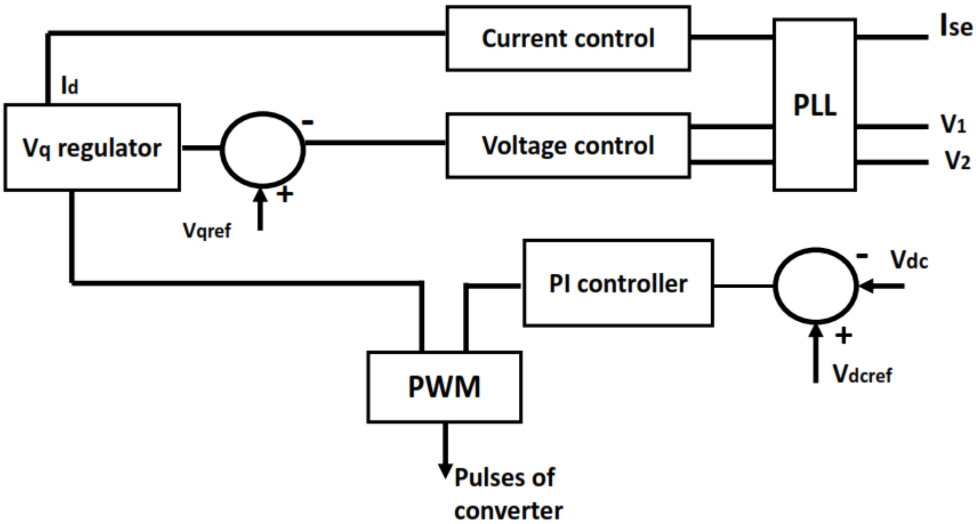


**Figure 4.9** Control of SSSC.

The voltage value in quadrature axis is entered to $V_q$ regulator is necessary for getting predict of the converter voltage with the $I_d$ current signal. The direct current is utilized for charge or discharge DC capacitor.  Phased locked loop (PLL) utilized in the extracting of data for the frequency and phase of the signals. The ensuring of synchronization of positive sequence components for the current has been achieved by the PLL signals [56]. The PLL output is valuable for determining the 3-phase AC voltages and currents in the d-q axis. The final step is utilizing of pulse width modulation to process the product signals from the controller and $V_q$ regulator.

# CHAPTER 5

# RESULTS AND SIMULATIONS

## 5.1 Introduction

This chapter presents the results obtained by the utilizing the TCSC, STATCOM and SSSC after connecting these devices individually to the proposed study network called the Kundur System. The Kundur System is a proposed power system that has specific values that are used as a fundamental basis for the comparison of the results obtained through the simulation. The Kundur System consists of two areas that were formed to demonstrate the significance of utilizing it to detect the inter-area oscillations. The system consists of four generators that are interconnected with transmission lines to emulate a real electrical power network. When the system is subjected to a certain fault, the voltage fluctuates and the oscillations negatively impact the network. The harmful effects of these oscillations require damping as quickly as possible to maintain the sustainability of the system, ensure stability and protect the flow.

## 5.2 Inter-Area Oscillation

The purpose of applying TCSC, STATCOM and SSSC devices with the network is to reduce or suppress fluctuations in the power grid during operation. Therefore, how these oscillations also observed and processed should be explained. The term "inter-area" is a nomenclature for the frequencies that occur during operation of the power system. The inter-area oscillation is an ingrained phenomenon due to the increasing interdependence of power grids and transmission lines. It can be observed when a set of generators are oscillating with another group or plant. This usually results in fluctuations between the two groups of generators that are separated by distance. It can also occur when long transmission lines interconnect two remote generation sites. The frequencies of these oscillations are generally between (0.1-0.8) Hz [4].

Breakdowns and blackouts are significant concerns if the inter-area problems are not considered. Therefore, the treatment of these oscillations will benefit the system in general. It also improves the transfer of electric power, regulates the voltage and improves the stability. A typical inter-area oscillation is illustrated in Figure 5.1 and PSS may be an efficient way to get rid of these oscillations However, PSS is unable to cope with inter-area oscillations due to limited signal diversity.

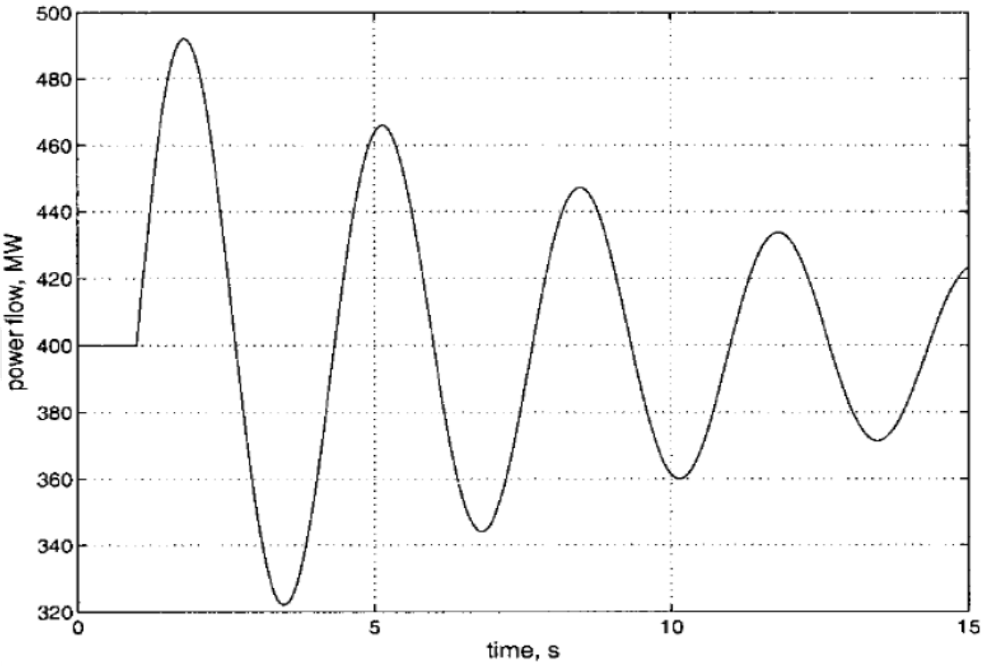


**Figure 5.1** Inter-area oscillation simple example [57].

The FACTS devices can suppress inter-area oscillations effectively due to the ability to control the full capacity of the electrical transmission lines. According to Equation (5.1) and Equation (5.2), the damping ratio and frequency oscillation can be getting [58]. where (f) is the frequency of oscillation and (σ) is the damping factor.

$$\xi = \frac{\sigma}{\sqrt{\sigma^2 - \omega^2}} \tag{5.1}$$

$$\gamma = \sigma \pm j2\pi f \tag{5.2}$$

### 5.2.1 Kundur System

The Kundur System was used for the purposes of studying and analysing the dynamic operation of TCSC, STATCOM and SSSC FACTS devices [59]. The Kundur System is comprised of two analogous areas that are connected with 220 km lines and has the value of 230 kV line to line voltage. The system contains four generators (16 kV/500 MVA), where the total power of each generator is 400 MVA and the total loads are

1375MW and 160MW. These are transferred from area one to area two. Kundur's two-area system is presented in Figure 5.2 [60].

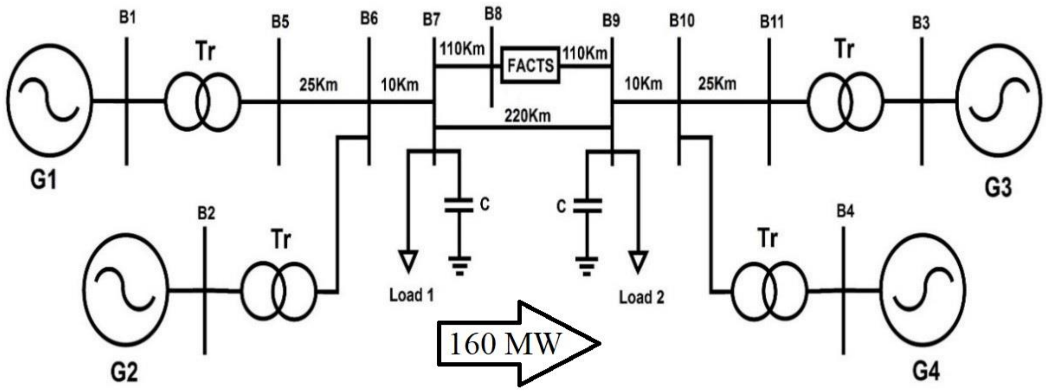


**Figure 5.2** Kundur system [60]

### 5.2.2 Simulation Studies

The simulation study was divided into four case studies, as listed in Table 5.1. Case 1 presents the application of the Kundur System without adding any FACTS devices. Case 2 refers to the application of TCSC to the Kundur System, where the TCSC is placed between bus no. 7 and bus no. 9. Case 3 utilizes STATCOM with the Kundur System, where the STATCOM is located between bus no. 7 and bus no. 9. Case 4 applies SSSC with the Kundur system, where the SSSC is applied between bus no. 7 and bus no. 9. All these devices are applied through buses bus no. 7 and bus no. 9 individually because this region can easily detect inter-area mode oscillations [11] [61] [59].

**Table 5. 1** Four case studies.

| Case No. | Inter-Area Mode |
|---|---|
| 1 | With No FACTS devices |
| 2 | TCSC |
| 3 | STATCOM |
| 4 | SSSC |

### 5.2.3 Case 1

This case study is the base case in which all FACTS devices are deactivated in the studied system. The Kundur System operates normally and then it is exposed to a 3-Ø ground fault at t= 0.2 sec. It then conducts measurements of voltage, active power and reactive power flow. The simulation model of the Kundur System is shown in Figure

5.3. The parameters of the networks are shown in appendix which has been testing the system operation and organizing its work. These values have been used for all case studies.

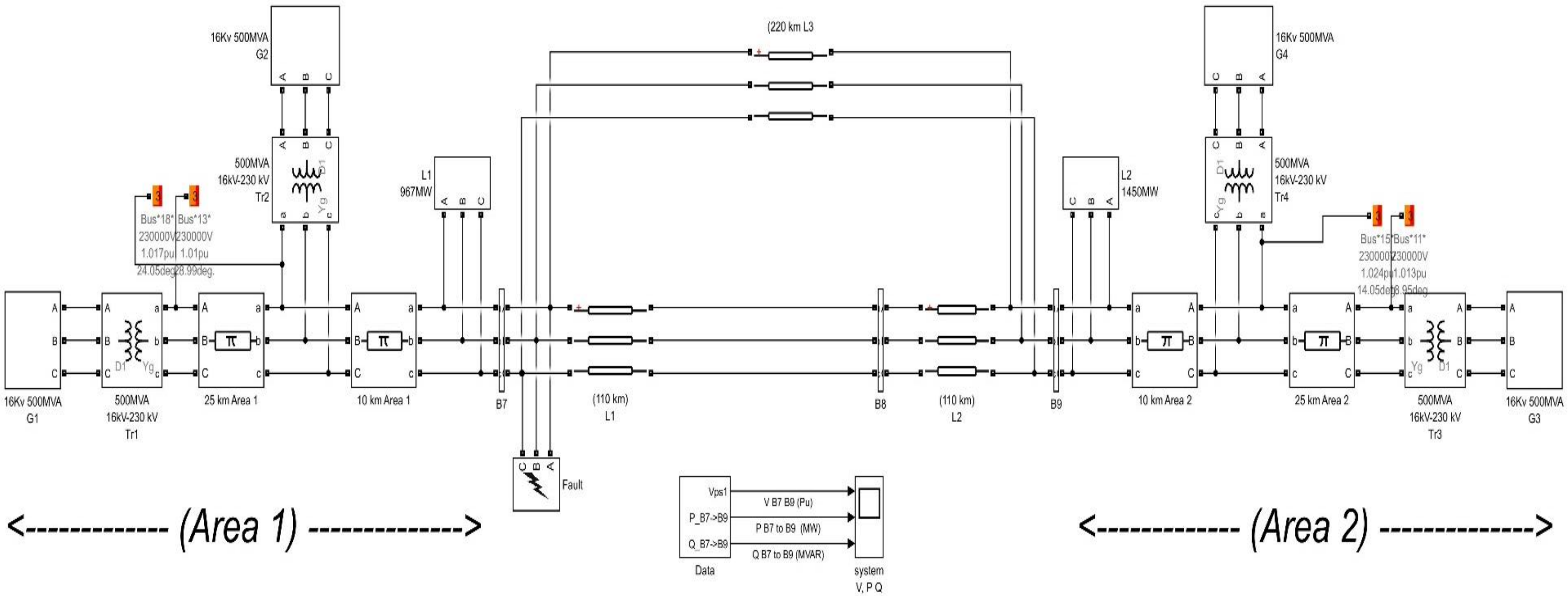


**Figure 5.3** Simulation model of Kundur system without FACTS.

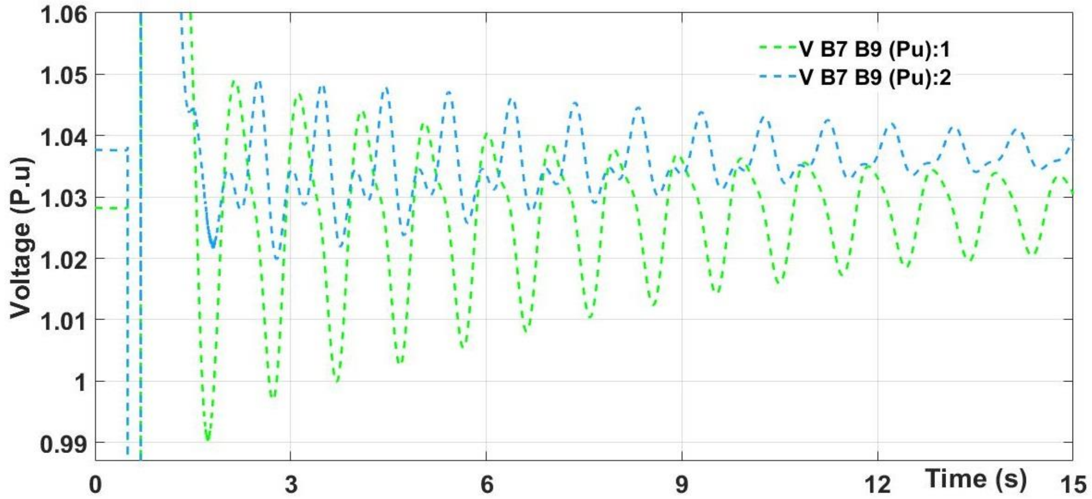


**Figure 5.4** Voltage measurement of B7-B9 of case 1.

Figure 5.4 shows the voltage measurements for bus no. 7 and no. 9. The values of the voltage are directly affected by the oscillations. The oscillations start after the fault occurs at 0.2 sec, reach a high value and then oscillate in the range (1.05–0.99) pu and (1.05–1.02) pu. These oscillations continue in the system for a period of time, about 15 sec. As a consequence of these high oscillations, the system becomes unstable.

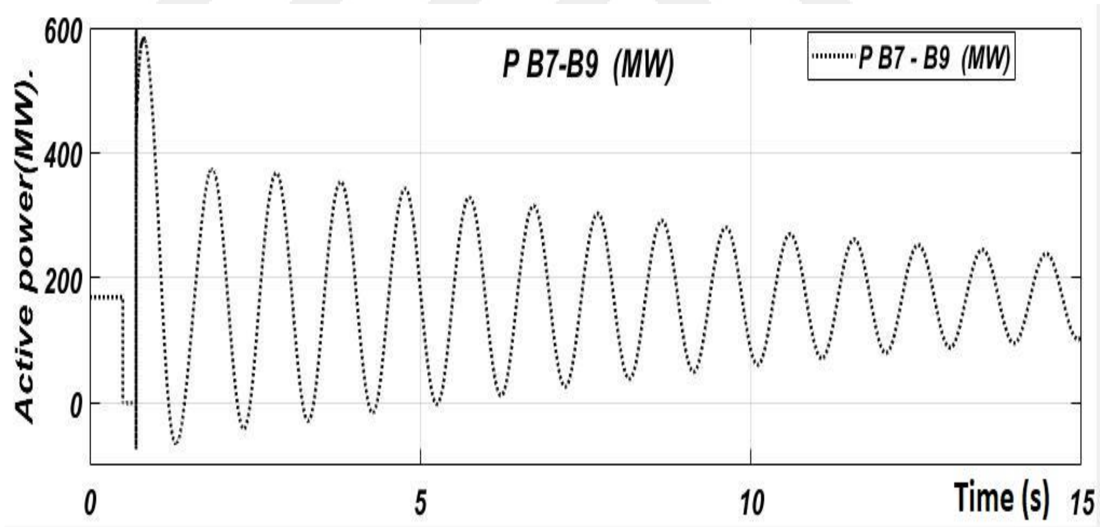


**Figure 5.5** Active power flow from B7-B9 case 1.

Figure 5.5 shows the power flow from bus no. 7 and bus no.9. The maximum value of the power flow reaches around 600 MW to – 110 MW. The power flow curve shows high oscillations, which indicates an unstable system after applying the fault at t= 0.2 sec. These oscillations are continuous during the time period from 0-15 sec, so damping with a sufficient controller is required.

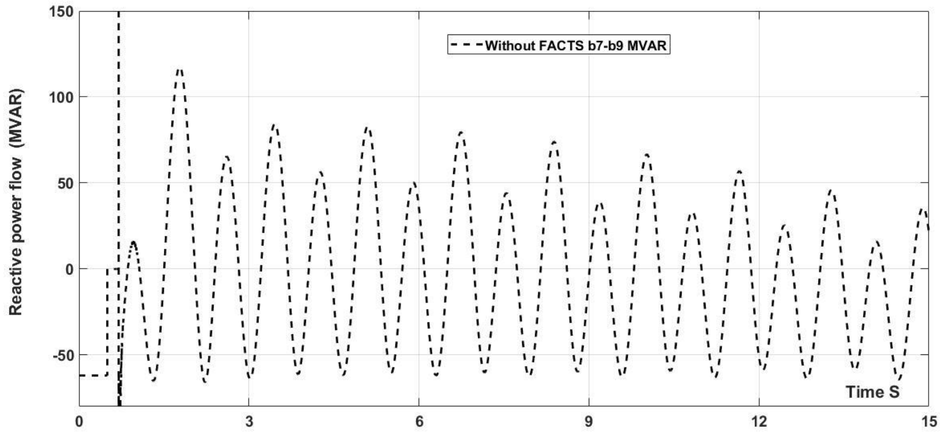


**Figure 5.6** Reactive power flow between B7-B9 of case 1.

Figure 5.6 shows the reactive power flow from bus no. 7 and no. 9 where the effect of the fault is clear. A 3-∅ to ground fault caused a fluctuation in the system with a maximum value of reactive power of 120 MVAR. The reactive power curve has continuous oscillations from 0 to 15 sec. Therefore, the system requires a controller to damp out these oscillations and recover stability.

### 5.2.4 Case 2

This case considers the application of TCSC with the Kundur System. The TCSC is placed between bus no. 7 and bus no. 9 because of the ease of detecting inter-area oscillations in these buses. The system is exposed to a fault which is 3-∅ to ground. Figure 5.7 depicts the simulation model for this case.

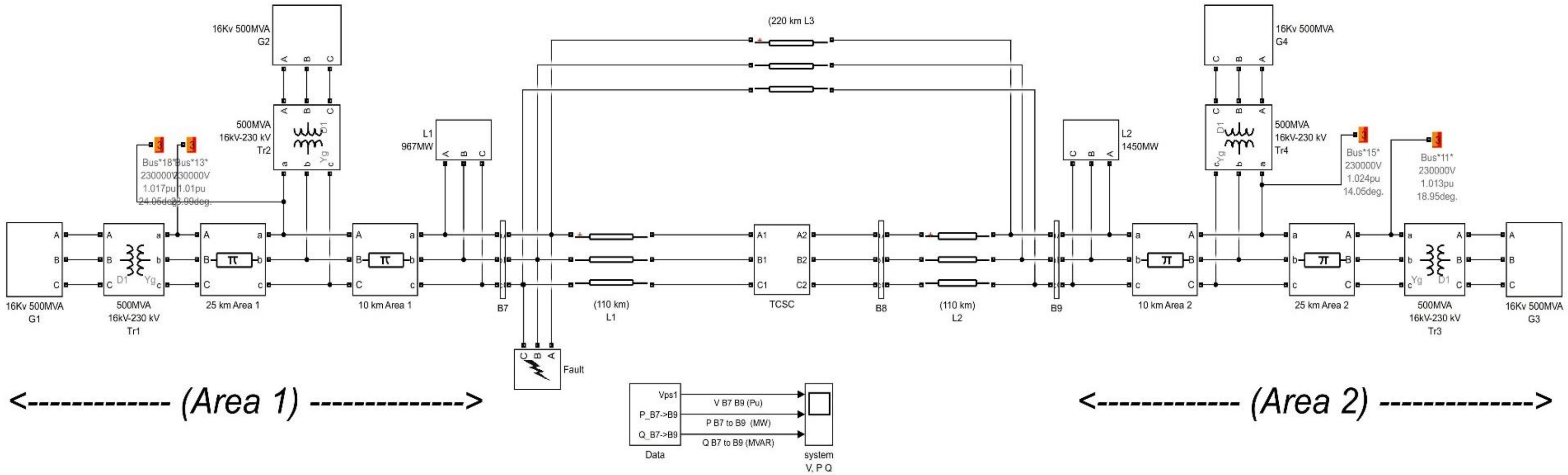


**Figure 5.7** Simulation model of case 2.

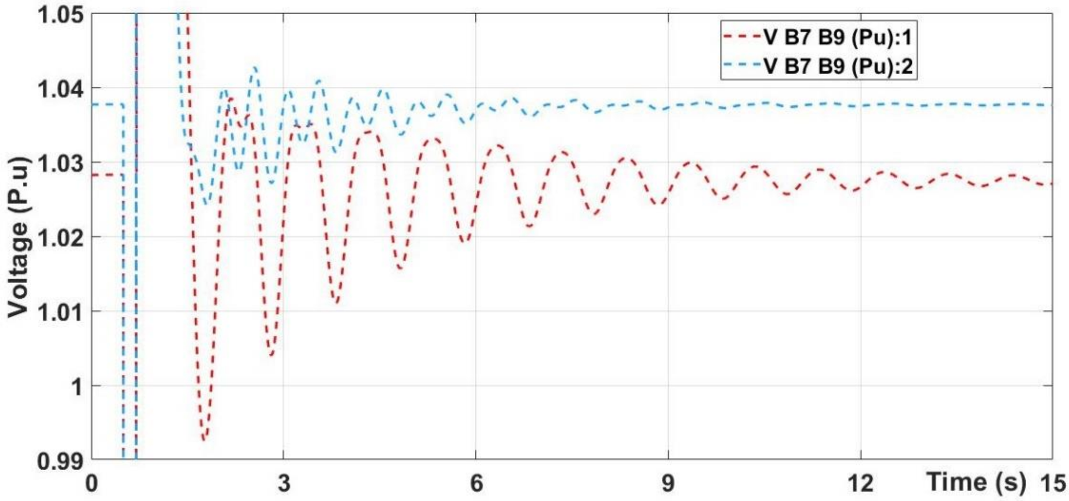


**Figure 5.8** Voltage measurement of B7-B9 of case 2.

Figure 5.8 shows the voltage from bus no. 7 to bus no. 9, where the oscillations start with the fault at 0.2 sec. The damping of these oscillations gradually appears after the TCSC controller begins operation. The settling time for the damping the oscillation clearly appears at about 9 sec. The controller succeeded in reducing the oscillations without eliminating them completely.

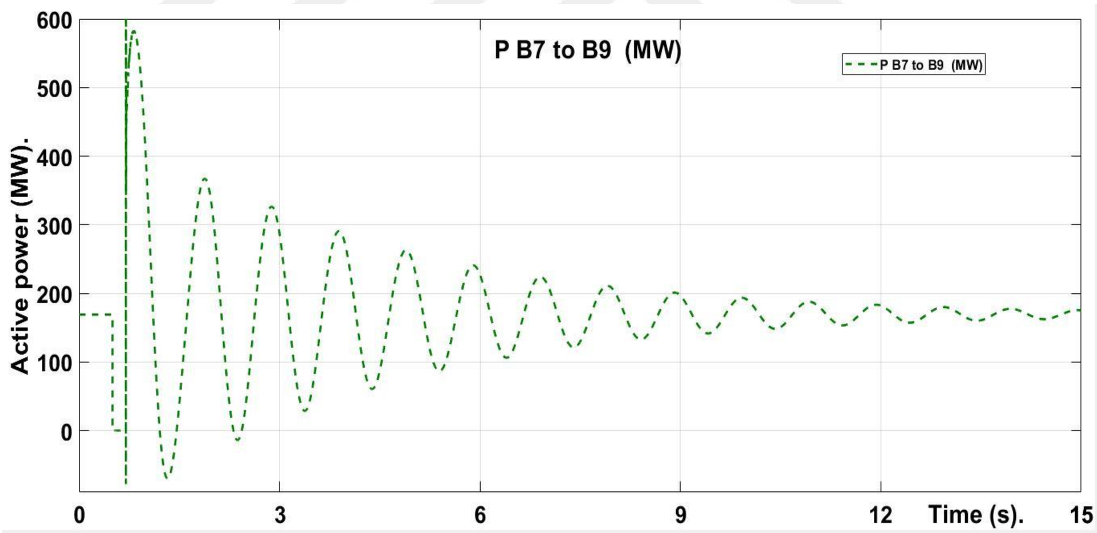


**Figure 5.9** Active power flow from B7-B9 of case 2.

Figure 5.9 depicts the curve of real power flow from bus no. 7 to bus no. 9. Large oscillations appeared in the line of active power flow during the fault that occurred at 0.2 sec. These oscillations are reduced progressively while the TCSC controller suppresses them. The active power flow settles to around 180 MW and continues to fluctuate after 10-15 sec.

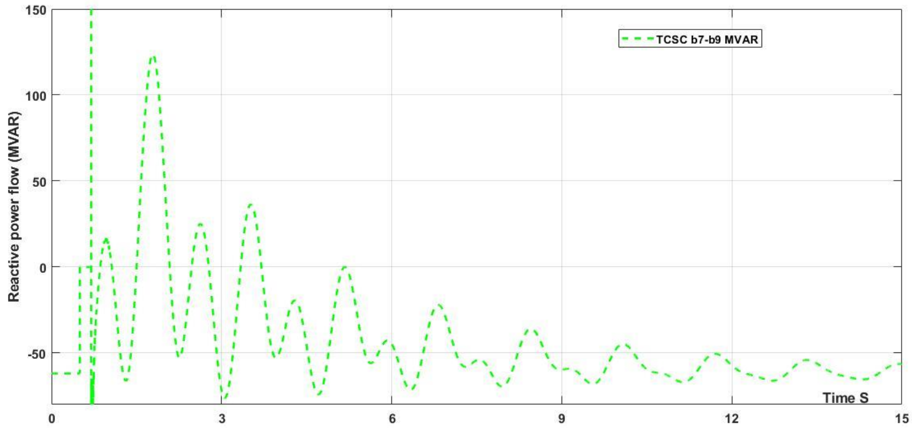


**Figure 5.10** Reactive power flow from B7-B9 of case 2.

Figure 5.10 shows the reactive power flow from bus no. 7 to bus no. 9. Great oscillations are present in the system after being exposed to a fault. The maximum range of around 125 MVAR occurred at time duration 1.8 sec. these oscillations are gradually reduces around -60 MVAR at time duration 13.4 sec.

### 5.2.5 Case 3

Case 3 shows the application of STATCOM to the Kundur System. The STATCOM is located at bus no. 7 and bus no. 9. The system is exposed to 3-∅ to ground fault at 0.2 sec. Figure 5.11 shows the simulation model for this case.

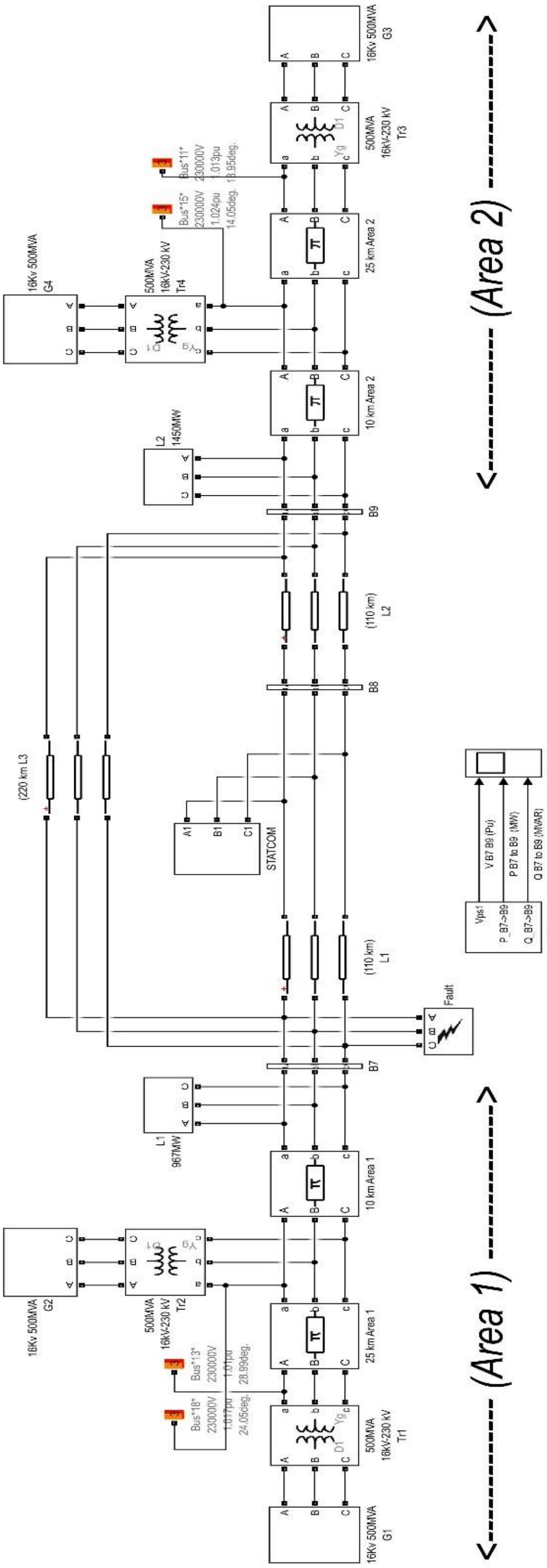


**Figure 5.11** Simulation model of case 3.

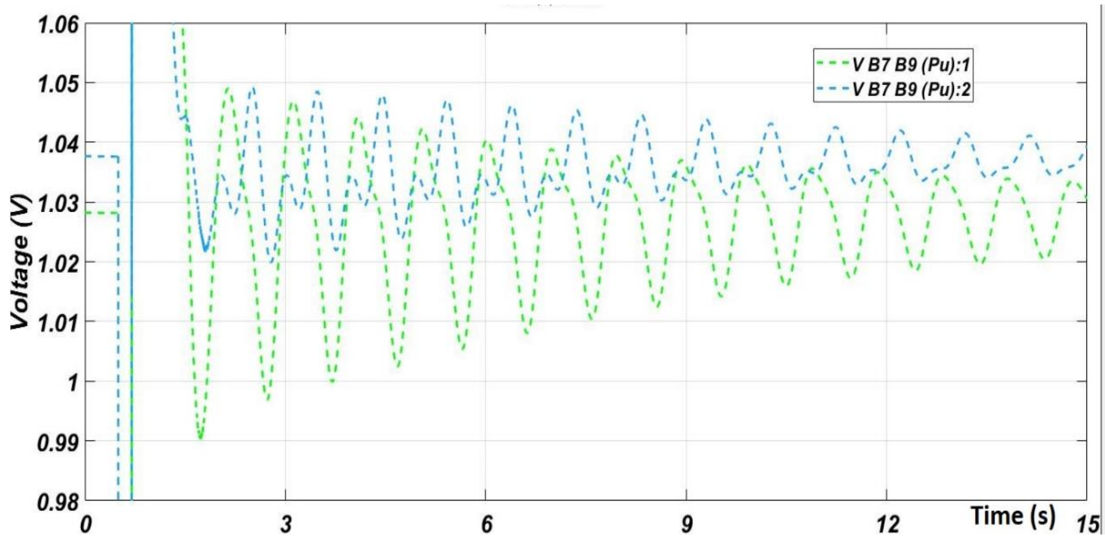


**Figure 5.12** Voltage measurement of B7-B9 of case 3.

Figure 5.12 shows the voltage measurements of bus no. 7 and bus no. 9 after the fault occurred at about 0.2 sec. The high voltage values that resulted are clear. The fluctuation in the system caused oscillations that stayed for between 9-15 sec and with a voltage range of 1.049 pu and 1.035 pu.

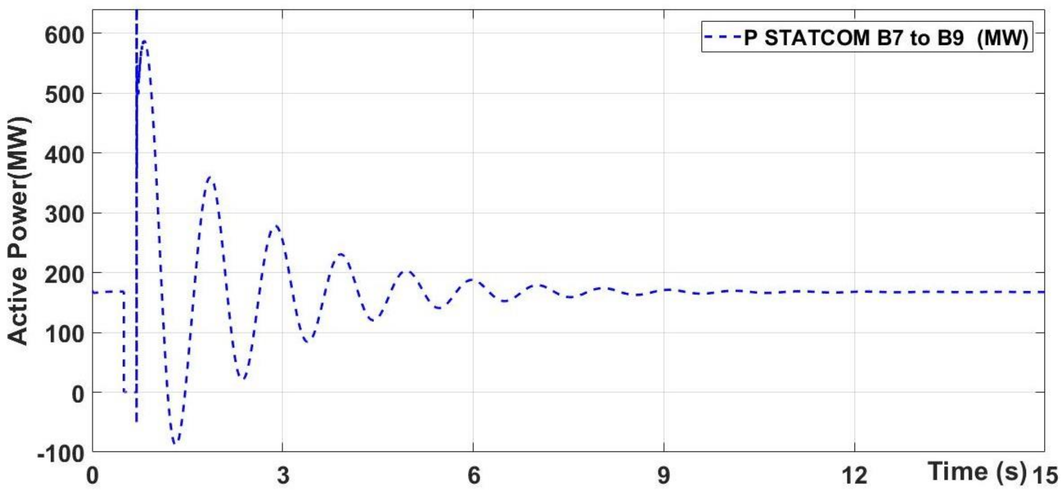


**Figure 5.13** Active power flow from B7-B9 of case 3.

Figure 5.13 Shows active power flow from bus no. 7 and bus no. 9. The fluctuation in the active power line is significant with a value 590 MW at 1 sec. Then system recovers to a stable condition gradually after the STATCOM controller works. The oscillations faded after about 9-15 sec with the active power value around 190 MW. This indicates a sufficient damping of the oscillations.

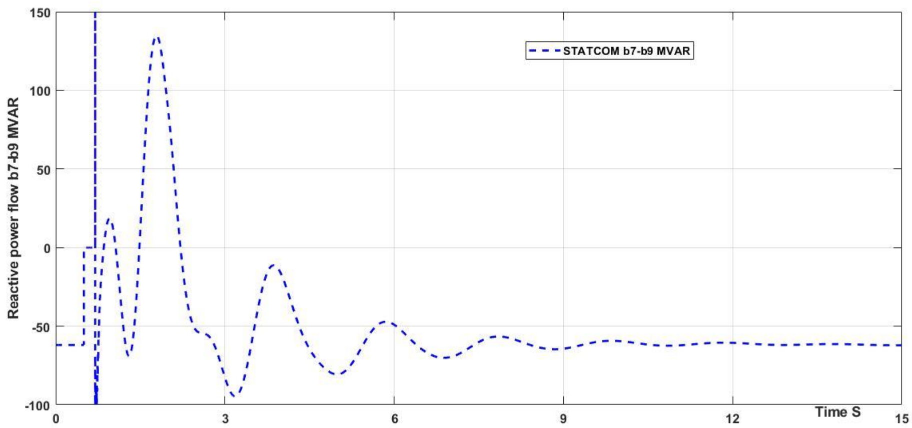


**Figure 5.14** Reactive power flow from B7-B9 of case 3.

Figure 5.14 shows reactive power flow for bus no. 7 and no. 9. After the fault at 0.2 sec, the STATCOM controller eliminates the oscillations progressively at time between 12.5 sec with a reactive power value about -60 MVAR.

### 5.2.6 Case 4

In this case study, the SSSC is added to Kundur System between bus no. 7 and bus no. 9. A fault that is 3-∅ to ground to the Kundur system is applied and the simulation model of SSSC is illustrated in Figure 5.15.

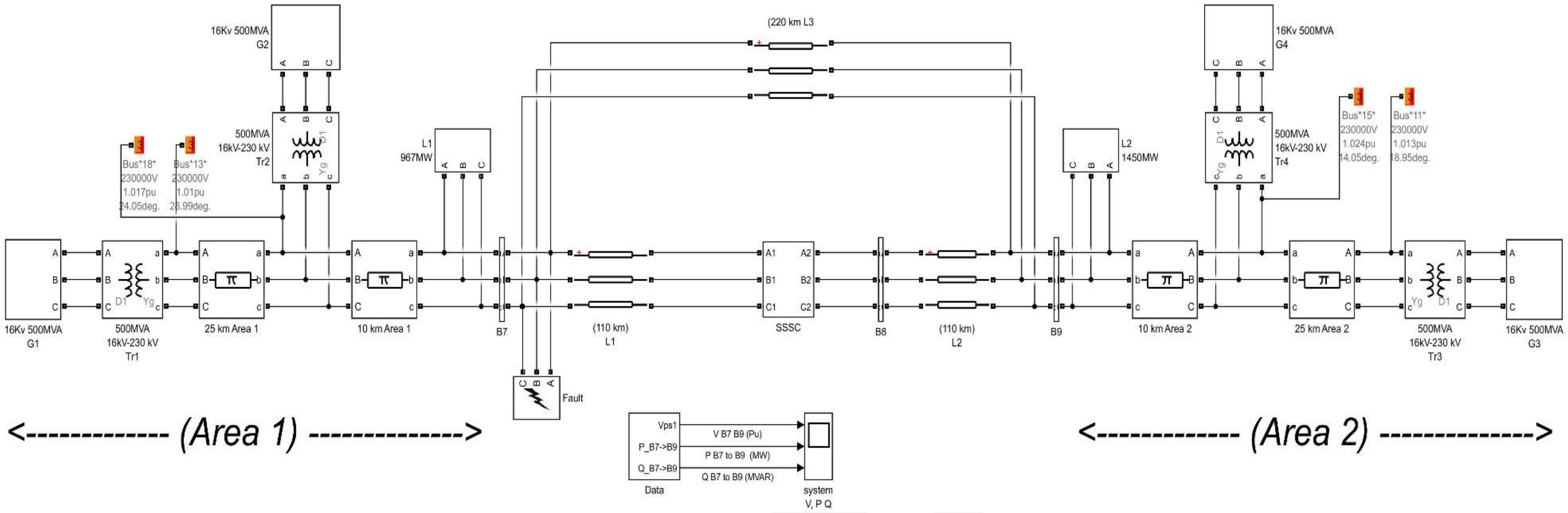


**Figure 5.15** Simulation model of case 4.

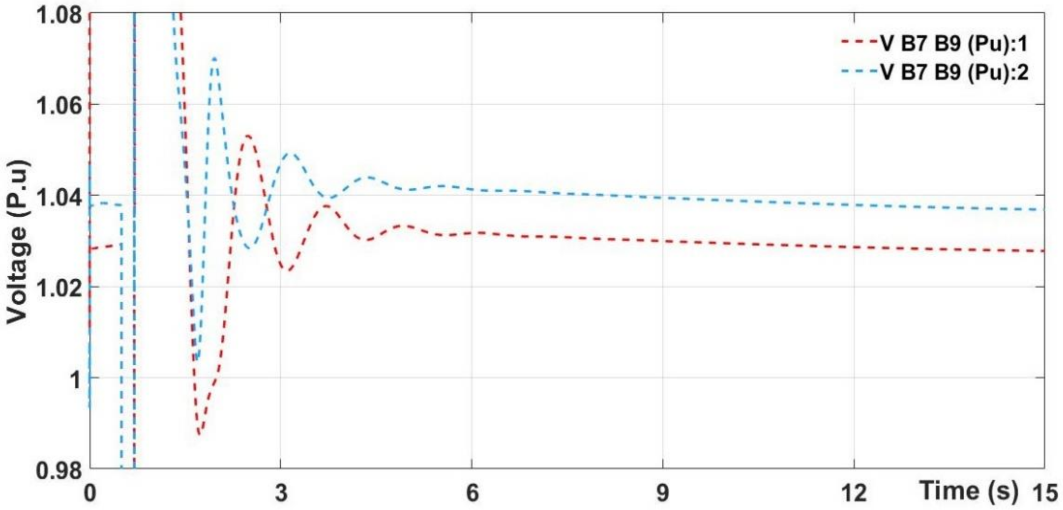


**Figure 5.16** Voltage measurement of B7-B9 of case 4.

Figure 5.16 Indicates voltage measurement of bus no. 7 and bus no .9. The damping of the oscillations that reached 1.07 pu and 1.01 pu after the fault around 0.2 sec is clear. Then these oscillations faded progressively after about 6 sec.

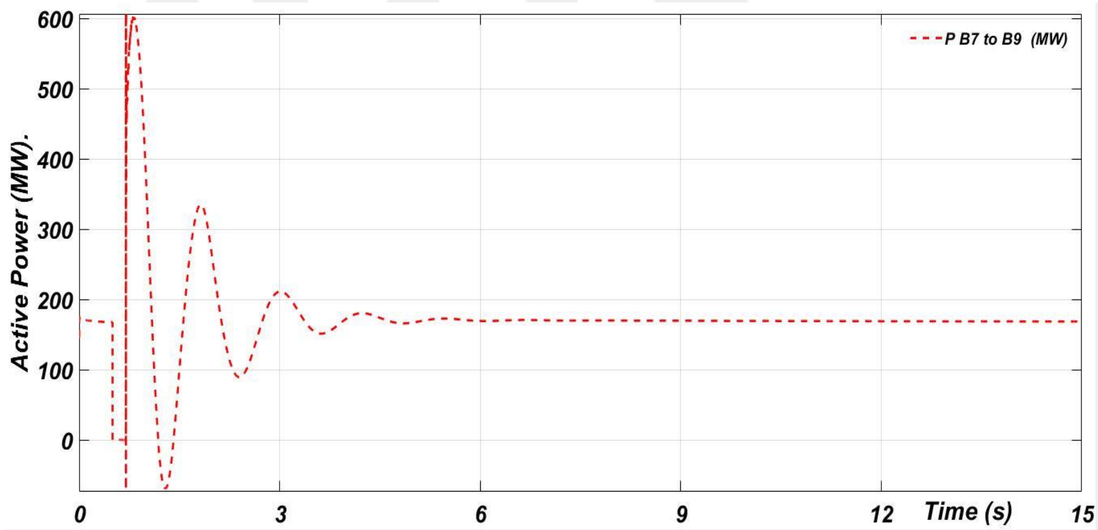


**Figure 5.17** Active power flow from B7-B9 of case 4.

The active power flow curve is shown in Figure 5.17. The SSSC controller provided successful damping although the fault at 0.2 sec caused a great oscillation with a range between 600 MW to -100 MW. The response of the system to the SSSC controller is high. The settling time starts at 5 sec. and stayed stable through 15 sec.

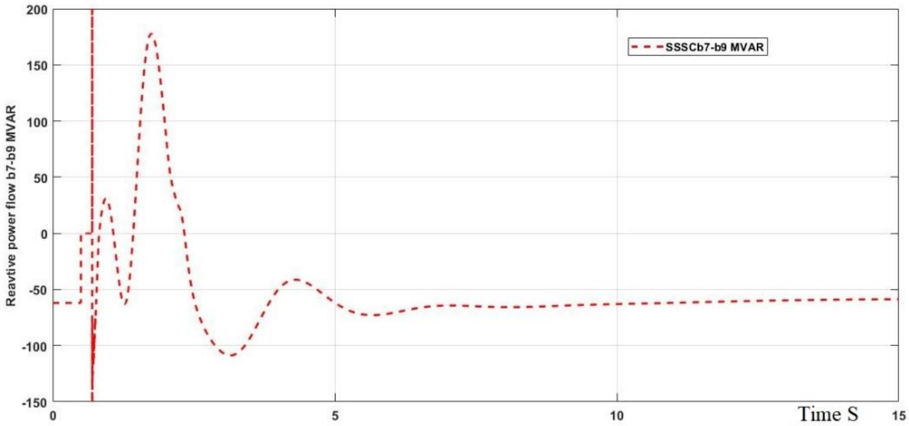


**Figure 5.18** Reactive power flow from B7-B9 in case 4.

Figure 5.18 shows a reactive power flow from bus no. 7 and bus no. 9. After the fault at 0.2 sec, the reactive power line has huge oscillations that caused significant fluctuation in the system. The huge oscillations 175 MVAR at time period about 1.8 sec which threatened the system. The SSSC controller successfully damped these oscillations. The settling time is around 10 sec as shown in the figure above.

### 5.3 Comparison of TCSC, STATCOM and SSSC

A comparison of the results obtained from each device, namely TCSC, STATCOM and SSSC, is necessary to determine the differences in the performance. The comparison in Figure 5.19 compares the active power for each case. The first (black) curve represents the state of the base grid without any FACTS device. These oscillations are clear and continuous in shape through the total time duration of the figure, and the system was unstable as a result of these harmful oscillations. It reached a maximum power of 600 MW and then fluctuated. The active power was about 280 MW after 12 sec and continued to fluctuate around this value for another 3 sec. The green curve represents the state after application of TCSC to the base grid. In this case, the oscillations reduced after the TCSC controller began to work. The TCSC enhanced the stability by reducing the harmful oscillations, but the system stayed unstable because these oscillations were not eliminated. The blue line indicates the application STATCOM with the base grid, and the damping of the oscillations can be easily observed in this case. The maximum power value was around 600 MW and the settling time was around 9 sec with a stable power value of about 185 MW. Red line refers to the applying of SSSC with the base grid. The addition of the SSSC controller eliminated the oscillations. The settling time was around 6 sec with a power value of about 180 MW, which indicated a stable condition. The best damping was obtained when the SSSC was used with the base grid in case 4. The SSSC controller was successful in providing an excellent damping range for oscillations with a sufficient stability.

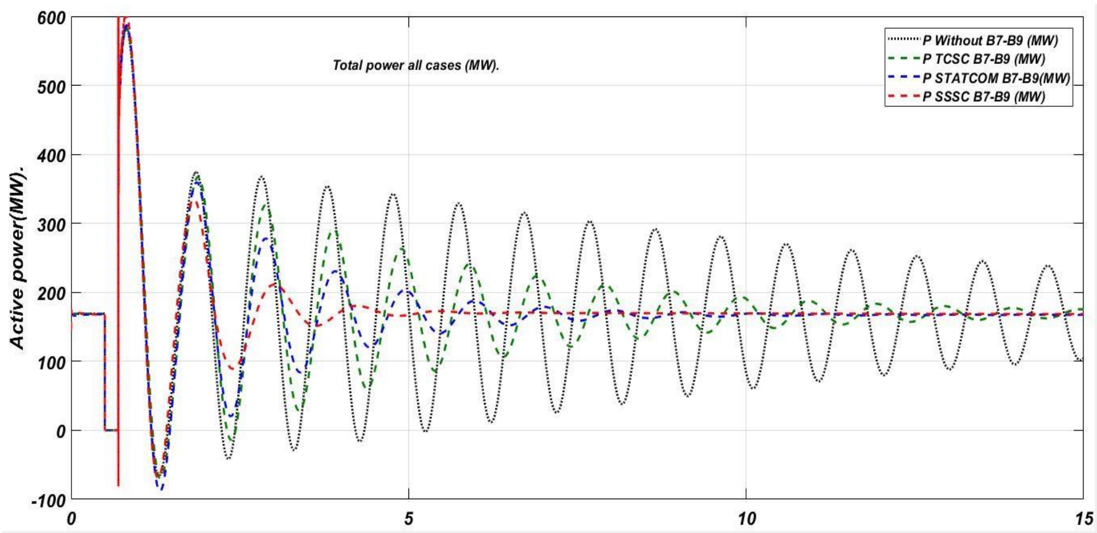


**Figure 5.19** Active power flow from B7-B9 for all cases.

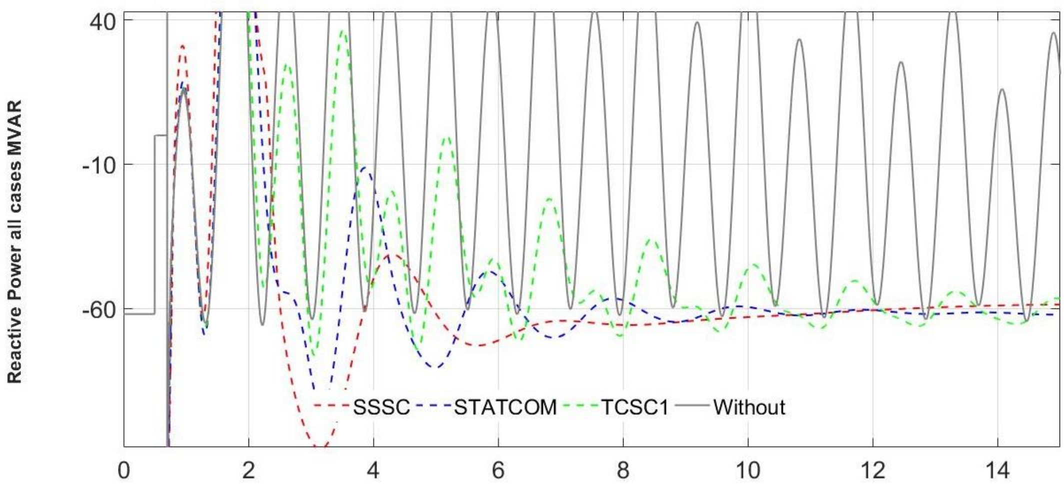


**Figure 5.20** Reactive power flow from B7-B9 for all cases.

Figure 5.20 shows reactive power flow of bus no. 7 to bus no. 9 for all studied cases. All these cases affected to applying fault at time period around 0.2 sec. The fluctuations that occurred in the systems as a consequence to unstable conditions indicated a required for damping of these oscillations. Case 1 indicating to the applying of Kundur power system without adding FACTS devices, the oscillations are huge and continuous along time iteration between 0- 15 sec. The harmful oscillations are threatened of the power system that required an appropriate controller to damping of these oscillations for ensuring optimal operation of power systems. Therefore, FACTS devices are individually connected to the Kundur system between bus no. 7 and bus no. 9. Case 2 indicates for the applying TCSC to the Kundur system which is represented in Figure 5.20 with green curve. The reactive power curve has great oscillations especially after applying a fault at t= 0.2 sec, but when TCSC controller starts working the oscillations reduced gradually without eliminating it. The oscillations in case 2 reach a continuous value around -55 MVAR at time period about 13 sec to stay with the same value along time iteration in the Figure. The best performance for damping unstable oscillations can be got by applying SSSC to the Kundur system. The SSSC controller success of damping oscillations with a stable value at time duration 11 sec. SSSC damped the oscillations effectively. Also, the reactive power flow curve reaches a stable value in a short time about 11 sec if compared to other studied cases. The oscillations of an inter-area mode were detected after conducting the power readings from Figure 5.19. The oscillating frequency and the damping ratio were obtained after applying Equation (5.1). The values in Table 5.2 represents the oscillating frequency and the damping ratio for all cases. These values are the basic criterion for determining the performance for each device in the system by the damping ratio. This value indicates the reduction of oscillations and optimum stability for the base system. The SSSC controller provided an excellent and damping ratio of about 11.90 with a sufficient oscillation frequency around 0.528 Hz.

**Table 5. 2** Values of oscillation frequency and damping.

| CASE | Oscillation frequency | Damping ratio |
|---|---|---|
| WITHOUT | 0.763 | 6.61 |
| TCSC | 0.681 | 8.13 |
| STATCOM | 0.597 | 10.20 |
| SSSC | 0.528 | 11.90 |

# CHAPTER 6

# CONCLUSION WITH FUTURE WORK

## 6.1 Conclusion

On perpetually, the oscillations of the power have been causing a very serious concern for the proper operation and security of the electrical system. These oscillations have major causes to occur, swinging quotient in the rotational type of electric generator as a consequence of fault occurs in the operation of the system, the switching in the transmission line, the instantaneous alteration that happens suddenly in generator's output, the alteration that happens suddenly in the loads which are crucial. The current work is aiming to find an ideal method to improve the stability of the electric grid of the studied system which is the Kundur's power system by comparing the dynamic operation of several FACTS devices separately in the network and deducing from the simulation results on the optimal performance and identification at the condition of a significant perturbation. The scrutinized results carefully are conducted to overall situations of the studied systems. The case no.1 was beheld by applying a system of four generator machine, 11 buses Kundur system to work normally and then the Subjugation of system to a simple disturbance which is 3-phase to ground fault. The extracting measurements are obtained from platforms simulation model are conducted. In the case no. 2, the TCSC implementation has been done with Kundur system. All required measurements underpinned by the simulation model. The same work was achieved with simulation for a STATCOM and SSSC facts devices. Taking into account the proper way of connecting to each device. The simulation results pointed out that with a proper placement and parameter setting of each FACTS device, it can enhance the power oscillation damping of the specific network power system and contingency conditions. The values of Table (5.2) has been studied to concludes that the SSSC can be present the best results for power oscillation damping and frequency oscillation. The value of damping ratio of SSSC is 11.90. This contributes to enhance power transferred and rising the stability power system.

## 6.2 Future work

1. Possible to extend this work to include the implementation of three FACTS devices with another grid system more complex to inquiry the troubles involve the numerous modes of power system oscillation.

2. Utilizing of different techniques controller for improving the dynamic performance system of the Iraqi National Grid with an ideal place of FACTS devices.

3. According to the subject of the thesis, the suggestion for adding another FACTS device has a shunt connected with a grid for the comparison for an accurate result.

4. Analysing the harmonics in the overall system and investigated to approach in order to reduce the system harmonics.

5. Replaced all devices with voltage source converter VSC that considered in this thesis; by a five-level multilevel-FACTS device and study the dynamic performance of the system.

6. Three phase faults with low impedance short circuit have been considered in this study that can be extended to discover the response of the system to other faults standers.

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## APPENDIX

Parameters of Kundur power system

Total generation

P=1402.32 MW, Q= -139.67 MVAR

Total load consumption

P=1388.38 MW, Q= -91.3 MVAR

The first Generator

V= 16 kV/1.0 Pu 08.22 deg P_capacity =500 MVA

Generation P=350 MW, Q= -14.3 MVAR

The second Generator

V= 16 kV/1.0 Pu 0.2 deg P_capacity =500 MVA

Generation P=352.32 MW, Q= -39.09 MVAR

The third Generator

V= 16 kV/1.0 Pu 5.4 deg P_capacity =500 MVA

Generation P=350 MW, Q= -25.9 MVAR

The fourth Generator

V= 16 kV/1.0 Pu 3.2 deg P_capacity =500 MVA

Generation P=350 MW, Q= -60.38 MVAR

The First Load

V= 230 kV/1.028 Pu   P=532.34 MVA          Q= -45 MVAR

The second Load

V= 230 kV/1.037 Pu   P=856.04 MVA          Q= -46.3 MVAR

Distributed parameters lines V=1.0Pu/230KV

1: Number of transmission lines for 10km=2

2: Number of transmission lines for 25km=2

3: Number of transmission lines for 110km=2

4: Number of transmission lines for 220km=1