JOSUE MBUYAMBA KAYEMBE
REACTIVE POWER COMPENSATION USING THE FACTS DEVICE STATCOM
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NEAR EAST UNIVERSITY
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M.Sc. THESIS

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Approval

We certify that we have read the thesis submitted by Josue Mbuyamba Kayembe titled **"Reactive Power Compensation Using the Facts Device STATCOM"** and that in our combined opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Masters in Electrical and Electronics Engineering.

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Declaration

I hereby declare that all information, documents, analysis and results in this thesis have been collected and presented according to the academic rules and ethical guidelines of Institute of Graduate Studies, Near East University. I also declare that as required by these rules and conduct, I have fully cited and referenced information and data that are not original to this study.

Josue Mbuyamba Kayembe

27/06/2022

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Abstract

Reactive Power Compensation using the Facts Device STATCOM

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M.S.c, Department of Electrical and Electronics Engineering

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Reactive power in power systems is a very important matter and it can be detrimental unless kept under strict control. Reactive power control gains importance especially with inductive loads, having low power factors. Inductive loads with low power factors draw higher currents from the power system and hence increase the line losses, increase line voltage drops and hence decrease the load voltages. These problems can be mitigated by doing reactive power compensation. Reactive power compensation is accomplished using several FACTS devices. STATCOM is one of the most popular FACTS device that is being used frequently nowadays.

In this thesis, the FACTS device STATCOM is used for compensating the reactive power in a 2-bus electric power system, with the sole aim to show that when compensated, it enhances the power factor of the supply, voltage regulation of the transmission line, voltage stability of the power system, and the efficiency of the transmission line. The power system consists of a 2-bus power system which supplies power through a short transmission line to an inductive load having a nominal real power of 3 MW and nominal reactive power of 3 MVAR. The simulations were carried out for transmission lines of 3 different lengths, which are respectively 10 km, 20 km, and 30 km. This enabled us to observe the effect of transmission line impedances on voltage stability, voltage regulation and efficiency. The supply voltage is 22 kV. The results of the simulations done with MATLAB/Simulink software have shown that the application of STATCOM reduces the reactive power burden on the transmission line, enhancing the power system's voltage profile and the transmission line's active power carrying capacity.

Keywords: FACTS Device; STATCOM; Reactive Power Compensation; Voltage Source Converter; Voltage Stability

Özet

Reactive Power Compensation by the Facts Device STATCOM

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Güç Sistemlerinde reaktif güç çok önemli bir konudur ve kontrol altına alınmaması durumunda tehlikeli olabilir.Düşük güç faktörlü endüktif yük durumunda reaktif gücün bilhassa kontrol altına alınması önemlidir.Düşük güç faktörlü endüktif yük durumunda güç sisteminden çekilen akım artar ve dolayısıyla hat güç kayıpları da artar.Hat empedansı üzerindeki gerilim artar ve bu da yük üzerindeki gerilimin düşmesine neden olur.Bu sorunlar reaktif güç kompanzasyonu ile iyileştirebilinir.Birçok Esnek Alternatif Akım İletim Sistemi(FACTS)cihazları ile reaktif güç kompanzasyonu yapılabilir.Statik Senkron Kompanzatör(STATCOM) günümüzde sıklıkla kullanılan bir FACTS cihazıdır.

Bu tezde, 2-baralı bir elektrik güç sisteminde reaktif güç akışının kompanzasyonu için STATCOM (Statik Senkron Kompansatör)FACTS cihazı kullanılmıştır.Kompanzasyon sayesinde tedarik barasının güç faktörünün,iletim hattının gerilim regülasyonunun ve yük geriliminin iyileştiği görülmüştür.Benzeri bir şekilde iletim hattının verimi artmıştır.2-baralı bir güç sistemi,3 MW nominal gerçek güce ve 3 MVAR nominal reaktif güce sahip endüktif bir yükü,kısa bir iletim hattı üzerinden beslemektedir.İletim hattı empedanslarının voltaj kararlılığı, voltaj regülasyonu ve verimlilik üzerindeki etkisini gözlemlememizi sağlamak için simülasyonlar 10 km, 20 km ve 30 km olmak üzere üç iletim hattı uzunluğu için gerçekleştirilmiştir. İletim hattı voltajı 22 kV'dur. MATLAB/SIMULINK ile yapılan simülasyonların sonuçları, STATCOM uygulamasının iletim hattı üzerindeki reaktif güç yükünü azalttığını, iletim hattının aktif güç taşıma kapasitesini artırdığını ve gerilim profilini iyileştirdiğini göstermiştir.

Anahtar kelimeler: FACTS; STATCOM; Reaktif Güç Kompanzasyonu; Gerilim Kaynağı Dönüştürücü; Gerilim Kararlılığı

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List of Abbreviations

CSC:	Current-Source-Converter
D-STATCOM:	Distribution Static Synchronous Compensator
EHV:	Extra High Voltage
FACTS:	Flexible AC Transmission System
FC-TCR:	Fixed Capacitor-Thyristor-Controlled Reactor
GTO:	Gate Turn Off
GUPFC:	General Unified Power Flow Controller
HV:	High Voltage
IEEE:	Institute of Electrical and Electronics Engineers
IGBT:	Insulated Gate Bipolar Transistor
IPFC:	Interline Power Flow Controller
MSC:	Mechanically-Switched Capacitor
MSR:	Mechanically Switched Reactor
PI:	Proportional Integral
PLL:	Phase Locked Loop
POD:	Power Oscillation Damping
PWM:	Pulse Width Modulation
SMES:	Superconducting Magnetic Energy Storage
SSSC:	Static Synchronous Series Compensator
STATCOM:	Static Synchronous Compensator
SVC:	Static VAR Compensators
TCPST:	Thyristor-Controlled Phase Shifting Transformer

TCSC:	Thyristor-Controlled Series Capacitor
TCSR:	Thyristor Switched Serie Reactor
TCVR:	Thyristor-Controlled Voltage Regulator
UPFC:	Unified Power Flow Controller
VSC:	Voltage Sourced Converter
VSI :	Voltage Sourced Inverter

CHAPTER I

Introduction

I.1 Overview

The need for electrical energy is constantly rising because of increasing industrialization and increasing population. This situation puts a big stress on the existing power systems, especially the transmission lines. The need for making new investments to expand the existing power systems, including the transmission lines is obvious. However environmental and economic constraints make the realization of new power projects difficult to implement. The demand to transmit more electric power presents a dilemma to the decision makers on power systems. Either new transmission lines should be installed or the capability to transfer power of the existing transmission lines should be increased to meet this demand. Constructing a new transmission line is very expensive and for this reason increasing transmission lines ability of existing lines to transfer more power has been found to be more economical and effective solution to this problem (Hingorani&Gyugyi,2000).

The main aim of the AC power systems is to generate active power, transmit it via transmission lines and then distribute it for general use. However, the loads connected to the power system are very seldom purely resistive. Most loads are generally inductive in nature. Capacitive loads are very rare. It is well-known that capacitors and inductors can store energy inside them. Capacitive loads store energy in the electric field. Similarly inductive loads store energy in the magnetic field during a quarter of a cycle and then return it during the next quarter of a cycle. This kind of power arising from the stored energy in capacitors and inductors, this power is referred to as reactive power and differs from the active power which is used to do work. There is no work done with reactive power, but it is necessary for the load to operate properly. Resistive loads do not require any reactive power. Reactive power is required for the operation of motor loads, which are inductive loads.

Power consumption in power systems generally occurs in inductive loads. Note that the current waveform in a resistor and the voltage waveform across it are in-phase whereas the current waveform in a capacitor or inductor and the voltage waveform across them are out of phase. This is the main reason for the existence of reactive power. The average active power being supplied by the generator causes a net flow of power to the load whereas the average reactive power supplied by the generator is zero. This is because the amount of reactive power flowing towards the load during a quarter of a cycle is equal to the power flowing back to the generator during the next quarter of a cycle. This means that reactive power is neither produced or consumed. Reactive power is stored temporarily and then released back to the supply. Reactive power is important because its back-and-forth flow in the transmission lines increases the current considerably in the line which in turn increases the ohmic power loss in the lines and increases the voltage drop in the line.

Reactive power flow is inevitable in power systems, because loads require it for its proper operation. However, the flow of reactive power in transmission lines adversely affects the power system performance. It causes voltage drop on line impedance to increase and worsen the voltage regulation of transmission lines. It causes the power loss in the lines to increase and worsen the efficiency of the line. These losses cause a reduction in the potential of active power transmission in the lines. To provide the loads with the reactive and real power they require, the generators have to make up for the power losses induced by reactive power and as a result the generation capacity of the power system has to be increased which would be costly. A well-designed reactive power compensation can mitigate the above adverse effects of reactive power on the power system.

Until 1980’s reactive power compensation was done by employing conventional methods, such as capacitor banks, reactors and synchronous condensers. The response of these conventional devices was not as rapid as desired to minimise the adverse effects caused by reactive power. Advances in power electronics technology made it possible to design new technologies, based on power electronics that would respond to adverse effects caused by reactive power very quickly.

In 1990’s two renown engineers, Hingorani and Gyugyi, developed a new system which they called Flexible Alternating Current Transmission System, abbreviated as FACTS, to compensate for the adverse effects of reactive power on transmission lines (Hingorani&Gyugyi,2000). They employed power electronic devices such as GTO’s and IGBT’s instead of conventional thyristors in designing their controllers. The electronic devices offered relatively high-speed and reliable switching. By making use of GTO’s and IGBT’s Voltage Sourced Converters, which act as the brain of FACTS devices were developed. FACTS Controllers developed in this way were employed to increase the real power carrying capability of existing lines, without adversely affecting the thermal and power stability limits of transmission lines.

FACTS technology offers additional opportunities to power systems as well. It provides an opportunity to improve the stability and controllability in power systems. Similarly, it offers another opportunity to ease congestion in the lines, by controlling both reactive and active powers. It also helps to dampen the power oscillations in power systems.

I.2 Statement of the Problem

Utilization of reactive power compensation techniques in power systems is a very useful tool for maintaining voltage stability, especially at the load buses. Loads connected to a power system draw real and reactive power over long transmission lines. Inductive loads having low power factor require more reactive power compared to inductive loads having higher power factor. As the load requires more reactive power, the currents on the transmission lines increase, increasing their power losses. The voltage drop in the line impedance worsens the voltage regulation of the line and the magnitude of the load bus voltage drops. This is undesirable and an action should be taken to remedy it. Compensation of reactive power at the load bus is referred to as load compensation, is the correct solution. now, reactive power will be generated directly from the reactive power compensator, the STATCOM connected next to the load bus. There is no need for the power system to supply reactive power over the transmission lines any more. The reactive power transmitted by the transmission line reduces approximately to nearly zero.

In this thesis we will make use of a FACTS Controller called Static Synchronous Compensator, STATCOM, and carry out load compensation at a load bus.

I.3 Aim of the Thesis

This thesis aims to study a 2-bus power system which supplies power through a short transmission line to an inductive load having a nominal real power of 3 MW and nominal reactive power of 3 MVARs. The nominal powers are so chosen to make the power factor of the load low at a value of 0.7071pf lagging. This is a relatively very bad power factor. We intentionally choose such a load having a bad power factor to study the worst case. From the supply, the load requires a high amount of reactive power, will enable us to observe its negative effects on the voltage stability, efficiency and voltage regulation more clearly. The supply bus voltage in this study is chosen as 22 kV, line-to-line, which is within the limits of medium voltage (MV) classification.

Generally reactive power compensation is not done for short transmission lines if the loads connected to them have normal power factors. The transmission line in this study although short, it is connected to a load having a very bad power factor and for this reason reactive power compensation is a must.

In this thesis, we will utilise a Static Synchronous Compensator, abbreviated as STATCOM to compensate for reactive power. STATCOM is a Flexible Alternating Current Transmission System (FACTS) Controller used for reactive power compensation on AC transmission systems. STATCOM has been extensively used in recent years all over the world to alleviate voltage stability and other drawbacks in power systems.

In this study STATCOM is connected next to the load bus because it has been found that it is most effective at that position. We will study the positive effects of reactive power compensation for 3 different lengths of transmission line, namely 10 km, 20 km and 30 km. Under these conditions the transmission line behaves as a Short Transmission Line (<80 km) and will be represented by a series resistance and inductance only. This will simplify the simulation of the transmission line by the MATLAB/Simulink. Different lengths of transmission lines will enable us to observe the effect of transmission line impedances on voltage stability, voltage regulation and efficiency.

MATLAB/Simulink software will be used to simulate the power system under consideration.

I.4 Significance of the Thesis

The significance of the thesis is that it proposes to make use of an effective power electronics-based FACTS device, the STATCOM, to compensate for reactive power in power systems, with the sole purpose to show that it improves the voltage stability, power factor of the supply, efficiency and voltage regulation of the transmission line. By implementing STATCOM, the transmission line is burdened with less reactive power. This opens up the possibility of increasing the transmission line's active power carrying capacity.

A two-bus power system was used in this study. The satisfactory results obtained from this study can be extended to STATCOM applications to power systems with more buses, in future work.

I.5 Limitations of the Study

MATLAB/Simulink was used for simulation of the power system under study. By using MATLAB/Simulink one can thoroughly analyse the results of the proposed model. The software can display current and voltage waveforms at different points. It displays the magnitudes of both reactive and active power wherever you wish in the power system. It also measures power factors at the buses.

By using MATLAB/Simulink software we studied the behaviour of the power system under different scenarios. This made it possible to understand more clearly the response of the system to several changes. The Electrical and Electronics Engineering Department lacks an advanced power system simulation lab and because of this we could not realise the 2-bus power system experimentally.

I.6 Overview of the Thesis

The thesis is divided into 5 chapters. They are:

Chapter I: Introduction

Chapter II: Literature Review on Conventional Reactive Power Compensators and the FACTS Devices

Chapter III: Operation of STATCOM and the Control System

Chapter IV: Simulation Results of the 2-Bus Power System, Before and After Compensation

Chapter V: Conclusion and Recommendation

CHAPTER II

Literature Review

II.1 Introduction

In this chapter different reactive power compensation techniques, ranging from conventional techniques to most recent FACTS techniques, will be studied and compared. Unless kept under control reactive power flow in transmission lines may cause detrimental effects on the whole power system (Padiyar,2007). Reactive power need of inductive loads, unless compensated by some means, may cause excessive power loss in transmission lines. Similarly, voltage drop on line impedance of the transmission line, consist of a resistor which is in series with an inductance, can harm the voltage stability at load buses. In the case that the utility's power factor is below the set value in the national regulations, the utility may have to pay additional fees for reactive power drawn from generators. To avoid penalty payments, utilities should compensate for reactive power themselves.

The reactive power generated and consumed in an electrical power system as a whole is balanced. This balance continues to exist whenever reactive compensation is done by using external devices as well.

II.2 Conventional Methods of Reactive Power Compensation

II.2.1 Capacitor Banks

The performance of transmission lines, especially those of medium length (between 80 and 240 km) and longer(>240km), can be improved by making use of static capacitor banks connected either as series or in shunt with each phase conductor of the line. Shunt connections are more widely used than series connections. Shunt connection is employed at all voltage levels whereas series connection is used more with EHV (>230 kV). Shunt connections can be either delta or wye. Power factor correction was first performed with shunt capacitors in 1914 (Frank&Ivner,1981). Shunt compensation is done at load buses where under normal operating conditions the load bus voltages, unless compensated, could be lower than the rated values. When the load voltage decreases beyond acceptable limits, it may harm the load. Reactive power is generated by shunt capacitors and supplied directly to the load. By doing so:

i. the reactive component of the line current, coming from the generator bus is reduced,
ii. the voltage drops in the line decreases, as a result it improves the voltage level of the load voltage,
iii. line losses are reduced,
iv. power factor of the supply is improved and
v. the burden on the generators and transformers are reduced.

By neutralizing the inductive reactance of the line, series capacitors reduce its effective overall reactance, and the voltage drop across the line impedance will decrease. This causes the voltage regulation of the system to improve. An example of this is shown in the following equation, which shows how much power is flowing between two buses.

$$P = \frac{V_1 \times V_2}{X} \times sin\delta \tag{2.1}$$

where:

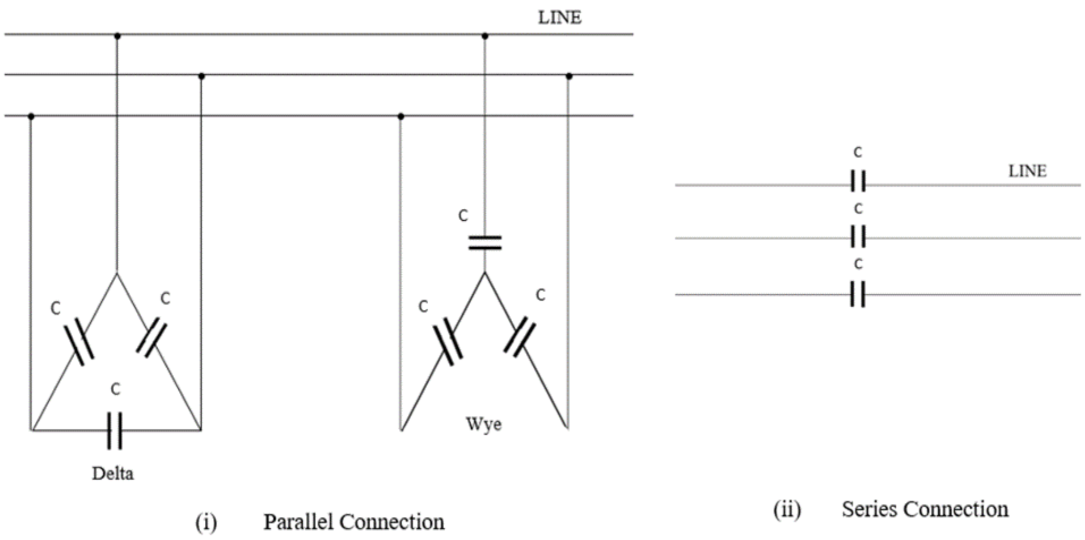
- V_1 : Magnitude of voltage at bus no.1
- V_2 : Voltage magnitude of at bus no.2
- δ: Difference of phase angle between V_1 and V_2
- X: Effective reactance between the buses

It can be seen from Equation 2.1 that a decrease in the overall line reactance X, between the two buses, caused by the capacitor's reactance, increases the active power transmitted. The line's overall reactance decreases

The reactive power need of inductive loads may vary in time, which necessitates a dynamic response from the shunt capacitor bank. It is possible to over-compensate or under-compensate when using a fixed capacitor bank. Variable compensation is achieved by either switching different capacitor banks to connect or disconnect successively from the power system, by using relays or circuit breakers.

Figure 1

Reactive Power Compensation by Capacitor Banks



II.2.2 Shunt Reactors

This kind of reactors are applied at HV long transmission lines(>240km) to offset the voltage rise due to Ferranti Effect (Cook et al.,2019). In the case of small or no loads connected to a very long transmission line, the Ferranti effect refers to the occurrence of a voltage increase at the receiving end, in comparison to the sending end voltage.

This effect can be reduced by a shunt reactor connected at the receiving end. By doing so it stabilises the line voltage during load variations. The equivalent circuit of long lines is modelled by a series resistance, inductance and shunt capacitance. Shunt reactors consume excessive reactive power and improve the performance of AC grid.

Shunt reactor absorbs the reactive power generated by shunt capacitors of the lines and keeps the voltage within desired limits it also reduces the voltage increase which in turn improve the voltage stability. It should be noted that when compensated, the power transport capacity of the line increases and thereby the efficiency of the transmission line increases. Traditionally, shunt reactors have a fixed rating that can be either permanently connected to the transmission line or switched on and off as needed.

The development of Variable Shunt Reactors (VSR) has taken place recently. By making use of on-load tap changer, the VSR rating can be changed in steps. Voltage stability can be maintained by continuously compensating reactive power as the load varies. With VSR, there is less voltage jumps compared to the case of switching on and off of the conventional fixed shunt reactors.

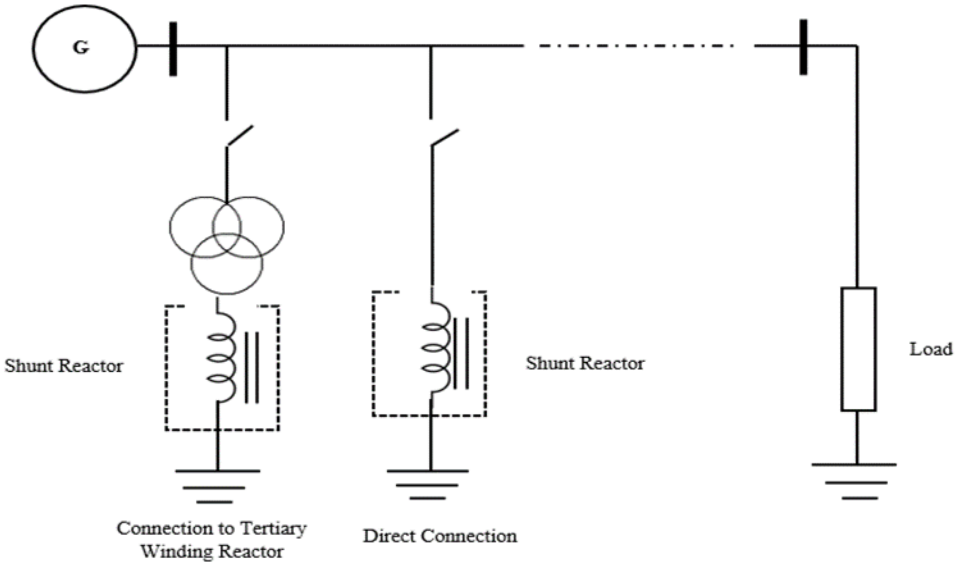
Shunt reactors are arranged between transmission lines and ground. Their place of installation is usually located at the end of overhead long transmission line or in central substation.

Shunt reactors and power transformers are similar in construction. Their size is big. Shunt reactors have one winding per phase whereas power transformers have two windings per phase. Shunt reactors can be oil-immersed or dry-type. Shunt reactors are usually connected directly to the bus, or transmission line or via a tertiary winding of a three-phase transformer to the transmission line. Shunt reactors are rated as MVAR whereas power transformers are rated as MVA. Typical shunt reactors ratings vary from 5 MVAR up to 155 MVAR per phase (Cook et al.,2019)

For long HV transmission lines, usage of shunt reactors are most important because they are very effective in absorbing reactive power in large quantities from transmission lines. Shunt reactors are must for 400kV lines and above. Shunt reactors have core losses during normal operation conditions and precaution must be taken for minimising the core losses when designing (Cook et al.,2019).

Figure 2

Reactive Power Compensation by Shunt Reactors



II.2.3 Synchronous Condensers

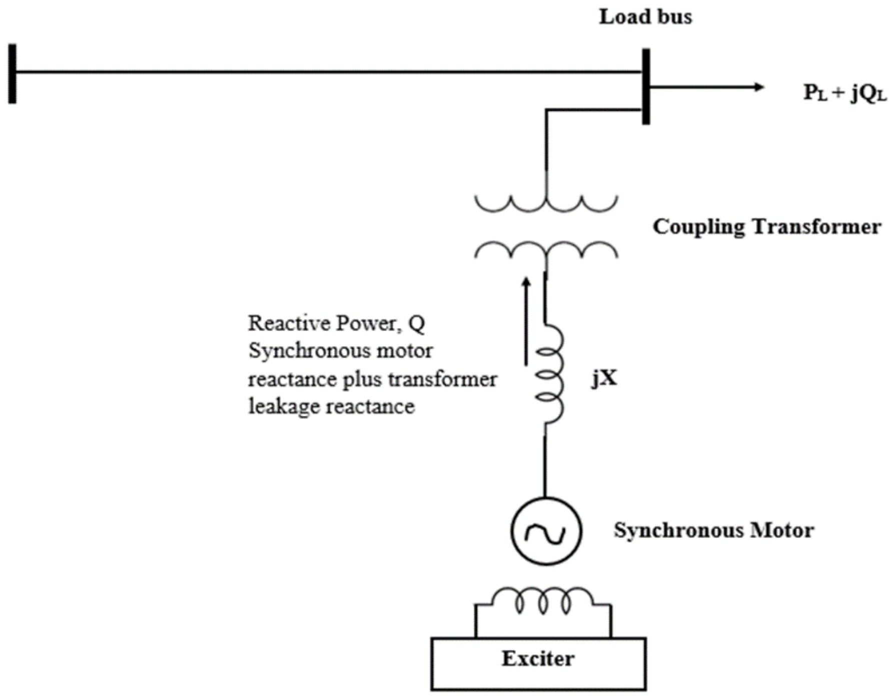
Synchronous condensers are rotating synchronous machines that operate at no-load and depending on whether the field winding is over-excited or under-excited generates reactive power or absorbs reactive power. Underexcited motors act like capacitors and supply reactive power to ac power systems, whereas overexcited motors act like inductors and absorb reactive power.

By making use of a controller the motor responds ‘synchronously’ to the need of ac system quickly and adjusts automatically the output reactive power to keep constant voltage at the terminal. Synchronous condensers require more maintenance work than static compensators because they are rotating machines. Synchronous condensers consume low real power because of low copper, iron and friction & windage losses of the rotating machine. To stabilize voltage levels on long transmission lines, synchronous condensers are used.

More than 50 years have passed since synchronous condensers were first used to control reactive power and voltage but nowadays, they are rarely used, because they require significant amount of protective and starting equipment (Dixon et al.,2005). Furthermore, they suffer higher losses and much higher costs when compared to static compensators.

Figure 3

Synchronous Condenser for Reactive Power Compensation



II.3 Flexible Alternating Current Transmission Systems (FACTS) Controllers

II.3.1 FACTS Concept

Power electronics devices were first used in HVDC transmission systems, both for regulating the flow of power in HVDC links and enhancing the system voltage stability. Thyristor valves and digital control were employed in the evolution of Static VAR Compensator used to compensate for reactive power in long transmission lines and voltage regulation (Padiyar,2007). Hingorani, by making use of power electronic devices, introduced the concept of FACTS, with an aim of improving voltage regulation and capability power transfer of existing transmission lines, ease congestion in lines and improve system security without adding new lines to the power system (Hingorani & Gyugyi,2000).

Hingorani led a large R&D Group at Electric Power Research Institute (EPRI, USA) on flexible transmission systems for many years. Another engineer Laszlo Gyugyi, led another R&D Team at Westinghouse laboratories (USA), collaborated with Hingorani and together they invented several important FACTS Controllers. Both of them are renown engineers who pioneered advances in many areas of power electronics.

II.3.2 FACTS Related Definitions made by IEEE Working Committee on FACTS

IEEE Working Committee on FACTS has made the following definitions for a better understanding of the topic.

Flexibility of Electric Power Transmission: The term flexible refers to a power system's ability to automatically adjust according to operating conditions to maintain a good static and dynamic safety margin.

Flexible AC Transmission Systems (FACTS): FACTS is the abbreviation for Flexible Alternating Current Transmission Systems.

FACTS Controller: An AC transmission system parameter is controlled by a power electronic system or other static equipment.

Before we proceed further in the topic, we have to decide on the terminology that we are going to use in this thesis. Most authors prefer to use the phrase ‘FACTS Controllers’, however recently some authors started to use the phrase ‘FACTS Devices’. In fact, both phrases are used to specify the same thing. In this thesis we will prefer to use the phrase ‘FACTS Controllers’ simply because the founders of FACTS technology, Narain Hingorani and Laszlo Gyugyi, prefer to use this one. Hingorani and Gyugyi state in their book why they prefer the word ‘Controllers’ over the word ‘Devices’ like this: the word ‘Controller’ describe a power electronic equipment that controls current, voltage, and power as part of a certain function.Power electronics use semiconductor ‘devices’ to realise a controller circuit. In this context ‘device’ sounds like a component. For this reason, we will use the phrase FACTS Controller from now on, in this thesis.

II.3.3 Advantages Offered by FACTS Controllers

Solid-state power semiconductor devices that have increased their voltage and current ratings-made possible by the technological advances-started to be utilised more and more in high voltage transmission systems. FACTS Controllers were one of the first area where these semiconductors were used to improve power systems, for controlling multiple parameters of the power system in a simultaneous and independent manner (Hingorani&Gyugyi,2000). FACTS Controllers have been extensively used over the past three decades for enhancing power system steady-state performance by:

- Transmission capability of existing lines is increased,
- Reducing the flow of reactive power, as a result the line will be able to carry more active power,
- Load sharing between parallel corridors,
- Improving voltage regulation,
- Preventing congestion in transmission lines,
- Maintaining voltage stability at buses,
- Maintaining dynamic and transient stability,
- Improving power quality,
- Damping oscillations of power systems and synchronous generators

FACTS Controllers provide the above opportunities as they are able to control most of the parameters. Some of these parameters are: phase angle series impedance, shunt impedance, , transmission line voltage, damping of oscillations and line current. FACTS Controllers add flexibility to the power system by upgrading the power transport capability close to its thermal limit. Rapid-response power electronics employed by FACTS Controllers, on the other hand, replaced mechanical switching in Conventional Compensators explained in section 2.2.

II.4 Classification of FACTS Controllers

II.4.1 Classification Depending on How They Are Connected to AC System

FACTS Controllers can be classified into four categories based on their connection to the power system (Hingorani, Gyugyi,2000). The aim of all controllers is for enhancing the stability, capability of power transfer and controllability of ac systems.

1). Shunt FACTS Controllers

According to the need, shunt controllers can function either as variable impedance sources like capacitors or inductors or as power electronics-based variable voltage sources. When connected to the power system, a shunt controller injects current into the system. A phase quadrature of the injected current implies that the voltage line is in phase with the current injected. The difference between the phase angle voltage and current phasors is 90 degrees, then the shunt controller only supplies or consumes reactive power. If the phase angle difference is other than 90 degrees then shunt controller can also provide or drain real power.

2). Series FACTS Controllers

Series controllers depending on the need may act as a variable impedance, such as that of a capacitor or inductor or a power electronics based variable source. series controllers are known for injecting voltage in series with the transmission line. The angle phase difference between current and voltage phasors is 90 degrees. The series controllers control real power. So that, the line impedance can be controlled.

3). Combined Series-Series FACTS Controllers

In a multiline transmission system, this system consists of separate series controllers that work together. The series controllers can be connected in a unified manner, where each series controller control active power of each line separately. Interline Power Flow Controllers (IPFC) are used for such connections and it will be explained later on in detail in this chapter.

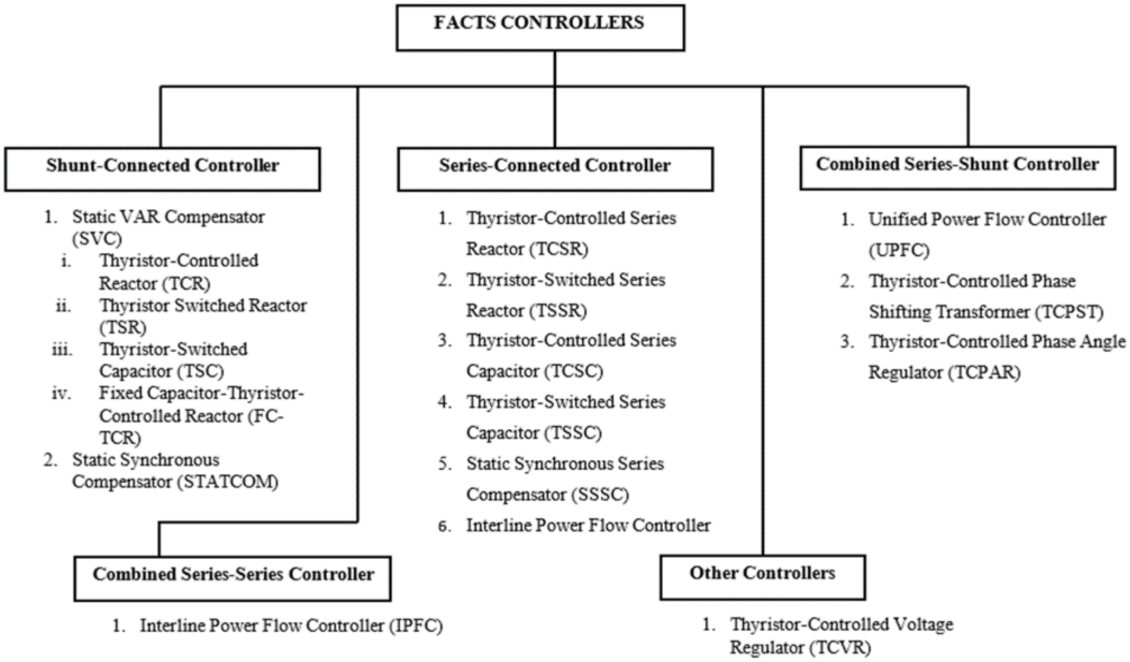
4). Combined Series-Shunt FACTS Controllers

The series-shunt device is a combination of separate series and shunt devices that are controlled in coordination. The shunt part of the controller injects current into the system while the series part of the controller injects voltage into the line. They allow multi-variable control, they are used to control the flow of active and reactive power, the voltage, and the phase shift angle. Such a connection is known as UPFC. If the controllers are connected via a DC power link (source of real power) then real power exchange can occur between the controllers. Combined Series-Shunt Controllers consist of UPFC, TCPAR and TCPST. Later on in this chapter these controllers will be explained.

According to how they are connected to AC systems, FACTS Controllers are classified in Table 1.

Table 1.

Classification of FACTS Controllers Depending on How They are Connected to AC System



II.4.2 Classification Depending on the Switching Speed of Power Semiconductor Devices

There are two generations of FACTS Controllers according to the switching speed of the power semiconductor devices (Hingorani&Gyugyi,2000):

II.4.2.1 First Generation FACTS Controllers

These employ conventional thyristors with gate turn-on only. These thyristors have no Gate Turn-off (GTO) capability. Response times are around 2-3 cycles. These are used to switch on and off components like capacitors and reactors to ac system, to provide or absorb reactive power, for regulating the power system. Examples are FC-TCR, TCR, TCSR, TCSC, TCPST and Thyristor-Controlled Voltage Regulator. These will be explained later on, in this chapter.

II.4.2.2 Second Generation FACTS Controllers or Converter-Based FACTS Controllers

These have faster response times, because they employ power semiconductors such as IGBT and thyristors with Gate Turn-Off (GTO) capability.

Second Generation FACTS Controllers generally use VSC rather than CSC based converters (Hingorani&Gyugyi,2000). One of the reasons why VSC converter is preferred to CSC converter is because VSC converter is cheaper than CSC converter. Examples of Second-Generation Controllers are STATCOM, SSSC, UPFC and IPFC. These will be explained shortly later on in this chapter.

As compared to the first-generation FACTS controllers, the second generation offers two main advantages:

1) They employ self-commutated converters such as Voltage-Sourced Converters which has the capability of absorbing or generating reactive power without requiring bulky inductors and capacitors, as in the case of Conventional Compensators explained in Section 2.2.

If required FACTS Controllers can be adjusted to generate or absorb real power, in addition to generating or absorbing reactive power. Energy storage units connected to the DC link capacitors make this possible. Possible energy storage units are batteries, fuel cells and superconducting magnetic energy storage (SMES) unit.

II.4.3 Classification Depending on the Number of Converters

There are several classifications of FACTS II controllers based on the number of converters they use (Hingorani&Gyugyi,2000):

- Single-converter FACTS Controllers: STATCOM is an example for such converters.
- Multi-converter FACTS Controllers: UPFC and IPFC are examples for such converters. Multi-converters are sometimes called Third Generation FACTS Controllers (Pravin&Mahajan,2016).

These controllers are described below.

II.5 First Generation FACTS Controllers

These are thyristor-based FACTS Controllers. Main examples are given below.

II.5.1 Static VAR Compensators (SVC)

This is a shunt controller. SVC is a FACTS controller for realising rapid reactive power compensation on high voltage transmission lines. The static var converter (SVC) exchanges inductive or capacitive current to keep or control specific electrical power system parameters (Hingorani&Gyugyi,2000). 60-600 MVAR is the range of ratings for SVC.

SVC is a general term for TCR, TSR and TSC. TCR is a First-Generation FACTS Controller whereas TSR and TSC are not. SVC is generally inserted in the middle of the line.

By controlling the thyristor’s firing angle of the valve, TCR is a thyristor-controlled inductor that has a continuously variable effective reactance. FACTS controllers have been replaced with TCRs as an affordable alternative (Sahu et al.,2015).

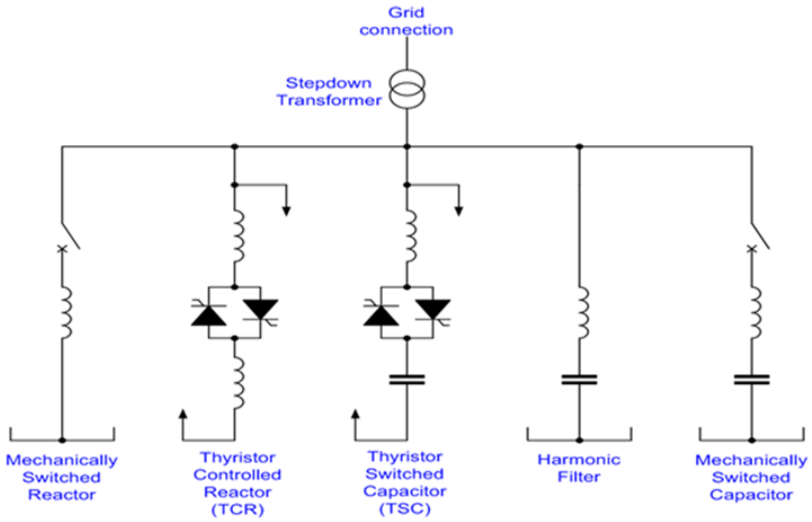
Using a thyristor-switched inductor, TSR are shunt-connected and have a stepwise variation of reactance. There are several TSR connected shunt to the AC system. TSR is not a First-Generation Facts Controller.

Figure 4 below shows a typical SVC configuration, TSR and TSC are connected shunt at the SVC bus and then coupled to the power system via a coupling transformer. Note that a MSR, a MSC and a harmonic filter are also connected (Hingorani et al.,2000) to the SVC bus. This modular form provides a customised solution for different requirement. The reactive power required is obtained by the coordinated control which gives a better and more precise response when in comparison with mechanically-switched compensation.

SVC sustains steady-state line voltage, performs reactive power compensation quickly, stabilises transient voltages and improves the load power factor.

Figure 4

Static VAR Compensator (SVC)

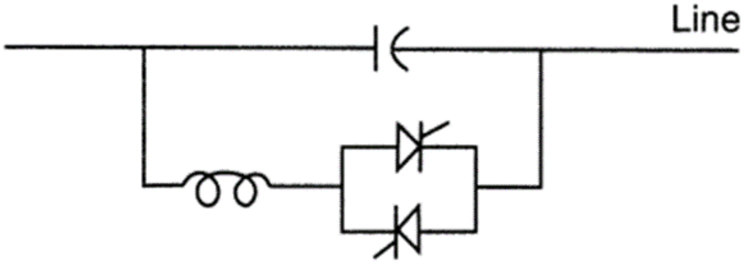


II.5.2 Thyristor-Controlled Series Compensation

This is a series controller. Using variable series compensation, you can both control the flow of active power in the line and improve its stability. (Abdulrazzaq,2015). In order to increase the power transmitted by a three-phase line, we need to add a capacitor with a fixed capacity in series with each phase of the line. This has the effect of reducing the inductive reactance of the line. As shown in Equation 2.1. Series compensation comes in many forms. We will only study TCSC and TSSC. Figure 5 TCSC which equally represents TSSC.

Figure 5

Configuration of TCSC and TSSC



II.5.2.1 Thyristor-Controlled Series Capacitor (TCSC)

TCSC is made up of a series capacitor bank, shunted by a Thyristor Controlled Reactor. By controlling the reactance of the inductor by firing angles, it is possible to control the effective reactance of the capacitor. This set-up produces a better variable series capacitive reactance between the two ends. by controlling the firing angle of the switches, the reactor control will be achieved. Note that the reactor reactance in series with the thyristor is designed to be much smaller than the series capacitor reactance. TCSC also damps power oscillations and mitigates subsynchronous resonance. It also very useful in helping power sharing between transmission lines.

II.5.3 Thyristor Switched Series Capacitor (TSSC)

TCSC can be described as capacitive reactance compensators using series capacitor banks shunted by thyristor-controlled reactors so that the series capacitive reactance can be smoothly varied. However, the TSSC is a capacitive compensator that employs a series capacitor bank that is interconnected by a thyristor-controlled reactor that provides stepwise control of series capacitive reactance. There is no firing angle control in TSSC. TSSC was the first to appear in the series compensator family.

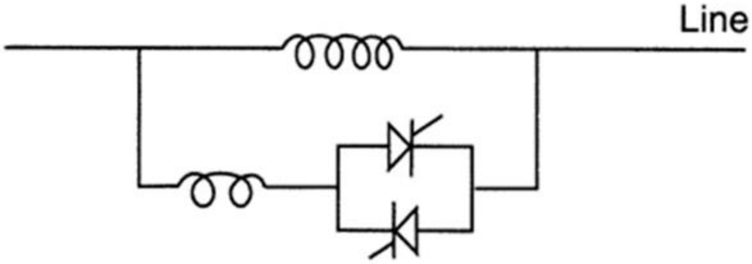
In TSSC the thyristor switch is either on or off. The capacitor is series connected with the line by turning off the thyristor externally or turned on to bypass the capacitor. For this reason, TSSC is not considered as First-Generation FACTS Controller.

II.5.4 Thyristor-Controlled Series Reactor (TCSR) and Thyristor-Switched Series Reactor (TSSR)

These are series controllers. They have similar configurations. The TCSR is an inductive compensator which consists of an inductor in parallel with thyristor switched reactor in order to provide a variable series inductive reactance. Figure 2.6 displays a typical configuration of TCSR and TSSR.

Figure 6

Configuration of TCSR and TSSR



In series with the line, the uncontrolled reactor begins to conduct when the thyristor firing angle is 180 degrees. Until the firing angle reaches 90 degrees, when the parallel combination of the two reactors is the net inductance, the net inductance decreases until it reaches 180 degrees. TCSR is under continuous control.

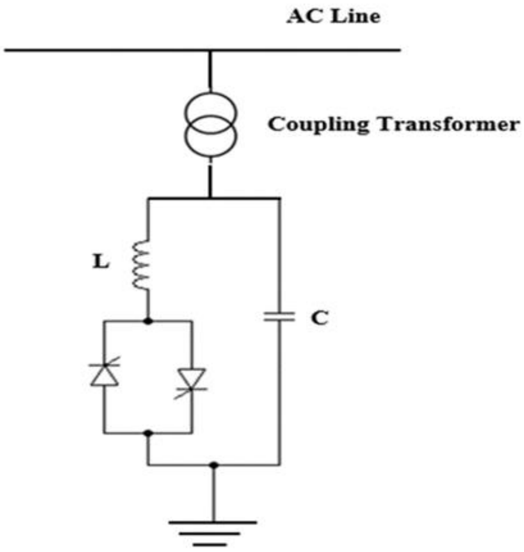
TSSR uses a series reactor that is switched by a thyristor to compensate series inductive reactances (Hingorani&Gyugyi,2000). This is similar to TCSR with the only difference that there is no control of the firing angle. The thyristor is either on or off. This causes a discrete control over the inductive reactance. For this reason, First-generation FACTS controllers do not include TSSR.

II.5.5 Fixed Capacitor Thyristor Controlled Reactor (FC-TCR)

FC-TCR is composed of a fixed capacitor and thyristor-controlled reactor. In this device, there is a continuous lagging and leading VAR provided to the system for the purpose of compensating reactive power. In order to supply lagging power to ac system, TCR is usually rated larger than the capacitor. Figure 7 shows the configuration of FC-TCR.

Figure 7

Configuration of FC-TCR



When the gating angle is 90 degrees full conduction is achieved. However, when the gating angle is between 90 and 180 degrees, we obtain partial conduction the reactor current fundamental component is reduced if we increase the thyristor gating angle. This is same as to increase the inductance, which reduced the amount of reactive power the reactor will absorb.

By using the close loop control of FC-TCR, the firing angle is adjusted automatically with the variation in the transmission line power. The aim of FC-TCR is to stabilize the bus voltage by reactive power compensation.

II.5.6 Thyristor Controlled Phase Shifting Transformer (TCPST)

This controller is known as TCPAR (Hingorani&Gyugyi,2000). TCPST is a special FACTS Controller with a series and shunt power transformer, utilised to control the flow of active power on 3-phase transmission lines, by regulating phase angle voltage difference between two buses.

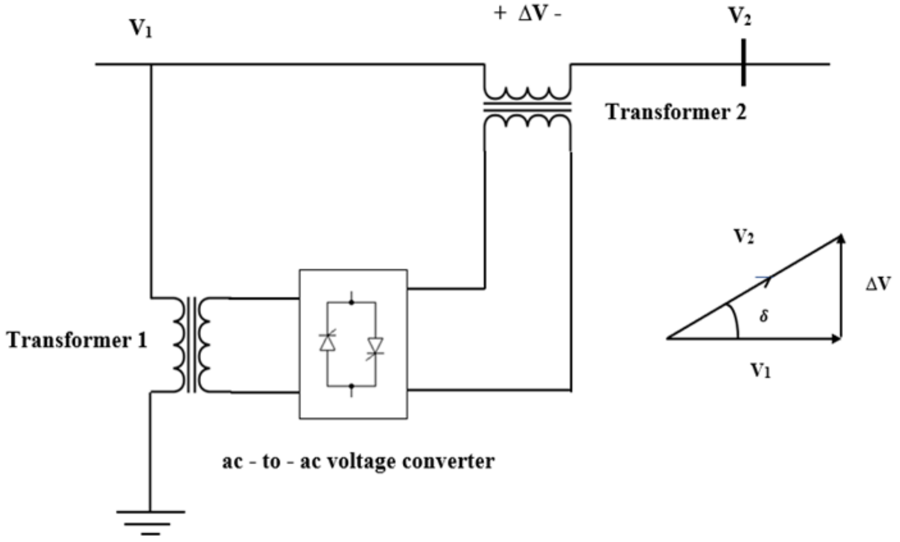
In practical power systems optimal active power loading of transmission lines cannot always be achieved because of the existing difference of phase angle between the sending and receiving end buses.

The IEEE Working Committee on Facts Controllers defines TCPST adjusted by thyristor switches aim to provide a quickly variable angle phase’. It consists of two power transformers. generally, phase shifting is accomplished by adding a derived series voltage phasor to the phase voltage phasor of the line. The phasor is derived from the shunt-connected transformer called excitation transformer, shown in Figure 8 as Transformer 1. Two power transformers are connected through an ac-to-ac thyristor converter (Khelfi et al.,2013).

The converter provides a voltage phasor ΔV to the secondary of the second transformer, which is will be add to the phase voltage phasor of the line, V_1. The overall voltage is V_2. For small angle variations V_2 magnitude is not very different than V_1. The voltage phasor magnitude of this ΔV is varied by the thyristor converter. In this way the angle can be varied as desired. This voltage phasor is always kept perpendicular to the phase voltage phasor. This is made possible by the thyristor converter. Figure 8 shows this configuration.

Figure 8

Thyristor-Controlled Phase-Shifting Transformer



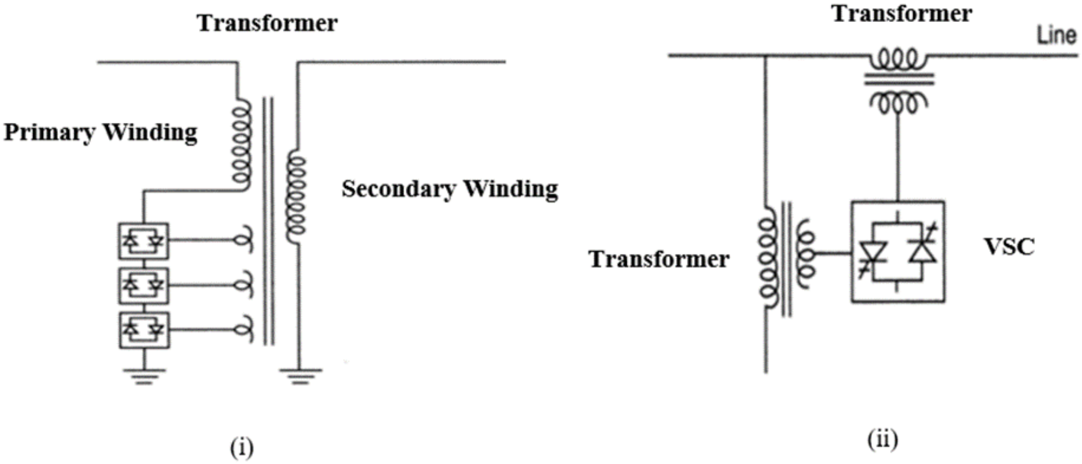
The first TCPST consist of shunt and series connected controller combined. The real power flow equation between two voltage buses is given by Equation 2.1. By controlling the phase angle difference between the two bus voltages, the flow of power in the transmission line can be increased or decreased.

2.5.7 Thyristor-Controlled Voltage Regulator (TCVR)

IEEE Working Committee on FACTS Controller defines TCVR as a 'is a thyristor-controlled transformer that allows a continuous control of voltage phase. The regulator TCVR is also a member of the combined FACTS family. TCVR price is relatively low'. For practical purposes, this may be a regular transformer with a thyristor-controlled tap changer or with a thyristor-controlled ac to ac voltage converter for injection of variable ac voltage of the same phase in series with the phase voltage of the line. Note that the phase angle difference between two buses is not changed since the injected voltage is in-phase with the bus voltage. This means that the active power flow between the two buses has not changed much. Varying the magnitude of bus voltage only affects the reactive power flow in the line. (Hingorani&Gyugyi,2000).

Figure 9

TCVR Based on (i)Tap Changing (ii)Voltage Injection



Voltage injection in comparison to voltage in TCPST is in-quadrature, whereas in TCVR voltage injection is in-phase with the voltage.

II.6 Second Generation FACTS Controllers

There are differences between second-generation and first-generation FACTS controllers because they employ VSC or CSC, instead of shunt reactors and shunt capacitors. VSC are preferred over CSC because they are more economical.

STATCOM, is one of the most popular FACTS Controller of Second-Generation. In this Master Thesis we will employ STATCOM to compensate for reactive power and voltage stabilization of a load bus and for this reason STATCOM will be studied here in more detail. STATCOMs are generally installed for supporting power system that have not good power factors and poor voltage regulations. Controlled by a sophisticated controller STATCOM is always connected in shunt with the power system bus.

Main examples of Second-Generation FACTS Controllers are given below.

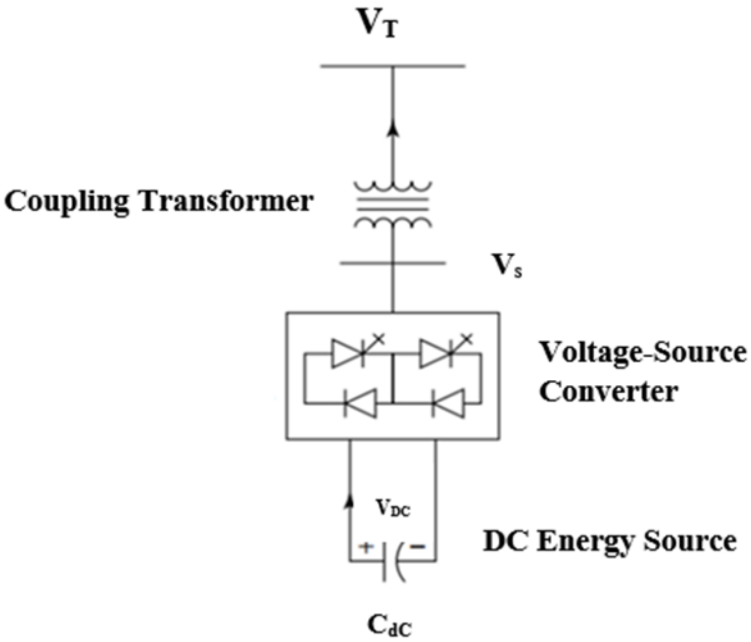
II.6.1 Static Synchronous Compensator (STATCOM)

SVC was explained in Section 2.5.1. TCR, TSR and TSC are some examples of SVC. What SVC do is to regulate voltage bus by injecting reactive power to the power system by making use of shunt capacitors or absorbing excess reactive power from the ac system, by using shunt reactor. The STATCOM does the same thing. Depending on the necessity, STATCOM can either inject or absorb reactive power from the ac system, without using any capacitor or reactor. Reactors and capacitors are replaced by VSC. For this reason, STATCOM is generally called an advanced version of Static VAR Compensator. Instead of shunt capacitors and inductors VSC is used which is energized by a DC storage capacitor. VSC behaves like DC-to-AC Inverter and generates a 3-phase voltage at the output terminals of the STATCOM.

Statcom has a control circuit which can adjust the phase angle and magnitude of the 3-phase output voltage, in accordance with the reactive power need of the ac system, for proper compensation. (Hingorani&Gyugyi,2000). The control circuit adjusts the phase angle and magnitude of the 3-phase output voltage, without being affected by the ac system voltage. By doing so the 3-phase output current of the STATCOM as stated in the definition can also be controlled. STATCOM made below by the IEEE Working Committee on FACTS Controllers. Figure 10 display the STATCOM block diagram.

Figure 10

Block Diagram of STATCOM



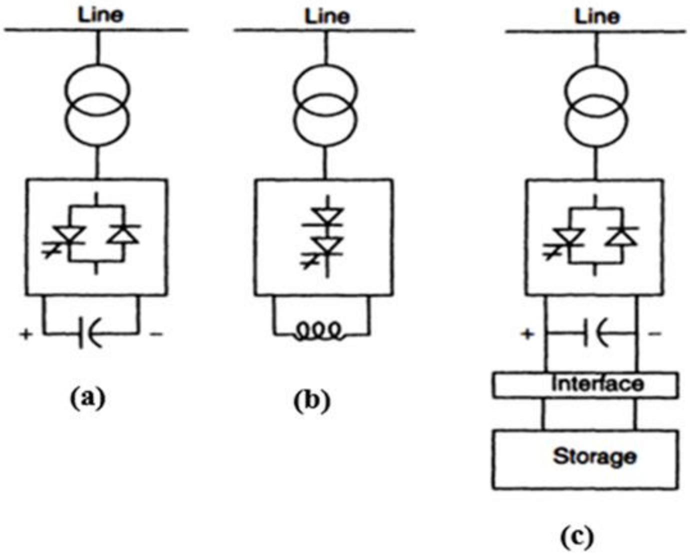
STATCOM enhances the voltage profile of the transmission system. Reactive power compensation by STATCOM reduces line power losses, improves the power factor of the line and stabilises the bus voltages of the power system. STATCOM by compensating reactive power, indirectly increases the active power transmission capability of the line and there is no need for the construction of new transmission lines (Patel et al.,2017). Generally, we connect STATCOM to the load side of the power system.

Voltage-Sourced Converters employ power semiconductor devices such as IGBT which switches at speeds faster than the thyristors which are used in SVC.STATCOM has additional advantages over SVC. It occupies less space. It is modular and can be shifted anywhere easily.

STATCOM has another big advantage over SVC. In addition to reactive power, with the ac system to which the STATCOM is connected. This is very useful in damping power oscillations in power systems. This has been already mentioned in the definition of STATCOM, by the IEEE, where inductive current injection is mentioned. Different STATCOM topologies are shown in Figure 11.

Figure 11

STATCOM Topologies (a)Based on VSC (b)Based on CSC (c)Based on External Storage



The word ‘static’ in STATCOM implies that there is no rotating part in it, whereas the word ‘synchronous’ implies that the working principle of STATCOM is similar synchronous motors, also known as synchronous condenser, used for compensating reactive power. In comparison to the sluggish mechanical inertia of the motor, STATCOM respond to variations faster.

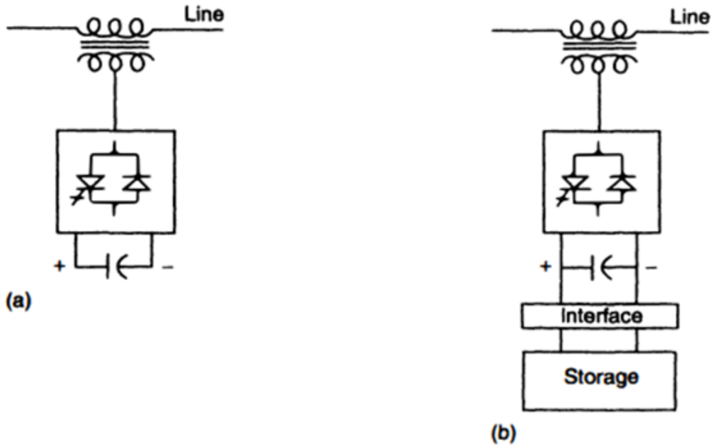
STATCOM has been used for compensating EHV, HV and MV transmission lines in many countries. In order to differentiate from others, STATCOMS used for compensating reactive power at Distribution Systems (11 kV and 22 kV in this country) are sometimes called DSTATCOM.

2.6.2 Static Synchronous Series Compensator (SSSC)

SSSC is different from STATCOM in that the 3-phase voltage output of the Voltage-Sourced Converter is connected in series with the 3-phase transmission line, and not as shunt, as in the case of STATCOM. Figure 12 shows the configuration for SSSC.

Figure 12

SSSC Configurations with and without external storage



The amount of voltage injected in series with the line is quite small in comparison to the line voltage. This voltage is adjusted to be in quadrature with the line current i.e., the injected voltage phasor lags the line current phasor by 90 degrees, which is the case for a capacitor. The magnitude of the injected voltage is adjusted, irrespective of the line current, to compensate the line (Murali et al.,2013). The voltage injected is almost in quadrature with current of the line, because a small amount of real power is needed for the power losses in the inverter.

As in the case of STATCOM, SSSC can be connected to an external voltage source, such as a fuel cell, SMES device or battery. Such a connection will allow real power exchange with the line, thus controlling the resistance of the line, just like the reactive power controlling the reactance of the line. In addition to reactive power this will enable exchange of real power with the ac system. SSSC and AC systems do not require external voltage sources to exchange reactive power.

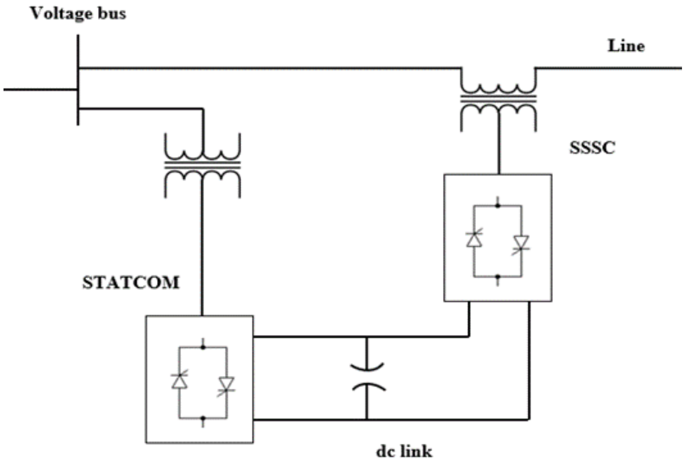
2.6.3 Unified Power Flow Controller (UPFC)

The UFFC has been proposed for the first time by Gyugyi in 1991. In order to control and compensate ac transmission lines dynamically in real time, the UPFC was developed. UPFC has been designed to control simultaneously or selectively, in a ‘unified’ manner, the parameters affecting the flow of power in the transmission lines, such as bus voltages, line reactance between buses and phase angle between bus voltages, as seen in Equation 2.1. A UPFC configuration is shown in Figure 13. It consists of a series SSSC and a shunt STATCOM which are coupled by a common DC link. Reactive power is injected by STATCOM to the ac system or absorbed reactive power from the ac system to maintain voltage stability, whereas SSSC controls the flow of active power in the transmission line (Kumar et al.,2013). UPFC controls both the bus voltage and the flow of power in the transmission line.

UPFC controls independently the flow of reactive and real power in a single transmission line (Hingorani&Gyugyi,2000).

Figure 13

UPFC Configuration



2.6.4 Interline Power Flow Controller (IPFC)

HV transmission lines carry electric power directly from power stations to substations. Other MV transmission lines leave the substation and distribute power to different regions. Some of these lines may be overloaded while others underloaded with power. This is an undesirable situation and congestion of power in the lines should be eased. IPEC by controlling the active power in the lines, optimizes the power flow in multi-line transmission systems.

IPFC was developed by Gyugyi in 1998, as an extension of UPFC. This technique is used at substations to compensate a number of transmission lines. UPFC employs a single SSSC whereas IPFC uses one SSSC per 3-phase transmission line, to control the flow of active power in multiple transmission lines. Real power flow in each line is independently adjusted by each SSSC. There is a DC link between the AC terminals and SSSC to facilitate the bidirectional flow of real power. In this way IPFC makes it possible to transfer active power between the lines that are compensated to equalize the transits of active power on the lines or to unload an overloaded line to another less loaded one. IPFC is a multi-line FACTS device. Such a configuration is shown in Figure 2.14

In some cases, the structure of IPFC can contain a STATCOM, coupled to the DC link. Figure 15 shows such a configuration (Dixon el al.,2005).

Figure 14

IPFC Configuration

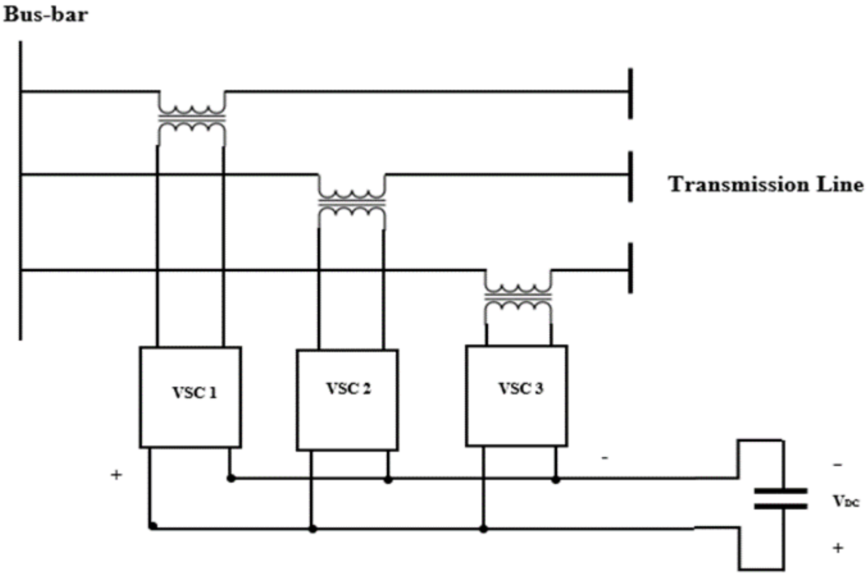
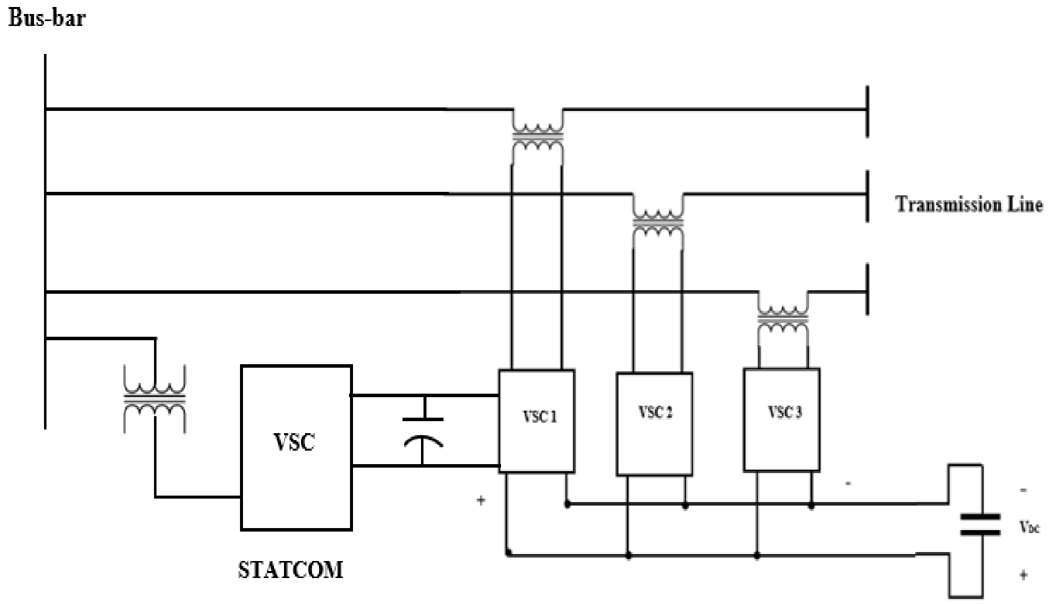


Figure 15

IPFC Configuration with STATCOM

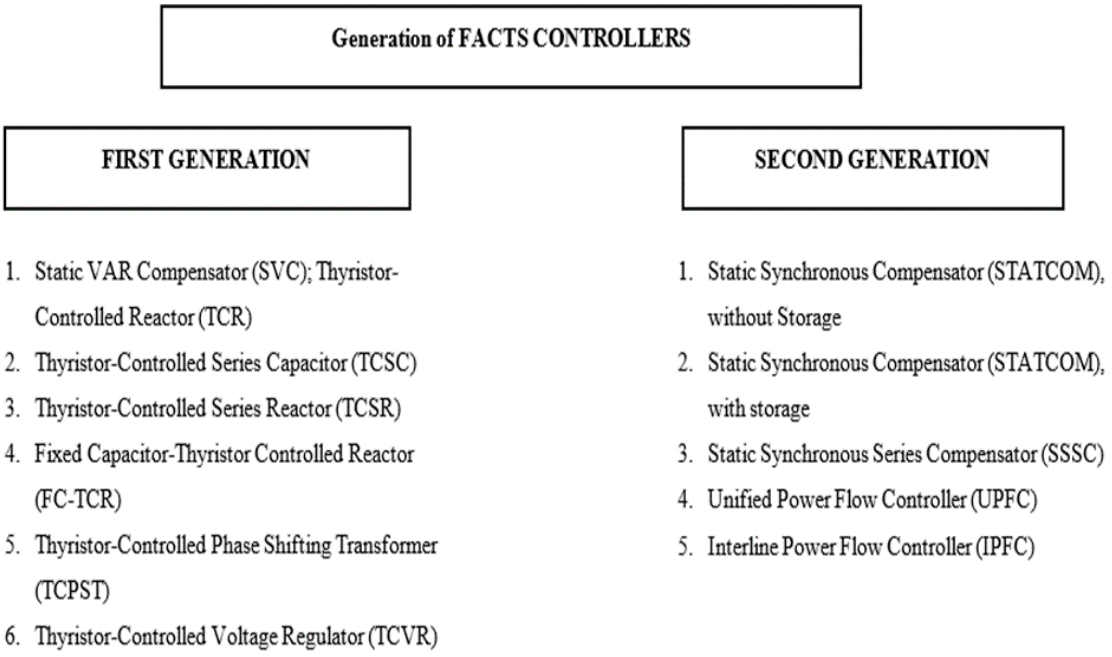


A novel configuration of IPFC, similar to the figure above, but consisting of three VSC converters, namely one shunt controller (STATCOM) and two series converters, is called General Unified Power Flow Controller, GUPFC. GUPFC simultaneously controls 5 power system quantities: the bus voltage and the flow of reactive and real power on two lines (Singh et al.,2011).

Table 2 shows First and Second-Generation FACTS Controllers.

Table 2.

Generation of FACTS Controllers



Generation of FACTS CONTROLLERS

FIRST GENERATION

1. Static VAR Compensator (SVC); Thyristor-Controlled Reactor (TCR)
2. Thyristor-Controlled Series Capacitor (TCSC)
3. Thyristor-Controlled Series Reactor (TCSR)
4. Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR)
5. Thyristor-Controlled Phase Shifting Transformer (TCPST)
6. Thyristor-Controlled Voltage Regulator (TCVR)

SECOND GENERATION

1. Static Synchronous Compensator (STATCOM), without Storage
2. Static Synchronous Compensator (STATCOM), with storage
3. Static Synchronous Series Compensator (SSSC)
4. Unified Power Flow Controller (UPFC)
5. Interline Power Flow Controller (IPFC)

II.7 FACTS Controllers and Their Attributes

Table 3 summarizes the attributes of various FACTS Controllers that we have studied until now (Hingorani&Gyugyi,2000).

The flow of active power over a transmission line depends usually on three important parameters, namely, phase angle difference between the bus voltages and the voltage magnitude of the buses and the reactance of the transmission line, as shown by Equation 2.1 The FACTS Controllers generally change one or more of the above parameters to control the flow of active power. TCSC, TCSR, TCPST, SSSC and UPFC are good examples of such controllers.

Excess amounts of reactive power flowing in the lines increase the losses in the transmission lines because of increased line current and cause load bus voltage to drop, resulting in bad voltage regulation. Fluctuating non-linear inductive loads with low power factors (0.7pf lagging), such as arc furnaces, draw increasingly more reactive power and inject undesired current harmonics into the lines. Unless load compensation is done by limiting the reactive power, coming from the generator via transmission lines, the power system may be adversely affected. With a proper control of reactive power in the lines, such power quality problems can be reduced considerably. Injection of reactive power to the load bus, by various reactive power compensation techniques improves the voltage stability, of power carrying at all levels, and minimises voltage fluctuations. Power factor of the transmission lines improves and because the power that can be carried has increased, the power system stability improves as well.

To modify the electrical parameters of ac transmission lines series and shunt FACTS Controllers are used (Miller,1982). Series compensation modifies the transmission line series impedance and we make use of it for controlling the active power in the line, while shunt compensation by a capacitor or a reactor, will modify the load equivalent impedance and hence is used to control the reactive power in the line. A capacitor injected into the lines reactive power, controlled by a FACTS Controller or absorbed by a reactor, controlled by a FACTS Controller.

Traditionally, mechanically switched capacitors, fixed inductors or rotating synchronous condensers was used for compensating reactive power. At the present, Static VAR compensators employing thyristor-controlled reactors for injecting or absorbing reactive power and thyristor switched capacitors have been developed. VSC can be controlled to behave like a variable capacitor. TCR, TSR, TSC, FC-TCR and STATCOM are good examples of such controllers.

Table 3.

FACTS and their Control Attributes

FACTS Controllers	Control Attributes
TSR, TSC SVC, TCR,	VAR Compensation, voltage control, transient and dynamic stability voltage Stability, damping oscillations,
TCSC, TSSC	Active Power Control, damping oscillations, current control, voltage stability transient and dynamic stability,
TCSR, TSSR	Active power control, current control, damping oscillations, voltage stability, dynamic and transient stability
FC-TCR	VAR compensation, voltage control, damping oscillations, voltage stability, dynamic and transient stability
TCPST	Active Power Control, voltage stability, damping oscillations, transient and dynamic stability

Table 3 (Continued)

TCVR	Reactive power Control, damping oscillations, voltage stability, voltage control, dynamic and transient stability
STATCOM with and without Storage	VAR Compensation, voltage control, voltage stability, damping oscillations
SSSC, with and without Storage	Current Control, Active power Control, Voltage stability, damping oscillation, dynamic and transient stability
UPFC	Active and Reactive Power Control, VAR Compensation, voltage control, damping oscillations, voltage stability, dynamic and transient stability
IPFC	Active Power Control, voltage control, voltage stability, damping oscillations, dynamic and transient stability.

II.8 Advantages Offered by FACTS Controllers on Power System Stability, Angle Stability, Voltage Stability and Damping of Oscillations in Power Systems

Before we discuss the advantages offered by FACTS Controllers, it will be useful to revise our knowledge on power system stability, voltage stability, angle stability and damping of oscillations in power systems. Prior to studying Power System Stability, it will be beneficial to study how a power system is interconnected.

II.8.1 Interconnected Power Systems

A modern power system is designed to supply power on demand to various loads in a reliable manner, while operating efficiently. Thus, a grid of transmission lines operating at HV or EHV levels, is needed to carry power from generating stations to load centres (Padiyar,2007).

All generators and loads are connected together in a national grid and power is supplied to the loads by nearby generators. In case of nearby generator failure or maintenance work, uninterrupted power is supplied by other generators. Interconnection thus increases the reliability of the grid. Interconnection has a major drawback however. A fault which starts in a particular area of the power system can propagate and spread in the entire power system as a result it will cause a major blackout caused by cascading outages. Similarly, the system voltage drops due to high inductive loads and reactive power compensation is inevitable. If the generation capacity does not meet the load demand the frequency drops and shedding of load is inevitable. The power system frequency must be kept within 48.5-50.5 Hz range.

II.8.2. Power System Stability

A large power system consists of multiple synchronous generators operating in synchronism. They always rotate at constant speeds and generate voltages and thus currents at a fixed frequency, which is 50Hz in this country.

When a power system is subjected to disturbances, it must be capable of returning to normal and stable operation. This is how the stability is defined (Stevenson,1982).

Stability studies divide into 2, depending on the magnitude and nature of disturbance.

1) Steady-State Stability: capability of a power system to keep it stability, without losing synchronism, for small and slow disturbances such as gradual changes in load. Steady State Stability divides into 2. Static Stability is the inherent ability of the power system which does not require any external control devices. Dynamic Stability, however requires the use of external control devices to restore stability after small but longer lasting disturbances, e.g.,10 to 30 seconds.

2) Transient Stability: capability of a power system to remain stable for large disturbances, such as sudden application or removal of load, occurrence of a fault, loss of generation and outage of a line. Usually, such studies are done when new power plant and transmission lines are planned (Saadaat,1999).

II.8.3 Voltage Stability

We define voltage stability as ‘the capability of interconnected power systems to keep steady voltages at all buses in the system. In the ac power system, the lack of reactive power is the principal reason for voltage instability. ac generators have some limitation in generating reactive power.

Most of the loads are inductive and need reactive power for proper operation. Reactive power reaches the inductive loads via transmission lines. This causes the current in the lines to increase, which in turn increases the voltage drop across the line impedance. This causes in the load voltage to drop, causing voltage instability and thus limiting the flow of real power to the load. Voltage stability relies on the system to keep the equilibrium between load supply and load demand. Voltage stability is in fact load stability.

Voltage instability may cause voltage collapse in power systems.

II.8.4 Rotor Angle Stability

Synchronous generators generate electric power which is then transmitted and distributed to loads. Rotors of synchronous generators rotate at constant speed and generate voltage at constant frequency, which is 50 Hz in this country. Rotor angle stability depends on the ability of each synchronous generators to maintain equilibrium between mechanical torque and electromagnetic torque. Generator turbines supply mechanical torque to the shaft of the generator, whereas electromagnetic torque represents the output power of generator. Whenever load power increases generator instantly reacts to this. Meantime the rotor oscillates and is damped by the damper winding on the rotor. If the generator cannot supply the required power, then the load angle cannot settle to a new value and the rotor starts to oscillate and eventually loses synchronism and stops.

II.8.5 Damping of Oscillations in Power Systems

Whenever load changes or a system disturbance occurs, electromechanical oscillations are generated in the power system. This is because of dynamic nature of generation. Oscillations are observed in most of the variables like line current, voltage, power and frequency. The frequency of oscillations is between 0.2 and 3 Hz. It is necessary to dampen these oscillations effectively in order to maintain system security and reliability.

II.8.6 Usage of FACTS Controllers in Improving Power System Stability

Table 3 clearly shows that most of the controllers aid in oscillations damping and improve dynamic and transient stabilities. FACTS Controllers have the capability to control both the flow of reactive and active power in transmission lines and thereby improve power system stability.

It’s important to dampen power oscillations effectively because it is very crucial for rotor angle stability. Supplementary control actions can be applied to improve the damping of oscillations in power systems, to existing FACTS devices. These actions are known as POD control. Note that POD control has been used in conjunction with 2 FACTS devices, namely TCSC and UPFC and satisfactory results were obtained (Mandour et al.,2014).

CHAPTER III

Operation of STATCOM and the Control System

III.1 Introduction

STATCOM is amoung most essential FACTS controllers used to compensate a transmission line's reactive power .STATCOMs are usually installed for supporting power grid that have not a good power factor loads and poor load voltage regulation. Reactive power,unless kept under strict control,can have detrimental effect on power systems. Excess of reactive power in power system increases the voltage magnitudes at buses,whereas a deficit of reactive power reduces the voltage magnitudes at buses. Based on the VSC,the STATCOM can regulates system voltage by generating and directly injecting reactive power to the inductive or non-linear loads by bypassing the supply or by draining excess reactive power from the power system. In other words a STATCOM behaves like a controlled reactive power source and is used for stability improvements. It is a shunt-controller and hence it is always shunt connected with the transmission line (Patel&Ansari,2016).

Increasing demand on electric power by consumers has put great pressure on the power transmission infrastructure. during rush hours Power carried in the transmission lines reaches its peak value,causing high currents in the lines and hence big voltage drops in the lines,due to the inductive and non-linear loads.High currents in the transmission lines cause transmission line losses to increase and at the same time cause voltages at load buses to drop. This situation creates various problems,including power stability problems in the power system. STATCOM offers a solution to all of these problems by carrying out the compensation of reactive power. Reactive power required by the load does not have to come,all the way from the generator any more. As a result, the line current is reduced, thereby reducing the voltage drop in the line impedance and reducing the power loss on the line. The load voltages are restored.STATCOM in this way relieves the transmission line from the pressure imposed on it due to reactive power.

The statistics for FACTS Controllers,since the year 2005 confirm the increased utilisation of the FACTS device STATCOM for compensation of reactive power in power systems.(Gupta&Tripathi,2010). In Chapter 2,an introduction was made to STATCOM. Now a more detailed study of STATCOM will be made.

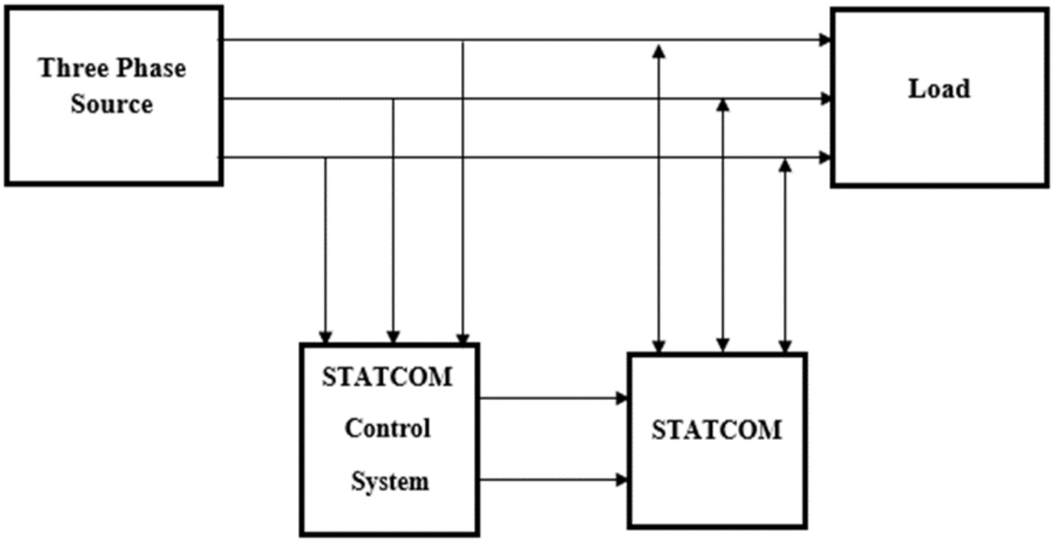
The first STATCOM was developed by the Kansai and Mitsubishi Electric Power Companies,and was put into operation in 1980 for regulating the HV transmission lines.Its rating was 20 MVAR.In 1995,a 100MVAR STATCOM was put in use at Tennessee(USA) for regulating 161 kV lines.One of the world’s largest STATCOM of 650 MVAR rating was commissioned by Siemens in 2017,in India.In Turkey,a 50 MVAR STATCOM was put in service in 2012,at Sincan Substation to regulate 154 kV lines(Vural,2012).There are many other projects in progress all over the world.

III.2 Structure of STATCOM

An example of a power grid employing a STATCOM to compensate reactive power can be seen in Figure 16. The STATCOM is placed shunt to the transmission line,in between the power source and the load. Reactive power compensation is done non-stop and the amount of reactive power varies in time,depending on the load variations in time. In other words it is a dynamic process. The STATCOM controller senses these variations in the load reactive power and by generating feedback signals direct the STATCOM generating the necessary amount of reactive power to stabilize the load voltage(Padiyar,2007).

Figure 16

Block Diagram of Power System Employing STATCOM



STATCOM is generally based on VSC, rather than CSC. VSC-based STATCOMs are used more frequently in power systems than CSC-based STATCOMs.

Figure 17 shows the block diagram of VSC-based STATCOM. It consists of 4 main parts:

(1) Voltage-Sourced Converter (VSC)

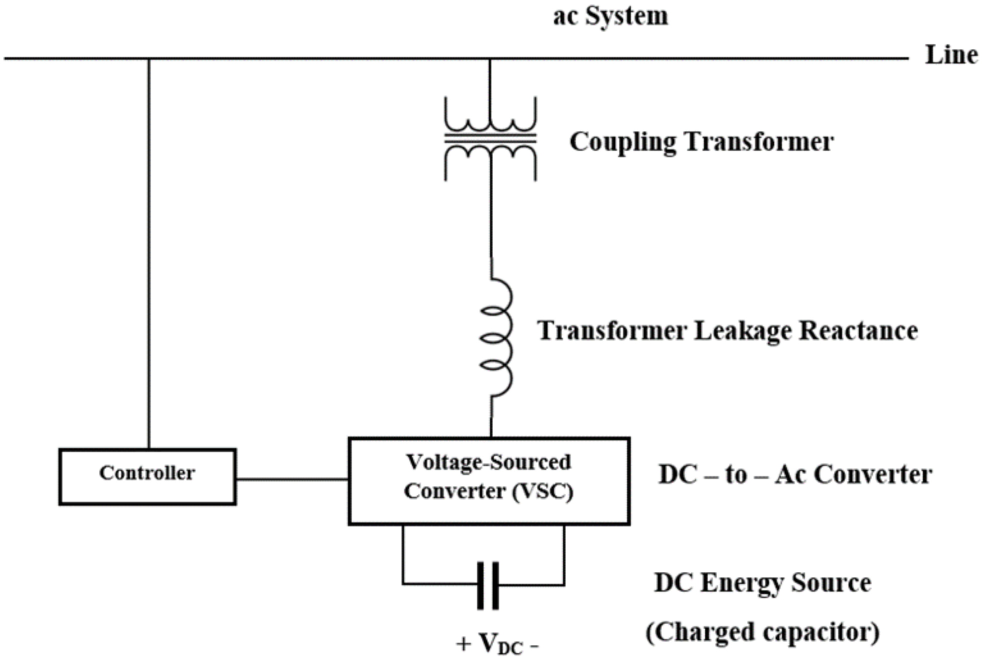
(2) DC Energy Storage

(3) Coupling Transformer

(4) Controller

Figure 17

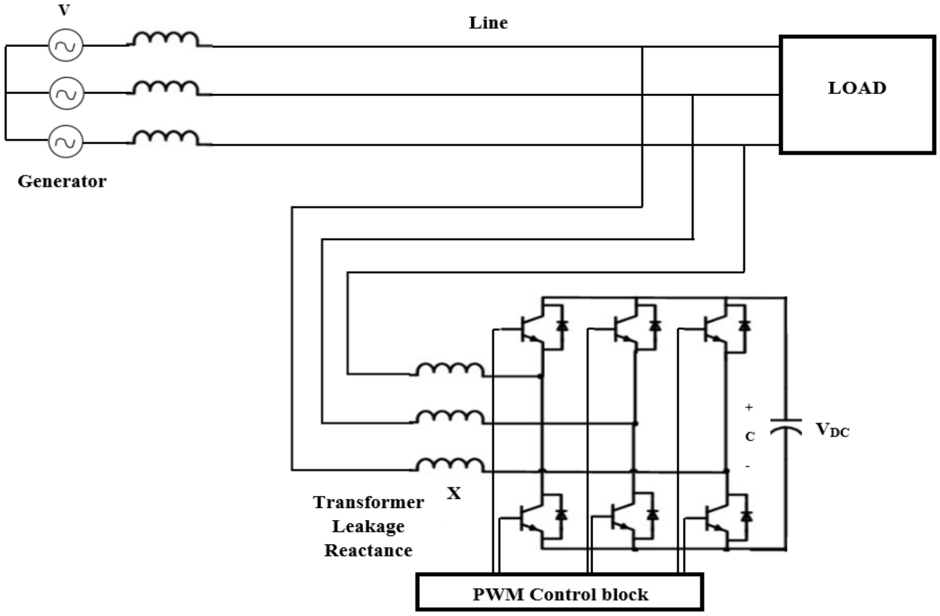
Block Diagram of VSC- based STATCOM



(i)Voltage-Sourced Converter (VSC) is basically a DC-to-AC inverter, employing self-commutated 6-pulse IGBT (Insulated-Gate Bipolar Transistor) switching device. VSC inverts the constant DC voltage on the charged capacitor. SVC generates a sinusoidal voltage at magnitude, frequency and phase angle, deemed necessary for compensation, by the control system. IGBT with an anti-parallel diode is employed. Diode performs rectification action whereas IGBT performs the converter action. IGBTs are convenient for high-current and voltage applications. Some STATCOMS make use of GTO, instead of IGBTs. In this thesis VSC employing IGBTs are being used for inversion. Figure 18 shows a 6-pulse VSC circuit.

Figure 18

3-Phase,2-Level and 6-Pulse VSC Circuit Based on IGBTs



In addition to generating a 3-phase voltage system, the VSC also generates the ac power system's frequency. The magnitude and the phase angle of the generated voltage are determined by the control system. It will be shown later on in this chapter that, it is the inverter’s voltage magnitude that determines whether reactive power is going to be injected to the grid or absorbed from the grid. STATCOM operation depends on VSI output voltage magnitude. For reactive power exchange only and no real power exchange taking place between STATCOM and ac system, the phase angle of STATCOM voltage must be adjusted to be in-phase with the ac system voltage, as shown later on by the equation 3.2. For reactive power absorption or generation by the STATCOM, the angle between the inverter’s voltage and current must be kept at 90 degrees.

Similarly, the current that flows in the transformer leakage reactance has a 90 degrees phase difference with both the STATCOM voltage and the grid voltage. Under this condition the amount of reactive power will depend only on the inverter output voltage, since we can only control this voltage and not the grid voltage. We can control the injection current by controlling the STATCOM output voltage. In this thesis we cannot control the amount of reactive power, by changing the value of leakage reactance of the transformer because it is constant. If the inverter voltage output magnitude is above the ac system voltage magnitude, then STATCOM injects reactive power to the ac system. If the inverter output voltage magnitude is below the ac grid voltage, then the STATCOM absorbs reactive power. If they are equal no injection or absorbtion occurs. If the phase angle difference between the inverter output voltage and grid voltage is intentionally adjusted to be a little less than 90 degrees, then in addition to reactive power, real power is also exchanged between STATCOM and ac system (Miller,1982).

The 3-phase voltage generated at STATCOM terminals are never out of phase with the grid voltage of the ac power system. This is the case if STATCOM exchanges only reactive power with the system. If STATCOM is employed for exchanging both reactive and real power with ac system, then the phase angles will be slightly different, to allow real power to flow, whenever required. When STATCOM phase angle and output voltage magnitude are equal to the transmission line phase angle and voltage magnitude then between them exchange of reactive power will not happen. The difference of the angle phase between STATCOM output voltage and current is always 90 degrees. When STATCOM behaves like a capacitor it generates reactive power and supplies it to the ac system. Now, reactive current flows from STATCOM to ac system. When it behaves like an inductor it absorbs excess reactive power of the ac system. In this case reactive current will flow from ac system to the STATCOM.

It should be noted that Voltage-Sourced Converter generates voltage independent of the power system to which it is connected (Hingorani&Gyugyi,2000). In VSC based STATCOMs reactive power reversals occurs with reversal of current and not the voltage.

(ii) DC Energy Storage

(a) without added external energy storage device

Figure17 shows that input to the VSC is the DC voltage on the charged capacitor, which is an energy storage device. VSC inverts the DC voltage across the charged capacitor to a set of controllable 3-phase output voltages.

The energy storage capacitor maintains its DC voltage, because VSC supplies only reactive power to the power system. The real power supplied to the converter by the charged capacitor is zero. Furthermore, it’s evident that at zero frequency reactive power is zero, the dc capacitor plays no part in the reactive power generation. Because the exchange of power between STATCOM and the grid is limited to reactive power only, and the current drawn by the converter is zero from the dc capacitor, and thus there is no need for the charged capacitor to have maximum energy storage in it.

It is important to note, that IGBT switches do not function losslessly in practical VSC converters. In order to compensate for its losses and maintain the capacitor voltage at the right level, an angle of a few degrees is created between the voltage of the converter's output and the voltage of the system (Hingorani&Gyugyi,2000).

(b) with added external energy storage device

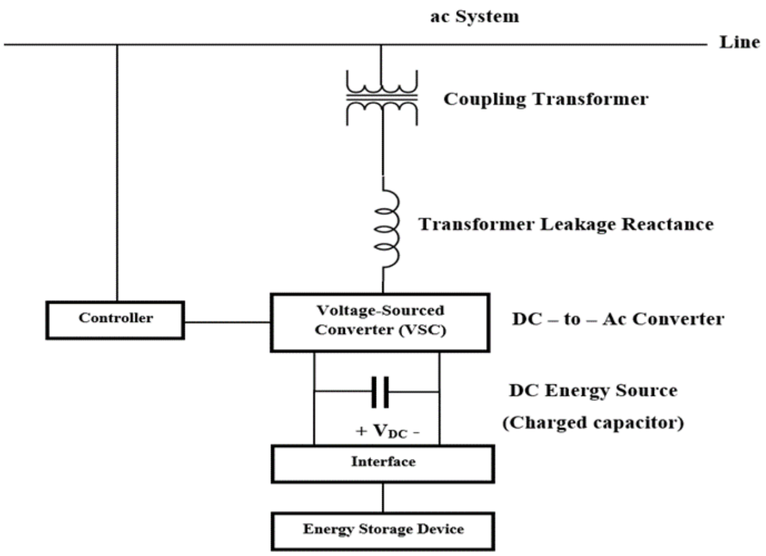
When the DC capacitor has a small storage capacity, and there is no added external storage energy device connected to it, the converter will not be able to absorb or supply real power from the grid (Hingorani&Gyugyi,2000). However, when STATCOM is supported externally by added DC storage devices, reactive and active power can be exchanged simultaneously with the ac power system. The added external energy storage DC devices can be Battery Energy Storage System (BESS), SMES or a large DC capacitor. A chopper, a dc-to-dc converter, connects external energy storage devices to the existing storage capacitor over an interface. For the exchange of real power and reactive power with the ac system, the line voltage and phase angle difference between the STATCOM output voltage should be very slightly different than zero.

The benefits of adding external energy storage system to STATCOM are significant. Whenever the frequency of the power system drops below accepted limits, compensation of active power on the line improves the power system frequency. It is also effective in controlling the power system transient stability. Also, if the load cannot receive the required active power from the supply, STATCOM can supply the missing power.

STATCOM with external storage independently regulates both reactive and active power in power systems. It also reduces voltage fluctuation, damps oscillations and harmonics, enhances voltage stability, system security and eases power flow congestion in power systems (Chakraborty et al.,2012). Figure 19 shows a STATCOM with added external energy storage devices.

Figure 19

Block Diagram of STATCOM with External Energy Storage Device



(iii) Coupling Transformer

Coupling transformer matches the output voltage of STATCOM with the ac transmission line voltage. It is connected shunt with the transmission line, as seen in Figure 20. Looking from the transmission line side, the coupling transformer behaves as a step-down transformer. The STATCOM output voltage is around 2-4 kV, which is much less compared to the line voltage.

Figure 20

STATCOM Connection to AC System via Coupling Transformer

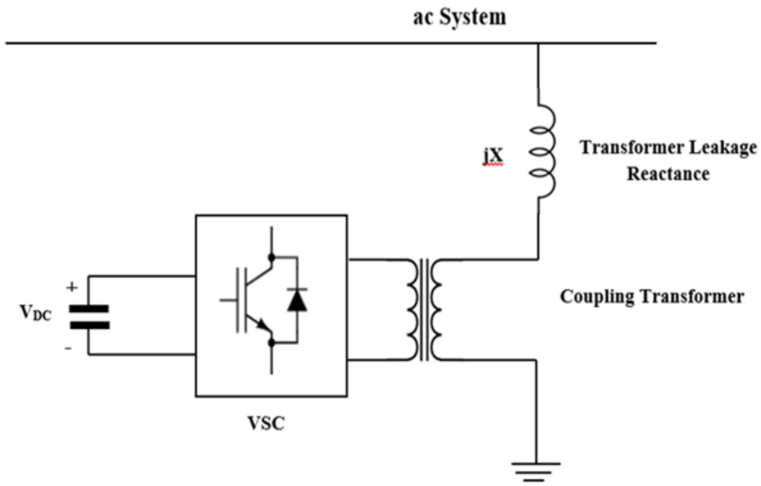


Figure 21 shows the STATCOM circuit. The coupling transformer is represented by its leakage reactance, X. In comparison to its leakage reactance Transformer's equivalent resistance is very small and will be this analysis.

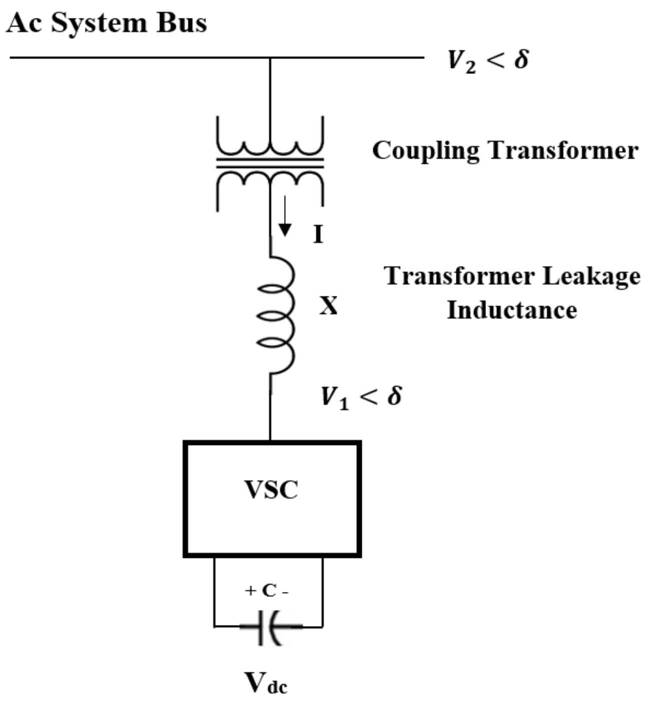
When STATCOM is exchanging only reactive power between and the ac grid, the phase angles of STATCOM output voltage, V_1 and line voltage, V_2 should be the same. The 3-phase STATCOM output voltages and 3-phase line voltages are then coupled via the coupling transformer leakage reactance. The voltage drop on the leakage reactance will have the same phase angle as that of STATCOM and ac voltage. This causes the phase angle of the current flowing between STATCOM and ac system to be in quadrature with the STATCOM voltage, V_1 and ac system voltage, V_2.

The flow of real power from ac system into the converter aim to supply the coupling transformer losses and converter losses due to the switching of IGBTs. Coupling reactance also helps to neutralise current harmonics generated by the VSC converter (Chakrabarti et al.,2008).

When the grid voltage is low then a coupling transformer may not be needed. STATCOM is connecting to the grid via a reactance.

Figure 21

Reactive Power Compensation by STATCOM (Phase angles of V1 and V2 are the same)



(iv) Controller

Whenever the magnitude of load voltage drops or increases beyond the rated value, because of inductive, capacitive and non-linear loads, a corrective action is implemented by the STATCOM control system. STATCOM is instructed by the control system to inject or absorb the correct amount of reactive power, such that the load voltage restores to its rated value. STATCOM block diagram for voltage mode control is depicted in figure 22.

Figure 22

Block Diagram of STATCOM Control System

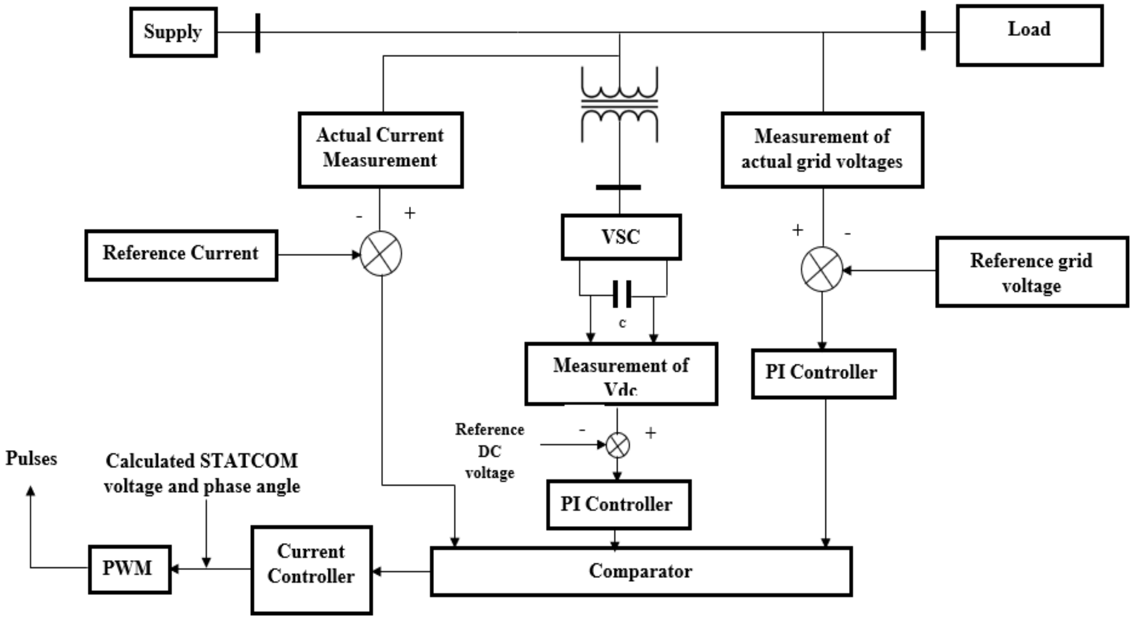


Figure 22 shows that, first the actual voltage load and actual current load are measured. The reference voltage load is compared with Actual voltage load, which is the rated voltage load. If there is no difference between them then there no need for action, because the load voltage is at its rated value. If a difference exists, then reactive power compensation will be done. To compensate for reactive power, a reference current is calculated using the rated voltage load and rated reactive power. This reference current will be compared with the actual load current measured. In a similar way, the actual voltage dc of the capacitor is measured and compared to the rated capacitor voltage. The capacitor discharges slightly with the continuous switching of the IGBTs. If there is a discrepancy between them, then active power flows from the ac grid to provide power for the switching operations and charge the capacitor. A corrective action is implemented and the control system takes action for generating the appropriate STATCOM output voltage, to compensate for reactive and active power.

It should be noted that for practical reasons, all comparisons in the controllers are not done by using voltages and currents in time domain, because PI Controllers can only operate with real numbers. In section 3.5.1.3 more details will be given, the analysis is done in what is called the direct axis and quadrature axis(d-q) frame. An active power is represented by the direct axis, while a reactive power is represented by the reactive axis. With the d-q frame it becomes possible to control the reactive and active power separately. This offers a big advantage to the control strategy. If the input quantities applied to the PI controller are sinusoidal then the controller may fail as the steady-state error cannot be forced to zero. In section 3.5.1.3 more detail about d-q frame will be given.

III.3 Basic Operating Principle of STATCOM

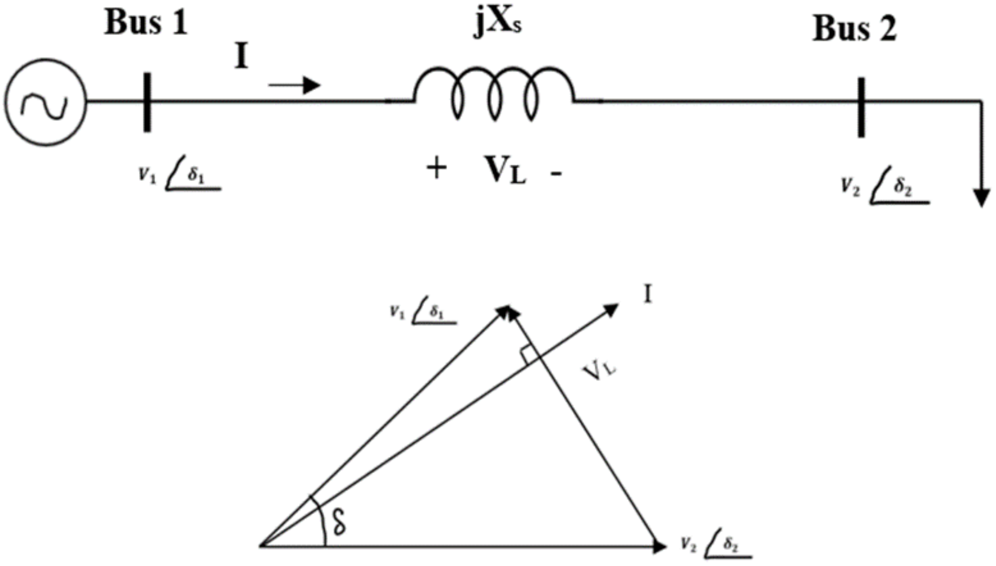
Before studying the special case of flow of power on a line between STATCOM and AC system let us calculate the general case of power flow between a general 2-bus system. Once the equations for flow of active and reactive power are derived, we can then adapt them to STATCOM-AC system.

A simplified case of power flow on a line for a 2-bus system is shown in Figure 23. Buses 1 and 2 may be any substations transmission connected by a line. X represents the line reactance (in analogy, it will represent the transformer's coupling leakage reactance in the case of STATCOM-ac system). The equivalent resistance of the line (in analogy, the coupling transformer's resistance) is relatively small compared to the leakage reactance and is therefore neglected in the following analysis. The line between the two buses is therefore lossless. By using this circuit, we can now calculate the reactive and real power at each bus. We can then calculate the flow of power in the transmission line.

Let $V_1 < \delta_1$ be the phasor voltage at bus-1(in analogy representing STATCOM output voltage) and $V_2 < \delta_2$ (in analogy representing the ac system voltage) be the phasor voltage at bus-2.

Figure 23

Single-Line Diagram Showing Power Flow Between STATCOM and AC System. Phasor Diagram of V-I Relations



The driving voltage drop in the line is the phasor difference VL, between the voltage phasors V_1 and V_2. The current I lags VL by 90 degrees, since it is an inductor.

$$I = (V_1 < \delta_1 - V_2 < \delta_2)/jX \tag{3.1}$$

Voltages V1 and V2 are magnitude-wise very close to each other and the phase angle difference between δ1 and δ2 is very close to zero. Note that the figure is drawn in exaggeration to show the phasors clearly. This means the voltage drop VL, on the line reactance is very small. From Equation 3.1 we can see that the current flow in the line is going to be control by controlling V_L. X and the angle difference δ are kept constant, and hence the controlling of reactive power is accomplished by controlling V_L only. VL magnitude is controlled by V_1, the STATCOM output voltage, since X, δ and grid voltage V2 are constant.

At each bus reactive and active powers can be calculated by circuit analysis (Hingorani&Gyugyi,2000). At Bus-1, the reactive and active power leaving are given by:

$$P_1 = V_1V_2sin\delta/X \qquad Q_1 = V_1(V_1 - V_2cos\delta)/X \tag{3.2}$$

Reactive and active power entering Bus-2 are given by:

$$P_2 = V_2V_1sin\delta/X \qquad Q_2 = V_2(V_1cos\delta - V_2)/X \tag{3.3}$$

It can be noticed that active power at Bus-1 and Bus-2 are the same. This is evident because between Bus-1 and Bus-2 the line is lossless. However, the reactive power at Bus-1 and Bus-2 are different because the leakage reactance X absorbs some reactive power.

Now that we have obtained equations for a 2-bus system we can extend it to power flow between STATCOM and AC system. Bus-1 can be taken as STATCOM bus and Bus-2 can be taken as the AC system bus. In this thesis we will study only regulation of load voltage by reactive power only. No exchange of real power between STATCOM and ac system will happen.

Because STATCOM was designed to exchange reactive power only, from Equation 3.2 and 3.3 that, for active power to be zero, phase angle difference δ must be equal to zero. This means δ_1 and δ_2 should be equal to each other. Bus-1 and 2 voltages are therefore in-phase. Bus-1 generated the reactive power equal to:

$$Q_1 = V_1(V_1 - V_2)/X \tag{3.4}$$

and the reactive power supplying to the ac system will be

$$Q_2 = V_2(V_1 - V_2)/X \tag{3.5}$$

The reactive power taken by the transformer leakage reactance is equal to the difference between Q_1 and Q_2.

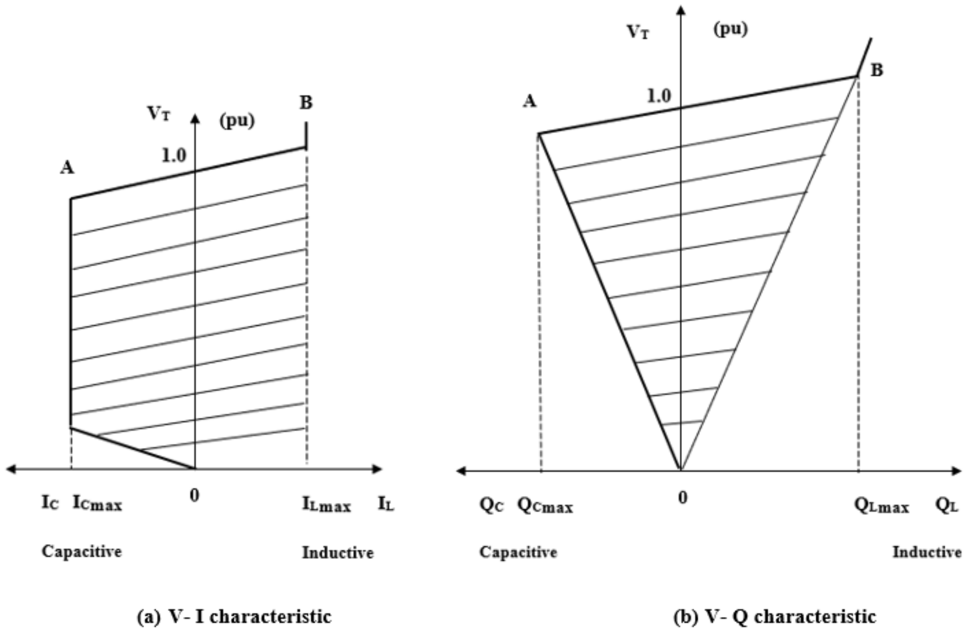
III.4 Operation of STATCOM

III.4.1 V-I and V-Q Characteristics of STATCOM

The STATCOM is essentially an alternating ac voltage source behind a coupling reactance, as depicted in Figure 21. Whenever load voltage changes, beyond acceptable limits, the STATCOM control determines the amount of reactive power to be supplied to the grid or the amount to be absorbed from the ac system. In this case STATCOM behaves like a controllable reactive power generator. The voltage/current(V-I) and voltage/ reactive power(V-Q) characteristics are shown in Figure 24 below.

Figure 24

V-I and V-Q Characteristics of STATCOM



(a) V- I characteristic

(b) V- Q characteristic

At the steady state operation of the power grid, it is desired to keep the voltage load bus at its rated value. At the regulated bus the voltage is controlled within a certain interval (Vmin, Vmax) that the reason of droop control, instead of a constant value Vref. From Figure 24 that the bus voltage is kept between acceptable Vmax and Vmin limits.

The main aim of the STATCOM control system is to instruct the STATCOM to generate the required amount of capacitive current Ic to inject the necessary amount of reactive power to the ac grid or inductive current I_L to absorb required reactive power from the ac grid for the sole aim to keep the load voltage at voltage levels between points A-B. Note that when the load voltage is at its rated value, Vref, then there will be no need for any STATCOM intervention and the current is zero. When the load voltage drops below Vmin or rises above Vmax, STATCOM takes action and restores them to voltage range between A-B.

From the figure we can see that the capacitive and inductive currents are limited by the operating limits of the VSI components. It can be seen from the figure that even at severe faults when the load voltage drops severely to low levels (to 0.2 pu voltage), STATCOM can still restore its voltage back to its rated value (Hingorani&Gyugyi,2000).

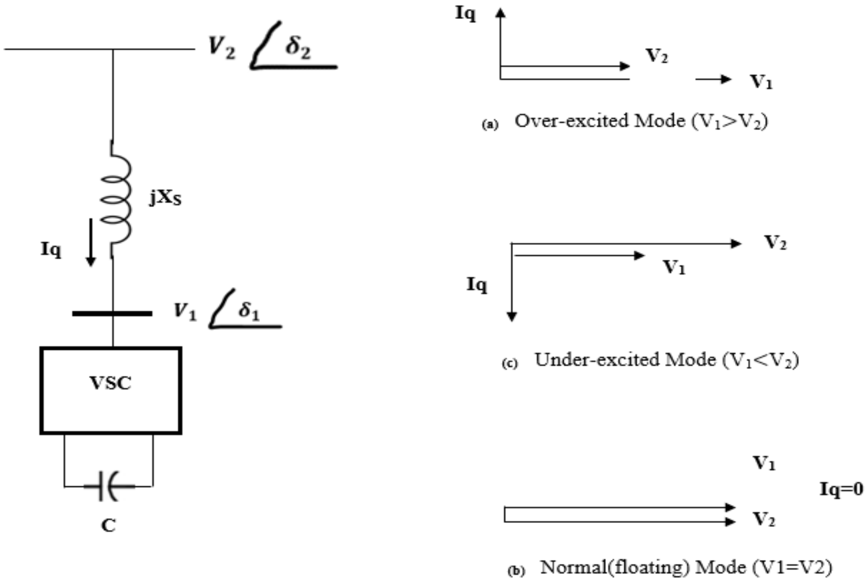
It can be seen from the V-Q characteristics that V is directly proportional to Q. This is expected since the STATCOM behaves like a constant current source.

III.4.2 Operation Modes of STATCOM

It can be easily seen from Equations 3.2-3.5 the STATCOM generates reactive power that can be controlled. STATCOM voltage V_1 is generated independently from the ac system voltage V_2. By changing the magnitude of V_1 you can change the amount of reactive power generated. STATCOM can operate in 3 modes. Figure 25 shows these modes.

Figure 25

Operation Modes of STATCOM



(a) Over-excited Mode ($V_1>V_2$)

(c) Under-excited Mode ($V_1<V_2$)

(b) Normal(floating) Mode (V1=V2)

(a) Mode 1: Over-excited mode of operation

In this mode, load bus voltage has dropped below its rated value, due to the load being inductive and having a low power factor. STATCOM control system senses this situation and instructs VSC change the magnitude of its output voltage by increasing it for supplying reactive power to the load bus, for restoring its voltage magnitude.

From Equation 3.3 it can be seen that if the STATCOM voltage V_1 magnitude is above the ac system voltage V_2, reactive power supplied by STATCOM, Q_1 will be positive. The magnitude of the output STATCOM voltage V_1 has therefore been increased intentionally, by proper pulses generated by the control circuit of STATCOM, to a value that is greater than the ac grid voltage. This means that a capacitive reactive current is going to flow from STATCOM through the leakage reactance to the ac system. STATCOM produces reactive power and compensates the reactive power at the load bus. The STATCOM behaves like a capacitor (Singh et al.,2011).

(b) Mode 2: Under-excited mode of operation

In under-excited mode the magnitude of the load voltage V_2 has increased beyond the rated value because of excessive reactive power at load bus, due to the load being capacitive. It is therefore necessary to drain some reactive power from the power system for restoring the voltage magnitude. From Equation 3.5 we see that when V_2 is greater than V_1, reactive power Q_2 at load bus becomes positive. The control circuit of STATCOM intentionally reduces the magnitude of STATCOM voltage V_1, by properly generated PWM pulses. Now inductive reactive current will flow from ac system to STATCOM through the leakage reactance. In this way the excess reactive power from the ac system will be absorbed by the STATCOM. STATCOM behaves like an inductor.

(c) Mode 3: Normal (floating) excited mode

In this mode, the magnitudes output voltage V_1 of STATCOM and ac system voltage V_2 are exactly the same. From Equations.3.3 and 3.5 we can see the power exchange will be zero. This mode is also known as the ‘floating’ mode.

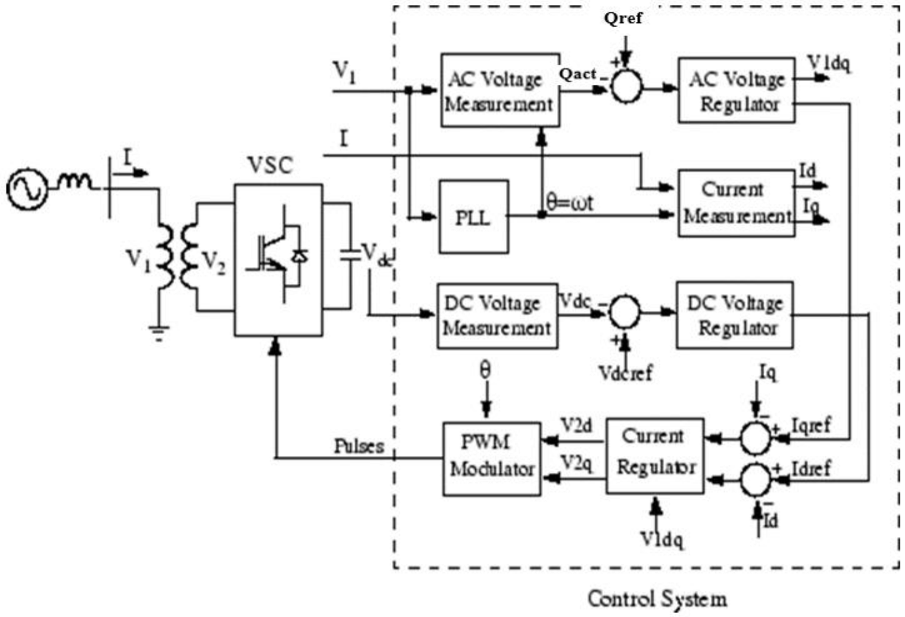
III.5 STATCOM Control System

STATCOM employs a sophisticated control strategy. The control system is activated whenever the load magnitude bus voltage deviates from the rated value, because of the load being inductive and with low power factor. The STATCOM control system was designed in MATLAB/Simulink.

Figure 26 depicts the STATCOM general diagram block of the control circuit. The control system has been assembled by using MATLAB/Simulink software. When STATCOM is connected to the power system, the magnitude of STATCOM voltage that would generate the right current to be injected for reactive power to the load bus or absorbing reactive power from the power has to be determined by the control system of STATCOM.

Figure 26

STATCOM Control System for Reactive Power Mode



It is most difficult to operate a PI Controller or any controller by employing 3-phase instantaneous currents and voltages, because of the complexity of calculations. The 3-phase system of time-varying voltages and currents is known as the a-b-c reference frame. Various feedback controllers including PI and PID controllers prefer to operate with constant current and voltage values, rather than time-changing current and voltage values. In this way PI controller can produce more effective and reliable control over the system. This new system with constant values is known as direct axis-quadrature axis-zero axis, or shortly as d-q-o reference frame which rotates at synchronous speed (Mobarek,2012). The transformation of a-b-c frame to d-q frame is explained in section 3.5.1.3 in detail.

From figure 26 we can see that, the actual 3-phase grid voltages, V1 are measured in a-b-c frame and are then converted from a-b-c frame to constant values in d-q-o frame, expressed as V1d and V1q.Similarly the measurement of 3-phase actual load currents in a-b-c frame will be done and converted to its corresponding constant values in d-q-o frame as Id and Iq. The control system aim to supply the reference reactive power (3MVAR in this study) to the load. The AC Regulator Voltage, which is essentially a PI-Controller, processes the difference between the reference and actual reactive power and generates a reference current for the reactive component of the current,Iq, ref.Iq, ref. is the reference reactive current component of the load current when the load receives rated reactive power from the supply.

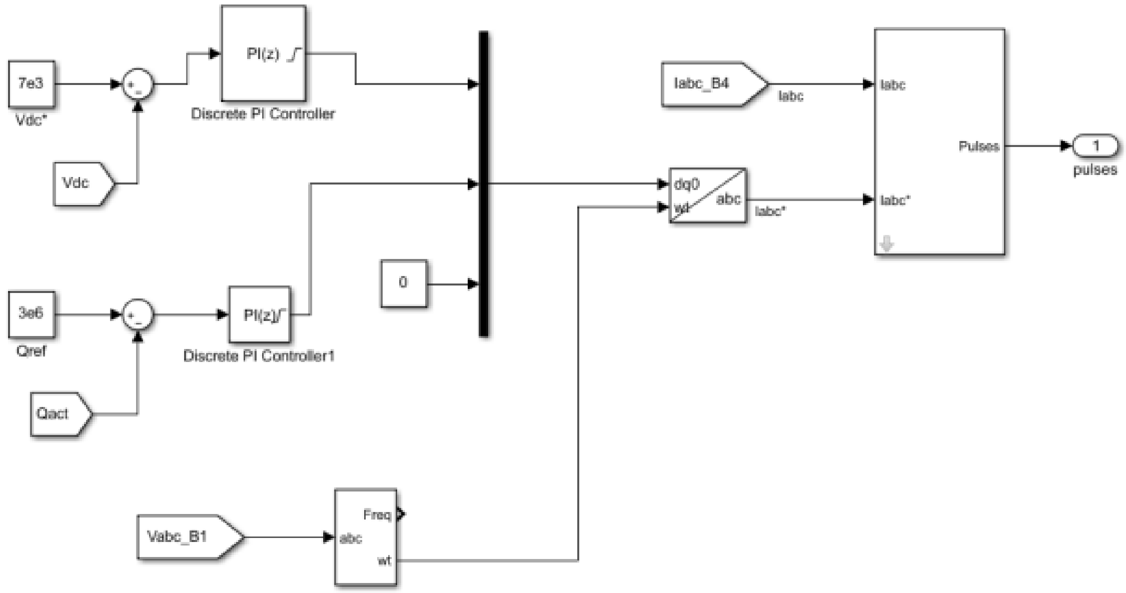
Similarly, capacitor’s DC voltage Vdc is measured, and compared with its rated value (7 kV in this thesis), which is taken as the reference voltage for the capacitor’s voltage, Vdc, ref. If they are equal then there is no need for any action. If they are not equal then a DC Voltage Regulator employing a PI controller generates a reference current for the direct-axis component of the compensation current, Id, ref. Exchanging power with the power system is determined by the converter's dc voltage reference.

A comparison of the active part of the measured load current Id, with the reference current Id, ref. and the comparison of the reactive part of the measured load current Iq, with the reference current Iq, ref. activates the Current Regulator which employs a Hysteresis Current Controller (HCC). HCC is a feed forward type regulator that predicts the STATCOM voltage output V_2(V_2d, V_2q) from the measured grid voltage V_1(V_1d, V_1q) (Mobarak,2012). Id, ref and Iq, ref are transformed into Ia, ref, Ib, ref and Ic, ref currents by Inverse Park Transformation. HCC compares the reference currents and actual currents and generate pulses for the inverter which are using for synthesizing the PWM VSC voltages. Thus, HCC controls voltage magnitudes and phase angles generated by PWM converters.

In this thesis we used a control system based on ‘Reactive Power Control Mode’. The implementation on MATLAB/Simulink is shown in figure 27.

Figure 27

Control System Used in this Study



This time the actual reactive power received by the load Qact, will be measured and a comparison with the reference reactive power of the load Qref, which is 3MVARs in this study. The PI-Controller generate a reference quadrature current Iq,ref. Similarly, the capacitor's actual DC voltage will be measured and a comparison with the reference DC voltage which is 7kV is going to be done in this study. A reference direct-axis current Id,ref. is generated by the PI-Controller. Because all load reactive power is supplied by STATCOM only, the grid's reference reactive power is zero. An a-b-c frame is used for converting reference currents.

HCC compares the reference currents with actual currents (Iabc and Iabc*) and generates pulses for the inverter which are used for synthesizing the PWM VSC voltages. The PWM converter is controlled by HCC in this way by controlling both its magnitude and phase angle.

III.5.1 Components of the STATCOM Control System

STATCOM Control System used in this thesis consists of 5 major components:

(1) Phase-Locked Loop (PLL)

(2) PI Controller

(3) Hysteresis Current Controller (HCC)

(4) Transformation of a-b-c frame to d-q frame

III.5.1.1 Phase-Locked Loop (PLL)

In the PLL, which tracks the frequency and phase angle θ of the grid voltage V_1, negative feedback is used to adjust the system's frequency and phase angle. PLL does this by using an inner frequency oscillator as shown in Figure 27. Because PLL is a controller, all operations inside PLL are done in the d-q frame.

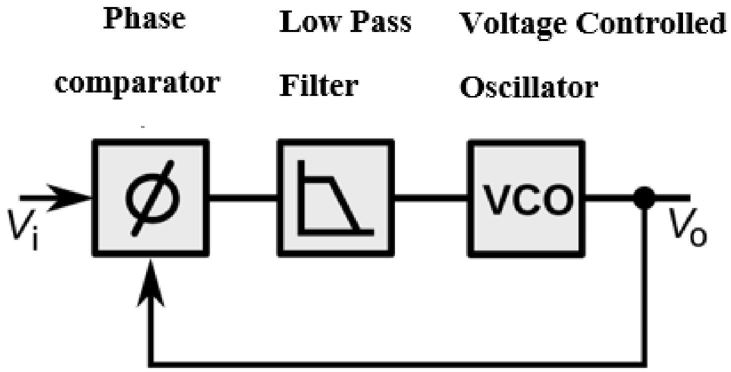
The phase angle θ obtained in this way is also used in obtaining the Park’s Transformation Matrix, which is used to convert 3-phase time-varying ac voltages and currents in a-b-c frame to constant voltages and currents in d-q frame. This is necessary because PI Controllers can only operate by using direct-axis and quadrature axis currents and voltages which are constant real numbers (Mali&Mahajan,2016). Whenever the grid frequency or phase angle changes, the PLL generates a reference signal and intervenes to gate pulses to make sure the voltage generated by VSI has the same phase angle and frequency.

If the STATCOM is used to compensate for reactive power only, then PLL adjusts the phase angle of the STATCOM voltage to be the same as that of the grid voltage. PLL does this by controlling the pulses for VSI accordingly. When the phase angles difference is zero, then exchange of real power does not take place between STATCOM and the grid. We can see this from Equation 3.2. If an exchange of real power is required then PLL adjusts the pulses to arrange the STATCOM voltage phase angle to be different than that of grid voltage keeps the phase angle difference between the voltage of STATCOM and grid voltage at a constant value, as desired by the control system.

It is obvious that when calculations in direct-axis and quadrature-axis frame are finished we have to return to actual a-b-c time-varying frame. For this we use the phase angle θ, of the grid voltage once again and construct the Inverse Park's Transform Matrix. By using Inverse Park's Transform we can calculate actual Ia, Ib and Ic phase grid currents from Id and Iq. The 3-phase reference currents and actual phase grid currents are compared separately by Hysteresis Current Controller. The reactive and real current error signals between reference and actual currents are converted into angle and magnitude of the wanted STATCOM converter output voltage, from which the right gate drive signals, are derived. Figure 28 shows the structure of the PLL.

Figure 28

Structure of the PLL



III.5.1.2 PI Controller

PI Controllers are feedback control loops that calculate error signals by comparing the output of a system with a set point. A proportional and integral constant is multiplied with the error signal in a PI controller loop. In this way the controller produces a correcting signal that reduces the error to zero. The set point is the magnitude at which the system should operate.

In the control system we are making use of two discrete type PI Controllers. One PI Controller is using for supplying 3 MVAR reactive power to the load. It does this by generating a reference grid reactive-current component, Iq, ref. We make use of the other

PI Controller to keep the capacitor’s voltage, Vdc constant at its reference value Vdc, ref which is 7 kV in this thesis. It does this by generating a reference active-current component Id. Whenever the capacitor DC voltage magnitude changes, for any reason, PI Controller takes action to keep it constant. When the capacitor voltage is kept at its rated value Idc will be equal to zero. Of course, this is the case when only reactive power compensation is done.

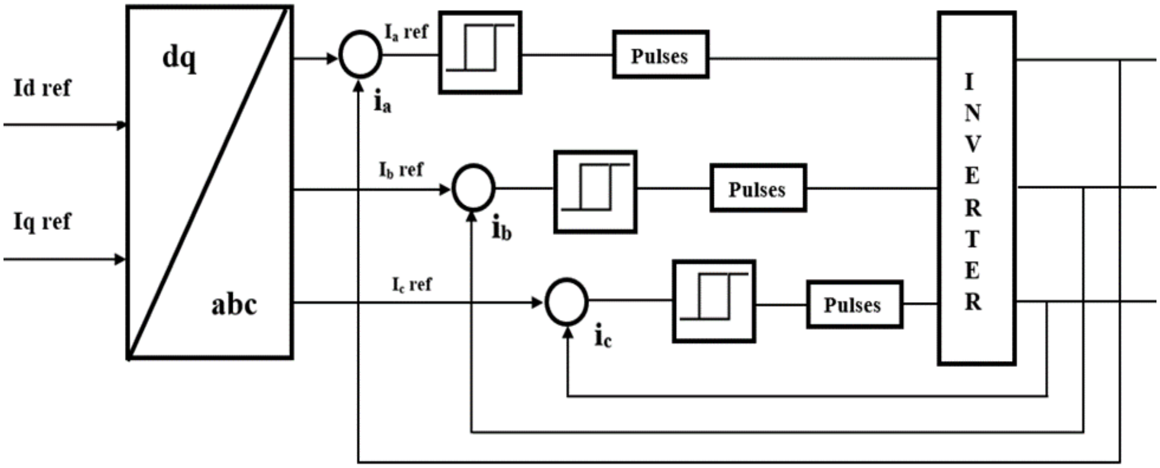
When an external dc source is connected to STATCOM and an active power compensation is needed, then the PLL creates a difference of phase between the STATCOM voltage and grid voltage in this way allows STATCOM and the grid to exchange active power. As the consequence the direct-axis component Id, of the STATCOM current will not be equal to zero. (Rastogi&Bhat,2015).

III.5.1.2 Hysteresis Current Controller (HCC)

HCC is used to control the STATCOM output current which supplies the nominal reactive power to the load. This current should be kept constant whatever the STATCOM voltage is. An error signal is generated by HCC by comparing the STATCOM output current with the reference grid current. HCC is a closed loop control system. Whenever the STATCOM current reaches the boundaries of the hysteresis band, the error signal triggers the HCC by producing pulses for the IGBTs of the inverter. (Ramesh et al.,2014). Figure 29 shows HCC circuit.

Figure 29

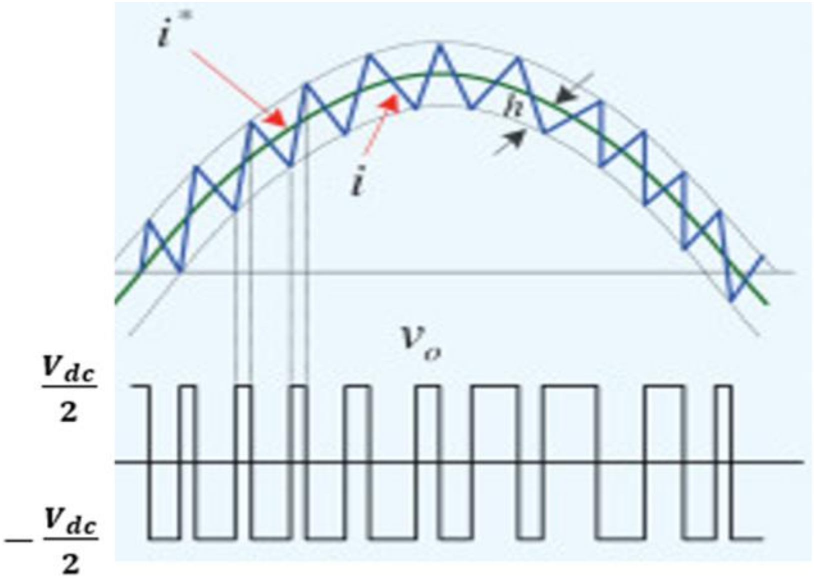
Block Diagram of HCC



A transistor switches to force the current down when the current reaches an upper limit. The current is forced to increase, when the current reaches a lower limit. Figure 30 shows the current waveform of the STATCOM output current.

Figure 30

Current Waveform of the STATCOM Output Current



III.5.1.3 Transformation of a-b-c frame to d-q Frame

The fundamental reason for transforming the three-phase instantaneous currents and voltages from conventional a-b-c frame into a synchronously rotating reference d-q frame is to make the calculations much easier. In d-q frame,3-phase voltages(currents) are converted into 2 constant voltages(currents)for mathematical reasons. It is easier now to control 2 quantities rather than 3 quantities.

All controllers make their decisions based on real numbers. In this thesis, we will do the reactive power compensation of a 3-phase load for restoring the load voltage, by providing all 3 MVAR reactive power of load locally, by a STATCOM. The control system uses a PI Controller for maintaining the required reactive power amount to the load. The comparators in PI Controllers can only compare real numbers and not time-varying numbers. This necessitates to transform 3-phase voltages, Va(t), Vb(t) and Vc(t) and 3-

phase currents Ia(t), Ib(t) and Ic(t) to constant (dc) numbers. Several transformation techniques have been developed over the years such as Clarke's, Park's, Kron's and Krause's. All of these transformation techniques employ the d-q theory of power systems. In this thesis we will use Park's Transformation to convert instantaneous 3-phase voltage and current values to dc values, to be used in the PI control system. After control action, dc values will be converted to 3-phase instantaneous values, this time by using Inverse Park's Transformation (Bhatt et al.,2019).

By using Park's Transformation, the actual 3-phase stationary frame (Va-Vb-Vc) is changed to a 2-phase stationary frame (Vα, Vβ), and then this 2-phase stationary frame is transformed to a new 2-phase frame d-q (Vd, Vq), which is designed to rotate at synchronous speed. The aim is to represent the measured grid voltages and currents in the a-b-c frame as a dc voltage in the d-q frame. The voltages and currents obtained by transformations (Vd, Vq) are fictitious. They do not exist at all but mathematically they are very useful. They are just useful tools for controlling the system.

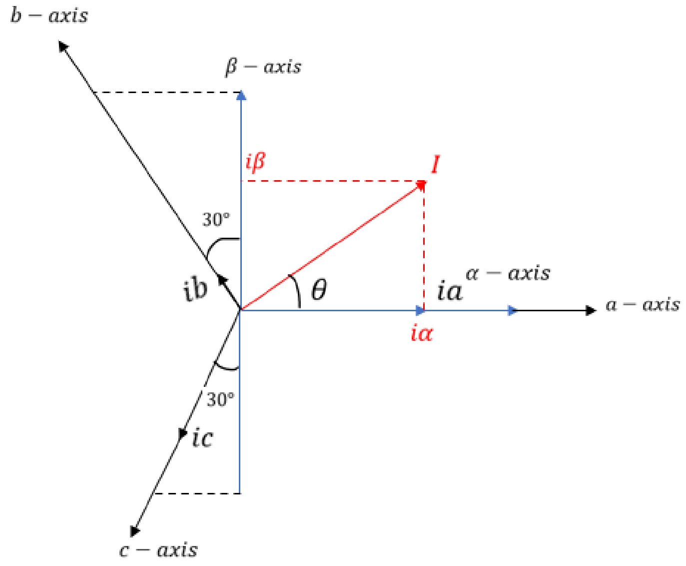
By controlling the quadrature-axis current, iq only, Park's Transformation allows us to control reactive power. A direct-axis current, id, can also be controlled to control the active power. These controls can be done irrespective of each other.

We will derive Clarke's and Park's Transformation Matrices now. Clarke's Transformation transforms 3-phase sinusoidal currents and voltages in time domain, known as the a-b-c frame, to 2-phase sinusoidal currents and voltages in time-domain, known as α- β frame, which are orthogonal to each other.3-phase sinusoidal currents and voltages are 120 degrees apart in the a-b-c frame, whereas 2-phase sinusoidal currents and voltages are 90 degrees apart in α-β frame. We will continue the analysis by using 3-phase currents only, keeping in mind that the results are equally valid for 3-phase voltages as well.

This technique is used in field-oriented control of electrical machines. The 3-phase winding on the stator is reduced to 2-phase winding to simplify the calculations. The Law of Conservation of Power requires the power in 3-phase system to be equal to power in 2-phase system. Similarly, the MMF produced by the 3-phase currents in a-b-c frame should be the same as the MMF created by the 2-phase currents in the d-q frame. MMF is defined as the multiplication of turns in a phase winding, by the current passing in it. The overall MMF produced by a 3-phase system is (3/2) times the MMF produced by one phase current only. The 2-phase currents in d-q frame produces an MMF which is equal to the MMF produced only by one phase of the 3-phase system. Clarke Transformation is modified by multiplying it with a constant number such that it produces the same overall MMF. Figure 31 shows currents in a-b-c frame and in α and β frame. For simplicity a-axis and α- axis are chosen to be coincident.

Figure 31

a-b-c Frame and α -β Frame



iα and iβ can be expressed in terms of ia, ib, and ic based on the above figure.

$$i\alpha = i_a - i_b.sin(30) - i_c.sin(30) = i_a - 0.5i_b - 0.5ic$$

$$i\beta = 0i_a + (\sqrt{3}/2)i_b - (\sqrt{3}/2)i_c$$
(3.6)

The 3-phase system is balanced, which implies

$$i_a + i_b + i_c = 0$$

i0 can be defined as,

$$i0 = (1/3)(i_a + i_b + i_c)$$

Because the 3-phase is balanced, i0=0 and therefore has no effect on the power and the MMF.It is a trivial component but it helps to make the Clarke’sTransformation Matrix a square matrix whose inverse can be calculated.Clarke’s Transformation is given below.The coefficient (2/3) is used to prevent any change in the magnitudes of currents during the transformation.Such transformations are called magnitude-invariant transformations.

$$\begin{pmatrix} i\alpha \\ i\beta \\ i0 \end{pmatrix} = \left(\frac{2}{3}\right)\begin{pmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/3 & 1/3 & 1/3 \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \tag{3.7}$$

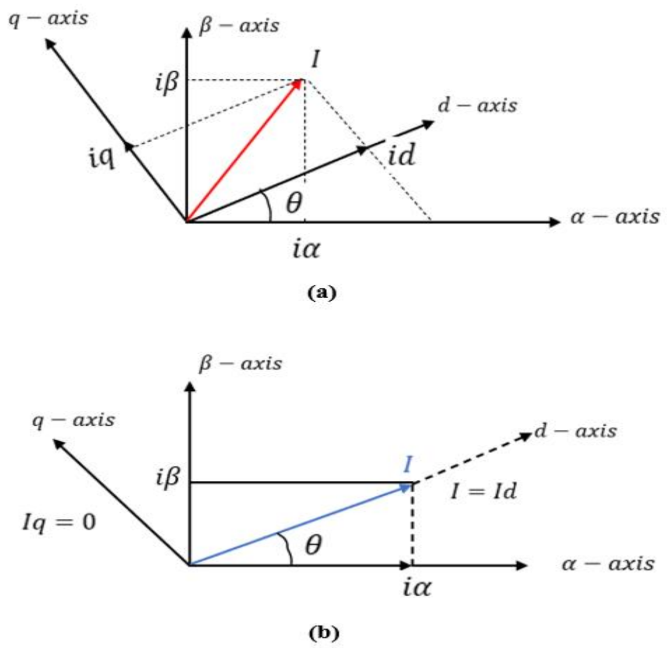
Equation 3.7 is not in compliance with the Law of Conservation of Power.We will now derive the modified Clarke’s Transformation which abides with the conservation of power:

The turns number in each phase of the 2-phase winding in the d-q system is increased by $(\sqrt{3}/2)$ times the turns number in each phase winding of the 3-phase system. Similarly,the current in the 2-phase system is increased by the same ratio,so that the 2-phase winding will produce the same amount of MMF,as in the 3-phase system. To preserve the reactive and active power during the transformation,the above matrix,Clarke’s Transformation Matrix should be changed as below:

$$\begin{pmatrix} i\alpha \\ i\beta \\ i0 \end{pmatrix} = \left(\sqrt{(3/2)}\right)\begin{pmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \tag{3.8}$$

Figure 32

α-β and d-q frames



In Figure 32 (a) the magnitude of the space vector I is not constant,because d-axis and space vector I rotate at different speeds.When d-axis is placed on the space vector I,then they rotate at the same speed.Due to relativity the magnitude of the space vector I is now a constant number.This causes the quadrature-component iq=0.

Resolving iα and iβ along d and q axes,id and iq are calculated as,

$$id = i\alpha . cos(\theta) + i\beta . sin(\theta)$$

$$-iq = i\alpha . sin(\theta) + i\beta . cos(\theta)$$

$$\begin{bmatrix} id \\ iq \\ i0 \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta & 0 \\ -sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (3.9)$$

The overall a-b-c to d-q-o transformation is obtained from Equation.3.8 and 3.9 as

$$\begin{bmatrix} id \\ iq \\ i0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & \cos(\theta - 120) & \cos(\theta - 240) \\ -sin\theta & -\sin(\theta - 120) & -\sin(\theta - 240) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.10}$$

The inverse transformation from d-q-o frame to a-b-c frame is,

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & -\sin(\theta) & \frac{1}{\sqrt{2}} \\ \cos(\theta - 120) & -\sin(\theta - 120) & \frac{1}{\sqrt{2}} \\ \cos(\theta - 240) & -\sin(\theta - 240) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} id \\ iq \\ i0 \end{bmatrix} \tag{3.11}$$

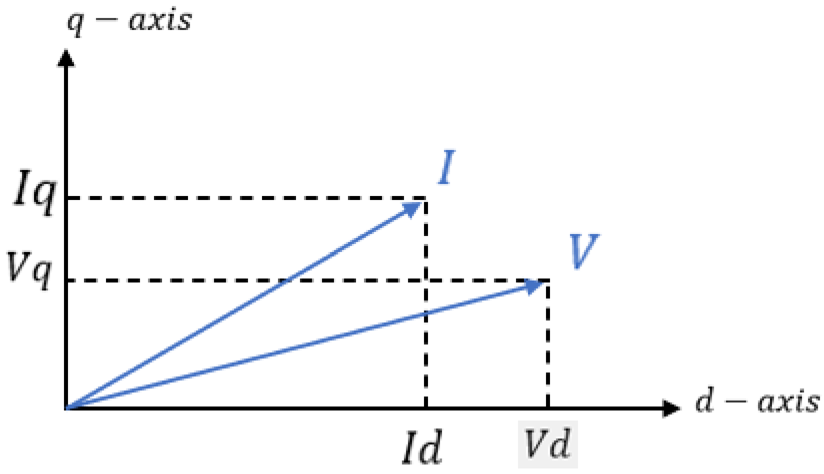
Note that all transformations are taken care of by the MATLAB/Simulink software.

III.5.1.3.1 Power Equation in d-q Frame

Figure 33 shows the calculation of reactive power(q) and active(p) in the d-q frame (Mali&Mahajan,2016). I and V are space vector current and voltage in d-q frame.

Figure 33

Active and Reactive Power Calculation in d-q Frame



$$p = Vd.id + Vq.iq$$

$$q = Vq.id - Vd.iq \tag{3.12}$$

For simplification of calculations,the voltage V vector in the d-q frame is always aligned with the d-axis.This causes the voltage vector V to be represented by its d-component only,making the q component zero.Puting Vq=0 into above equation,we get,

$$p = Vd.id \quad \text{and} \quad q = -Vd.iq \tag{3.13}$$

III.6 Conclusions

In this chapter principles of STATCOM operation has been fully studied, especially for the case when it supplies reactive power to the grid. STATCOM is not used in this thesis to compensate for active power. The control system operation will be eased. The STATCOM Control System is based on generating a voltage of appropriate phase angle and magnitude, by the VSI inverter for generating and injecting the correct capacitive current to the grid. In this way,3MVAR reactive power will be supplly to the load directly by the STATCOM. The generator and the transmission lines are relieved from the reactive power burden.

PI Controllers execute control actions only in terms of real numbers. For this reason, Park's Transformation had to be used as a mathematical tool. The MATLAB/Simulink software takes care of the mathematical transformation of time-domain a-b-c frame to the d-q-o frame and later on d-q-o frame to a-b-c frame. d-q frame is a must because mathematically it provides us an opportunity to control of the reactive and active power independently.

CHAPTER IV

Simulation Results of the 2-Bus Power System, Before and After Compensation

IV.1 Introduction

In this thesis, we studied a 2-bus power system consisting of a 3-phase supply feeding a 3-phase load, in need of 3MW and 3 MVAR power, over a 3-phase transmission line. The reactive power rating of the inductive load was intentionally chosen to be the same as the real power rating of the load, so that the power factor of the load becomes 0.7071, which is a very bad figure for the power system. This is a very extreme case that we do not come across in real life very often. The aim is to show how effective the reactive power compensation by STATCOM can be, under severe conditions. It is well-known that inductive loads with low power factors draw higher currents from the supply, compared to the loads with higher power factors. A very good example to loads that have a lagging power factor around 0.7071 is the arc furnace. Arc furnaces require very high currents to melt crude iron.

If such power systems are not compensated, it will be very costly to the supplier of the electric power, carrier of the electrical power over the transmission lines and the customer who buys the electric power. The main aim of all power systems is to transmit real power efficiently to customers over the transmission lines. The customers, on the other hand, receive this real power and use it to do work. But because the loads cannot always be totally resistive and inevitably it includes motors whose equivalent circuit has inherent inductances, the load voltage and current will be out-of-phase. This calls for the reactive power requirement of the load. This new component of power has to be supplied by the supplier of electric power.

This extra reactive power need of the load necessitates the magnitude of the supply current to increase, which in turn affects the power system adversely. Power loss on the transmission lines will increase with an increase in current in the lines. Similarly, the increased current will cause the voltage drop on the lines to increase. This will draw the load voltage below its rated value and may damage the load.

In this research, it is intended to show that by doing reactive power compensation by using STATCOM, it is possible to overcome all the problems stated above. In this case, reactive power will only be provided by the STATCOM. This means that the load reactive power will neither be supplied by the supplier nor transmitted all the way by the transmission lines and consequently voltage drop on the transmission and transmission line loss will not be increased. This will result, in an improvement of voltage regulation of the transmission line.

The compensation of reactive power made by using STATCOM relieves the transmission line from carrying reactive power to the load. This reduces the current in the transmission lines because the lines are left to transmit real power only. This provides a very good opportunity whereby the power transfer capability of the lines can be increased, because of the reduced currents in the lines, due to STATCOM. This is one of the main aims that the founder of the FACTS devices Hingorani wished to achieve when designing the controllers.

IV.2 Power System Under Study

The single-line diagrams of the power system when the compensation is connected when the compensation is not connected are shown respectively in Figure 35 and Figure 36. Both figures consist of a supply bus and a load bus. The 3-phase supply feeds a 3-phase load over a 3-phase transmission line. The supply, load and the transmission lines are all connected in wye. The supply voltage is kept constant at 22 kV, line-to-line, at a phase angle of zero. The phase voltage is 12.70 kV. The rated load power is 3 MW and 3MVAR.The transmission line length is not kept constant. The length of transmission line is varied for studying its effect on voltage regulation. This provides an opportunity to show how the introduction of STATCOM improves the voltage regulation. The impact of STATCOM on the power factor of the supply is also studied.

To illustrate the positive effect of reactive power compensation by STATCOM, we will perform simulations for 3 different lengths of the transmission line, namely: 10 km, 20 km and 30 km. The respective line impedances are 1+j3 ohms, 2+j6 ohms and 3+j9 ohms. Under these conditions, the transmission line behaves like a short transmission line and is represented only by a series resistance and an inductance. This simplifies the simulation of the transmission line. Different lengths of transmission lines will enable us to observe the effects of transmission line impedances on voltage stability, voltage regulation, and efficiency.

Figure 34

Single line diagram before compensation

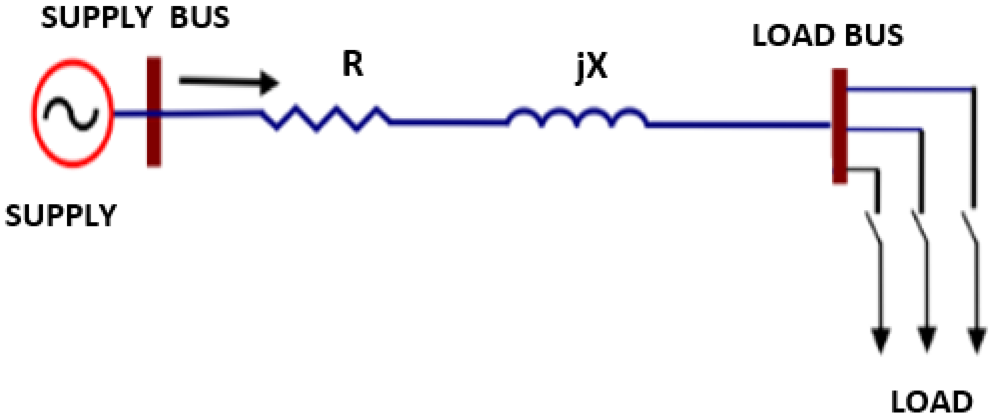
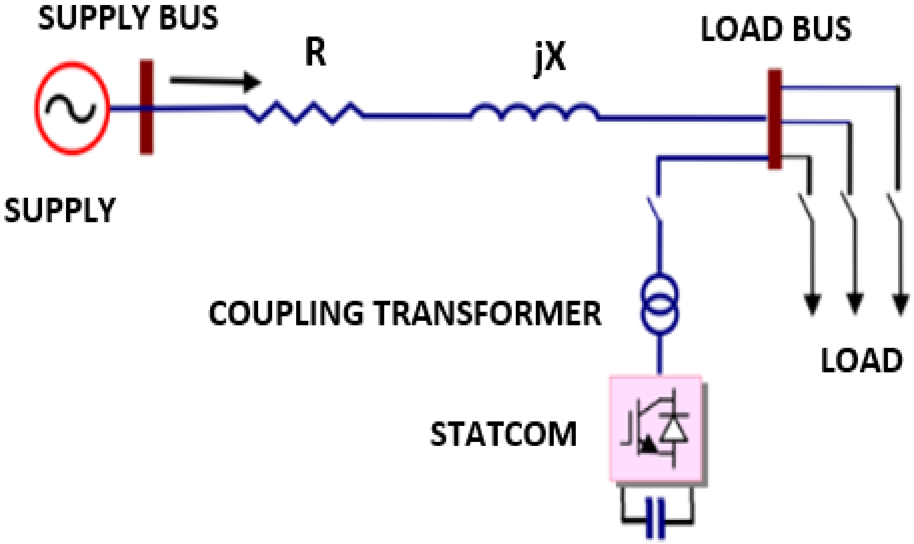


Figure 34

Single line diagram after compensation



The below table are provided with details about the power system under study.

Table 4.

Simulation Parameters of the 2-bus power system

Supply, Transmission Lines and the Load	
Supply voltage	22 kV(line-to-line),12.7kV (phase voltage)
Frequency	50 Hz
Rated Active Power of Load	3 MW
Rated Reactive Power of Load	3 MVAR
Transmission Line Lengths	10 km,20 km and 30 km
Resistance/km of Trans.Line	0.1 Ohms/km
Inductance/km of Trans.Line	0.9549×10^{-3} Henry/km
STATCOM	
STATCOM Rated Power	3 MVAR
STATCOM DC Capacitance	10 mF
Switch type	IGBT with anti-parallel diode
STATCOM DC Link Voltage	7 kV
PI Controller Parameters for Reactive Power	Kp = 12 Ki = -40
PI Controller Parameters for DC Voltage	Kp = 5 Ki = 10
Grid Reactive Power (Reference)	Zero

IV.3 Simulation results

Simulink/MATLAB software is used to perform the simulations. MATLAB/Simulink is a very useful software developed by MathWorks Co. for engineers. It is used to Simulink or test the response of the power system that you have designed on paper, before making it real. Once you see the results of the simulation then you can make changes in your design until you obtain the desired response.

You simulate the power system by using blocks or tool-boxes in the 'Simulink Main Library’. There are blocks representing generators, transmission lines, impedances, loads, transformers, filters, voltage-sourced inverters, and etc. There are also measurement blocks that measure current, voltage, active power, reactive power and power factor. Display blocks are also there, which display voltage and current waveforms changing with time. Most importantly you can design control systems incorporating PI and PID controllers.

In this thesis we have modelled the 2-bus power system first and then choose the appropriate blocks from the Simulink Main Library and assembled the power system, with measurement, display and control blocks in place. Simulations results with and without STATCOM compensation are presented and interpreted below.

IV.3.1 Simulation Results for 10 km Transmission Line Before and After Compensation

Figure 36 shows the simulation model without compensation.

IV.3.1.1 Simulation results before compensation for 10 km transmission line

Figure 36

Power System Simulation Model without Compensation

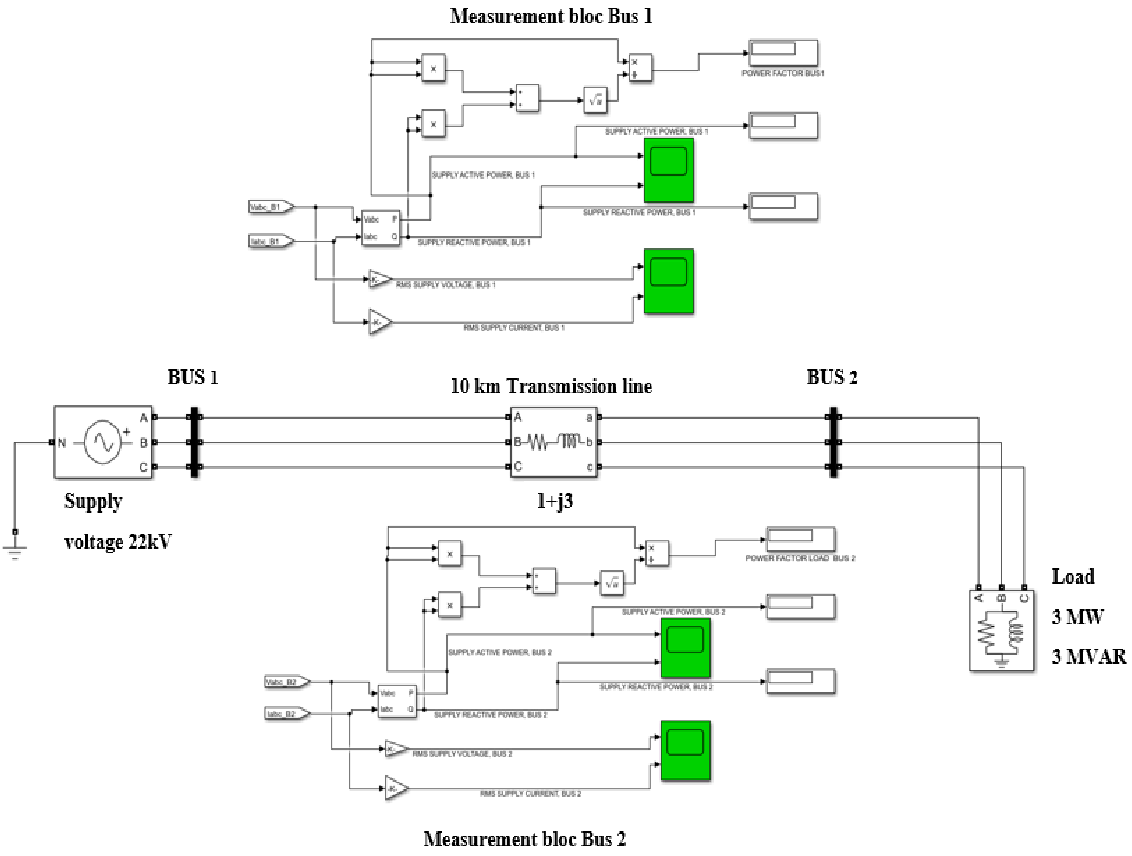


Figure 37

Active and Reactive Supply Power Before Compensation (Bus-1)

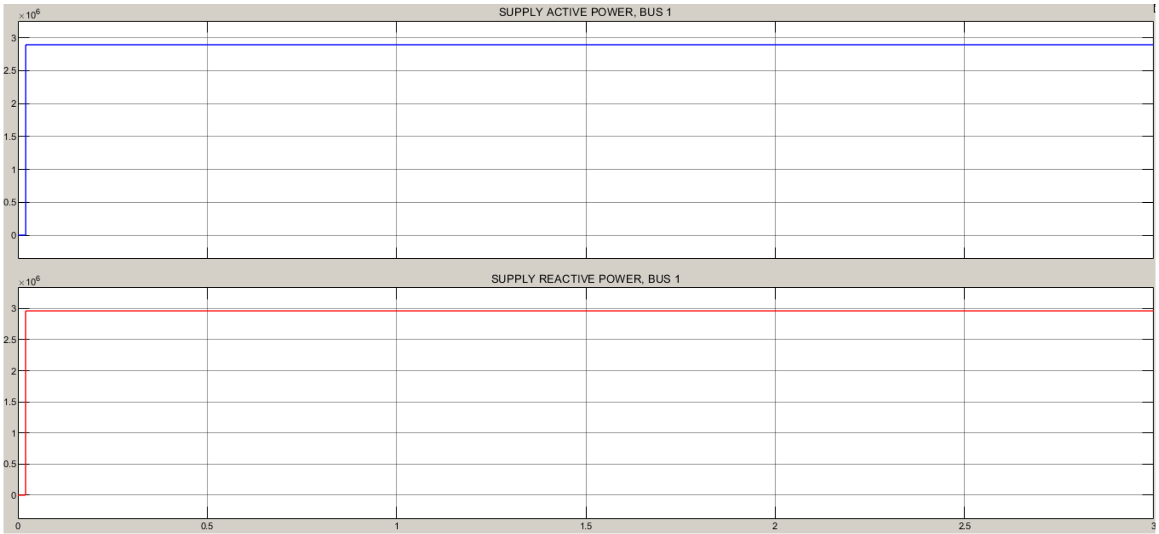


Figure 38

Supply Voltage and Current Before Compensation (Bus-1)

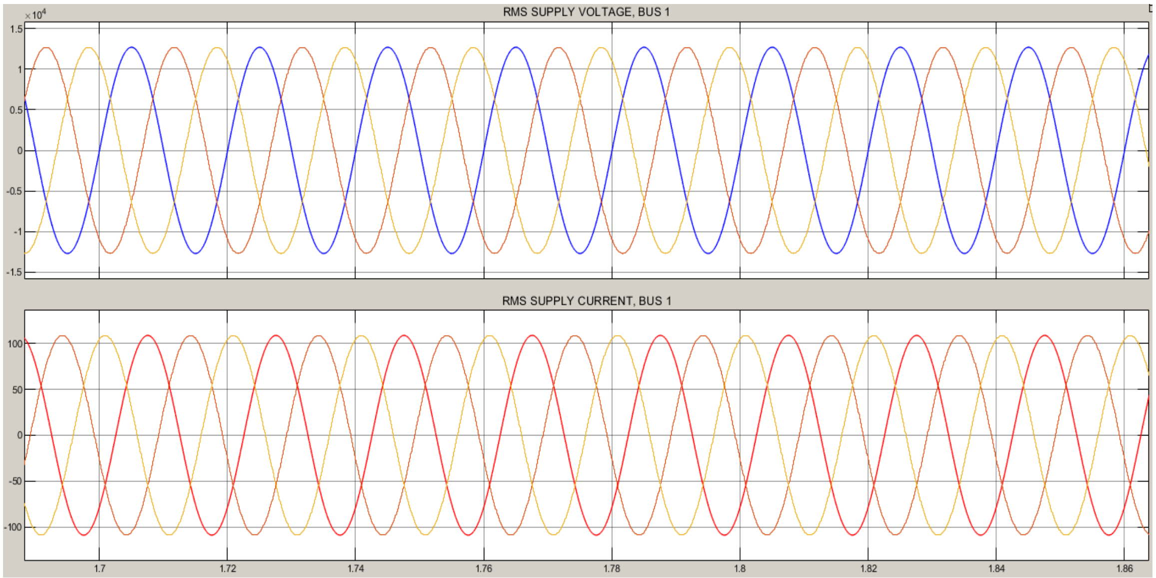


Figure 39

Active and Reactive Load Power Before Compensation (Bus-2)

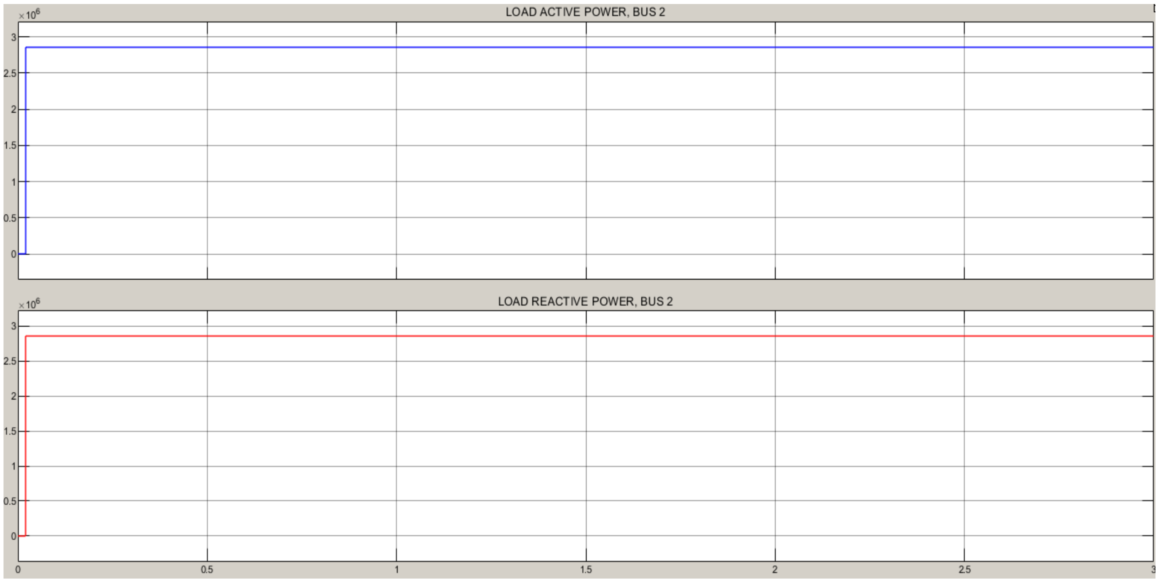


Figure 40

Load Voltage and Current Before Compensation (Bus-2)

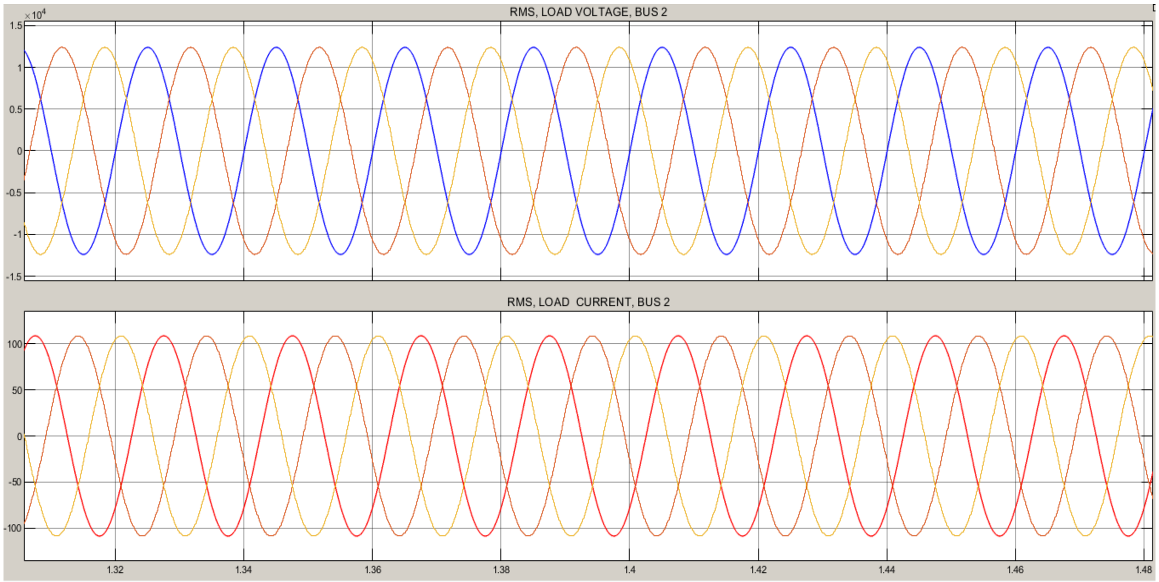


Figure 37 depicts the reactive and active power that the supply provides to the load. We can notice that; the active supply power is 2.892 MW and the reactive supply power is 2.962 MVAR. Figure 38 shows the supply rms voltage and rms current of the supply. It can be seen that the rms voltage and current at Bus-1 are 12.7 kV (always constant) and 108.7 A, respectively, and the power factor is 0.6985.

Figure 39 depicts the amount of reactive and active power taken by the load, which is 2.856 MVAR and 2.856 MW. Figure 40 shows the rms voltage and rms current of the load. We can see that the rms voltage and rms current of the load at Bus-2 are 12.4 kV and 108.7 A, and the power factor is 0. 7071. Let mention that the supply and load current are the same.

We can see from table 5, that the voltage drop at Bus-2 is 2.4% of the nominal voltage. This is within the limits of the allowable voltage deviation which is 5% according to the standards. Load voltage reduces because of the voltage drop on the transmission line impedance, which is 1+j3 ohms.

Table 5.

Simulation Results Before Compensation for 10 km Transmission Line

12.70kV rms, phase voltage; Length 10 (km) Line resistance 1ohm; Line reactance j3 ohms					
	Active Power (MW)	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**	**Power Factor**
Supply Bus 1	2.892	2.962	12.7	108.7	0.6985
Load Bus 2	2.856	2.856	12.4	108.7	0.7071

4.3.1.2 Simulation results after compensation for 10 km transmission line

Figure 41

10 km power system Simulink model after compensation

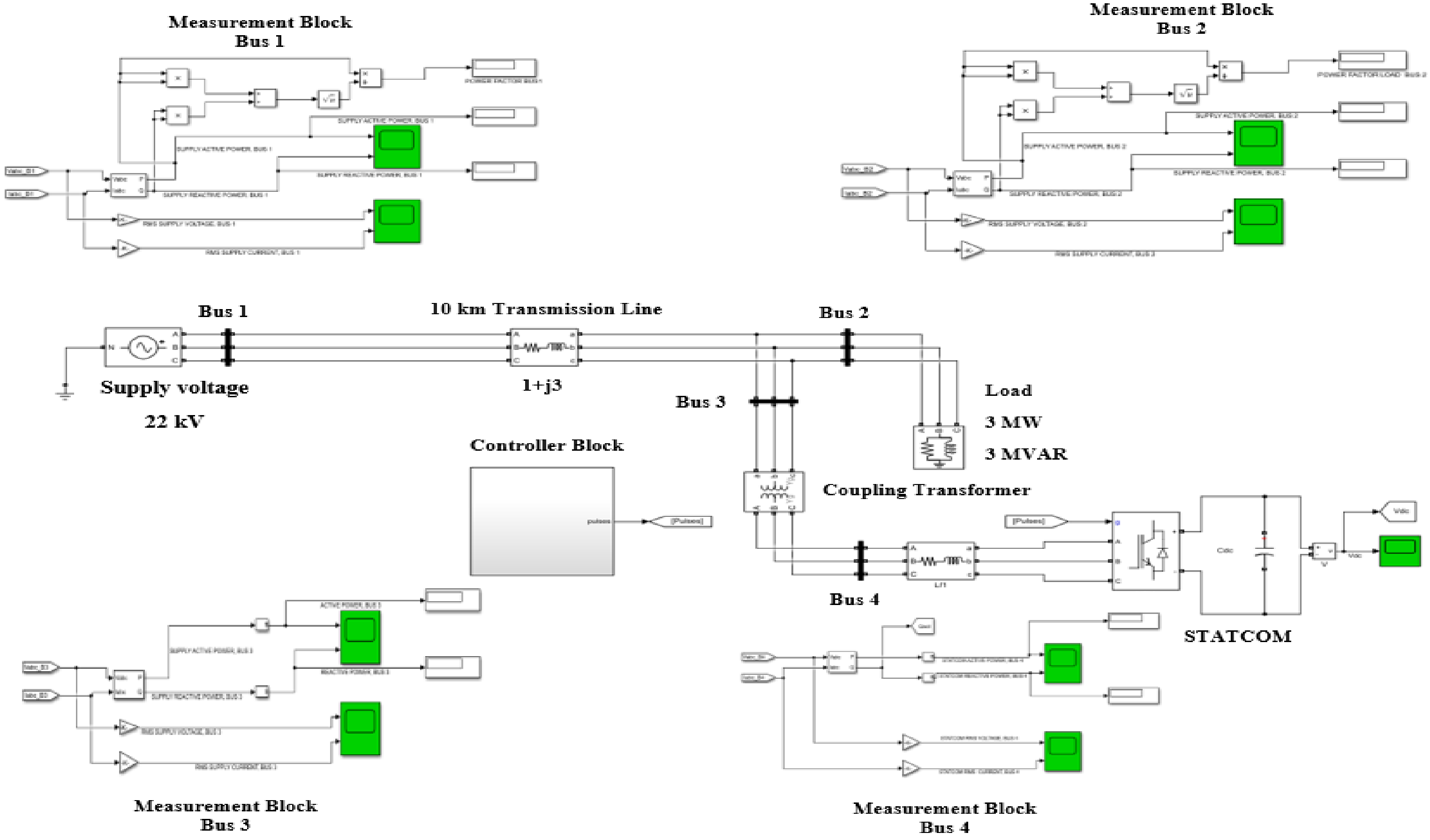


Figure 42

Supply Voltage and Current After Compensation (Bus-1)

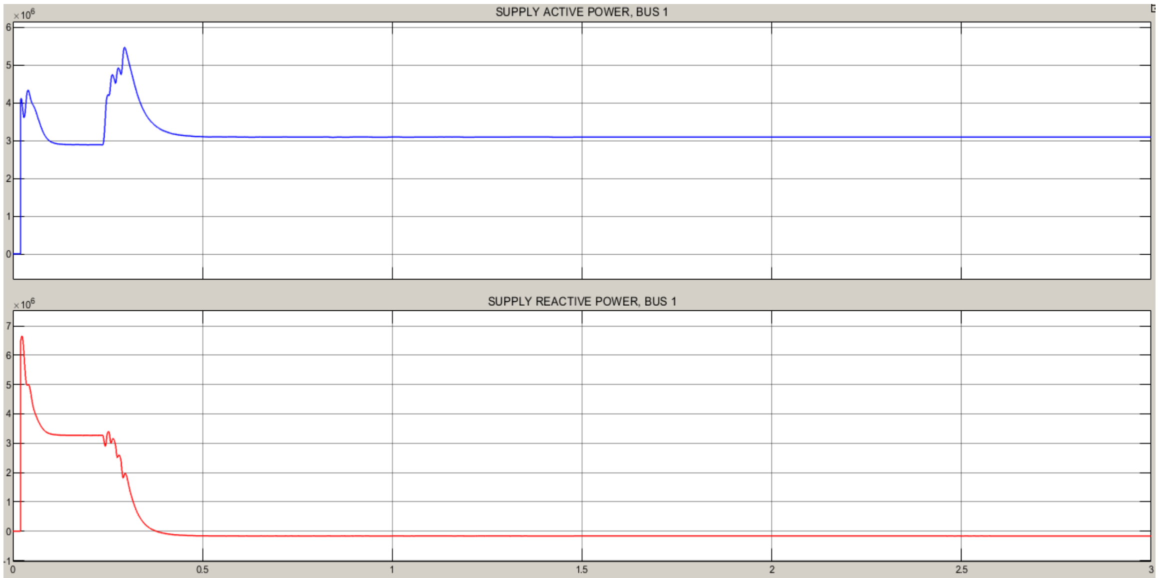


Figure 43

Active and Reactive Supply Power After Compensation (Bus-1)

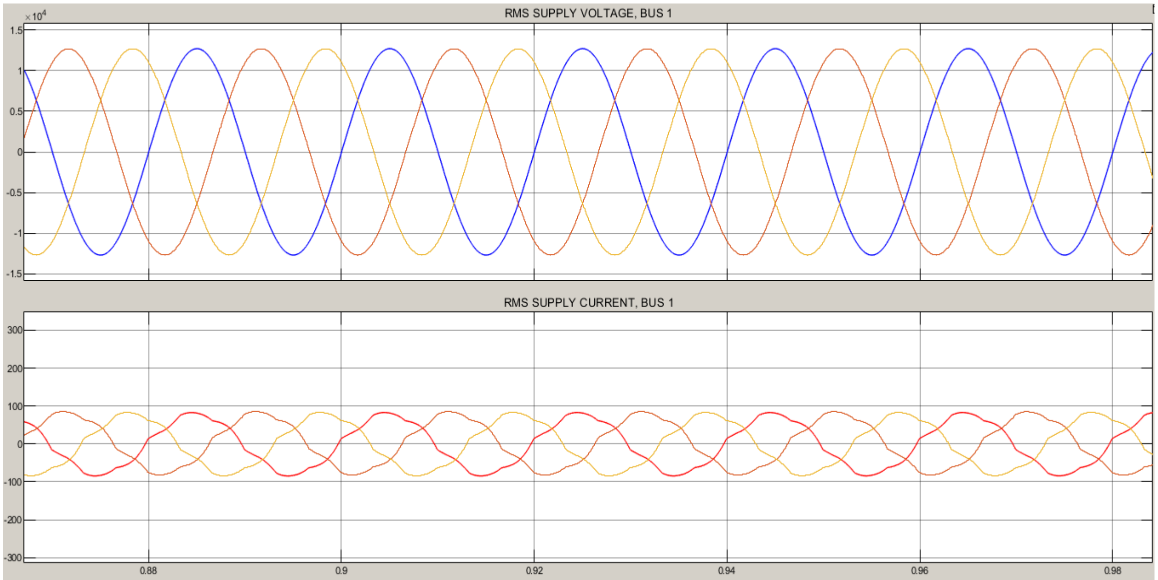


Figure 44

Load Voltage and Current After Compensation (Bus-2)

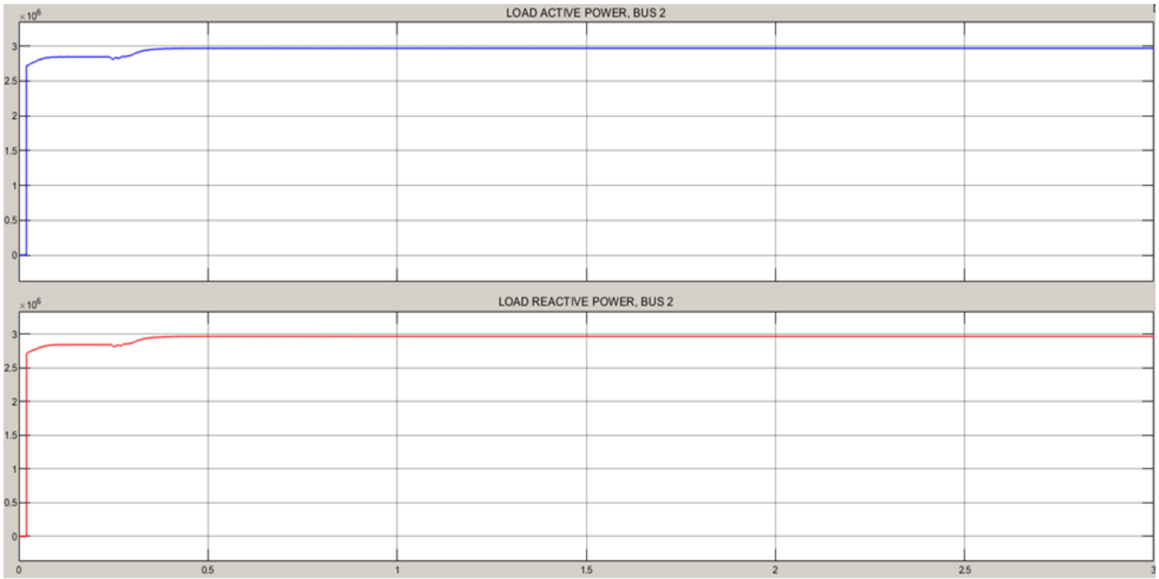


Figure 45

Active and Reactive Load Power After Compensation (Bus-2)

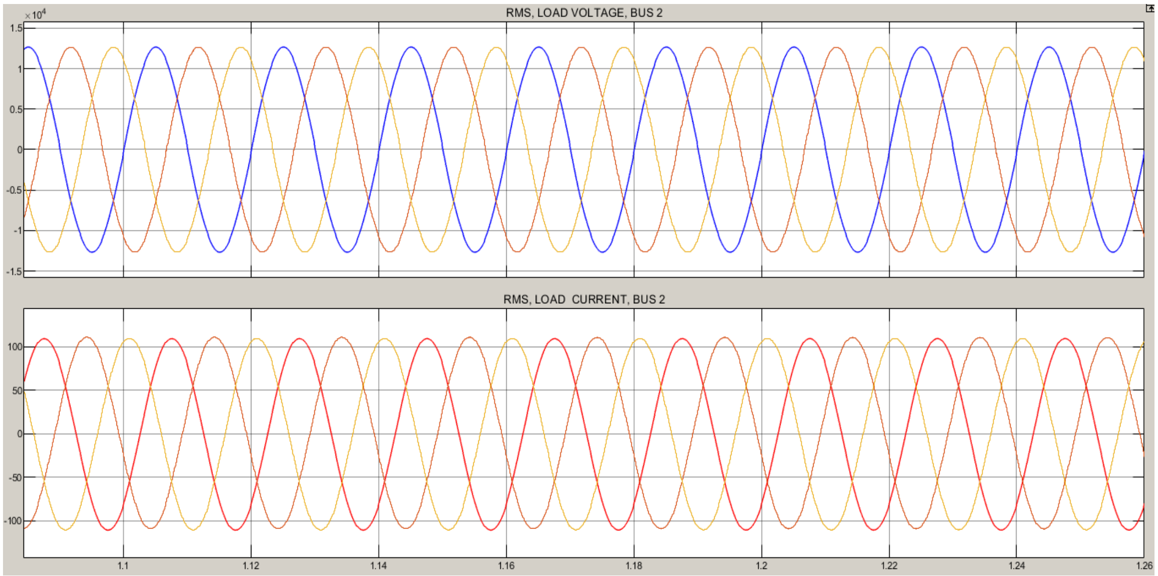


Figure 46

Active and Reactive Power at Bus-3 After Compensation

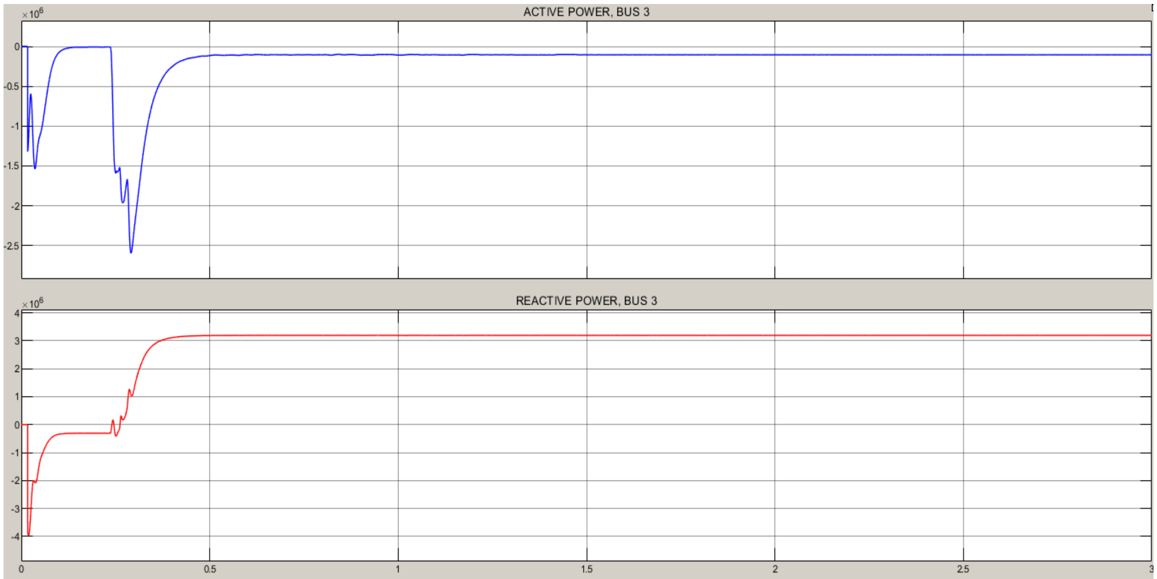


Figure 47

Bus 3 Voltage and Current After Compensation

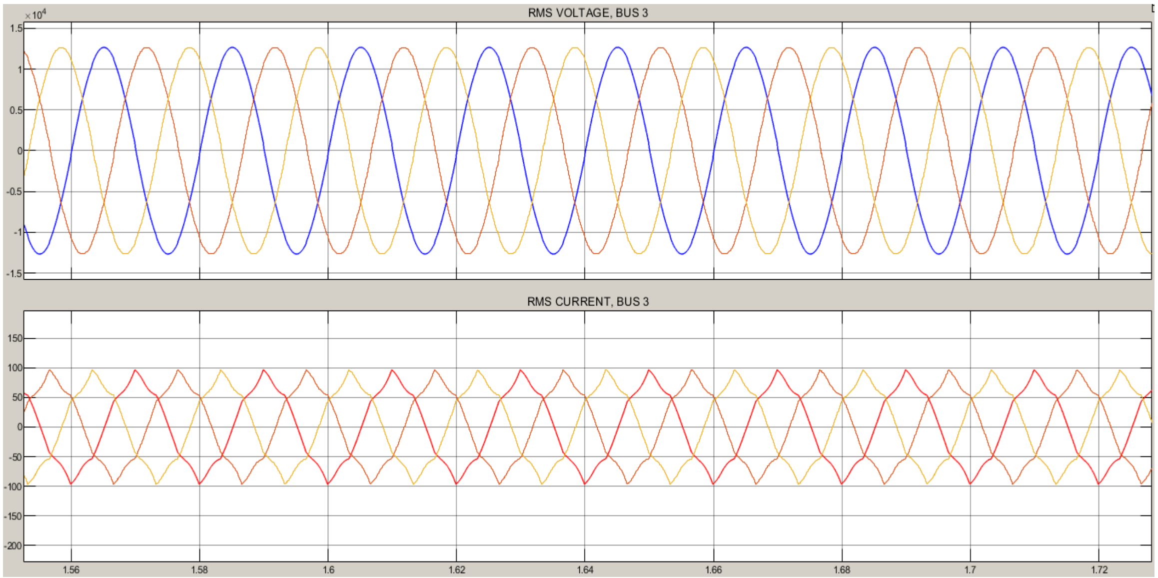


Figure 48

STATCOM Active and Reactive Power (Bus-4)

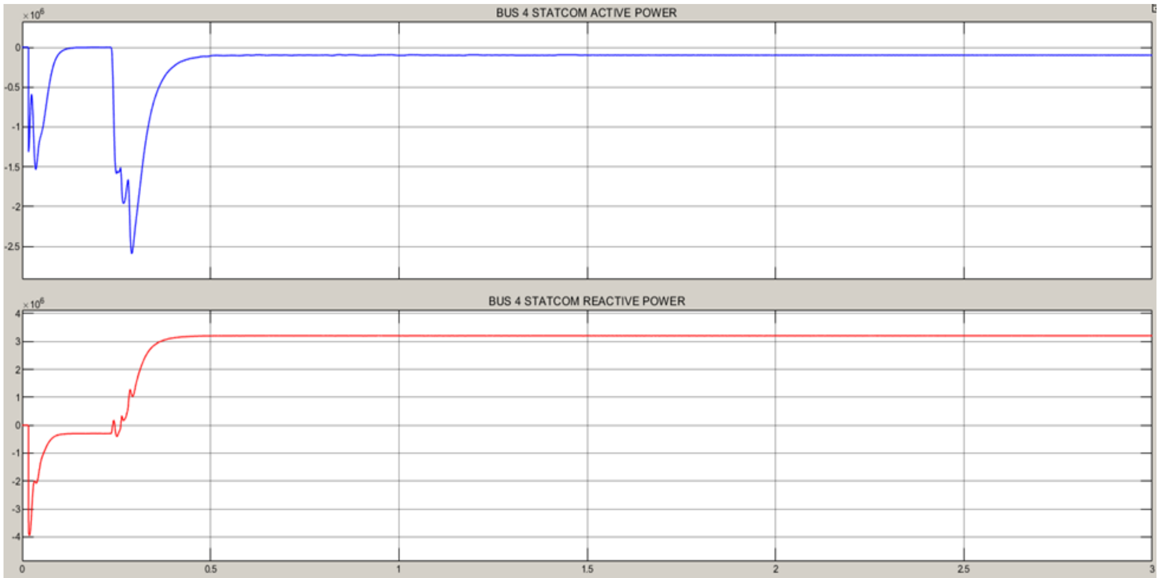


Figure 49

STATCOM Voltage and Current (Bus-4)

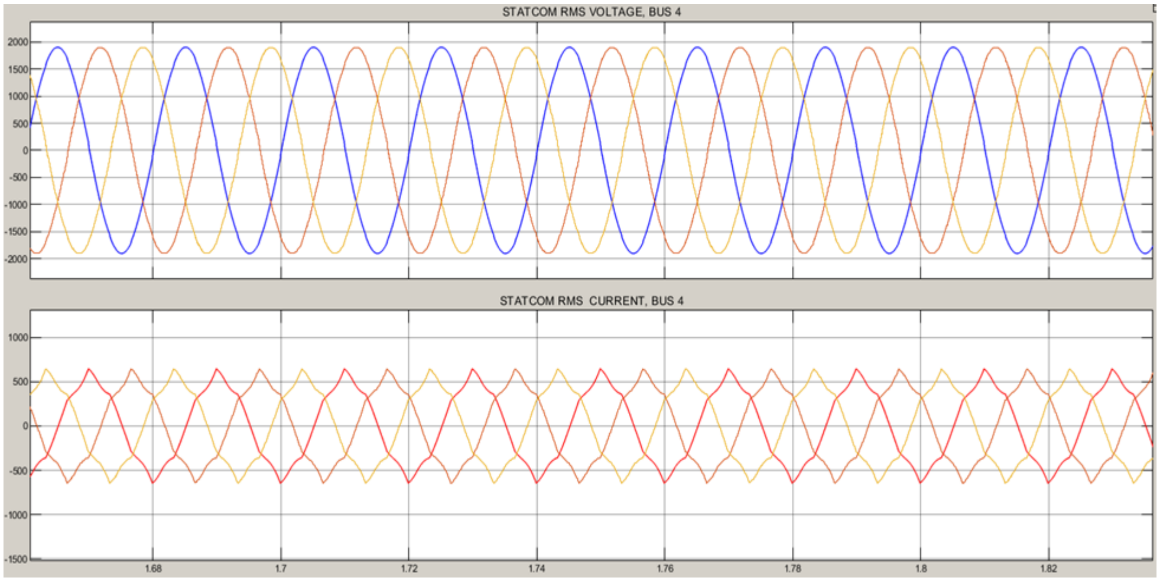


Figure 50 shows the STATCOM output current and voltage for one phase. It can be noticed that the current is distorted because of harmonics STATCOM output voltage has been generated by making use of the PWM technique. PWM is a modulation technique for controlling the width, in time, of an electrical pulse (which is at the same time the duration of the pulse), based on modular signal information (Borse, et al.,2014).

Figure 50

STATCOM output voltage and current for one phase

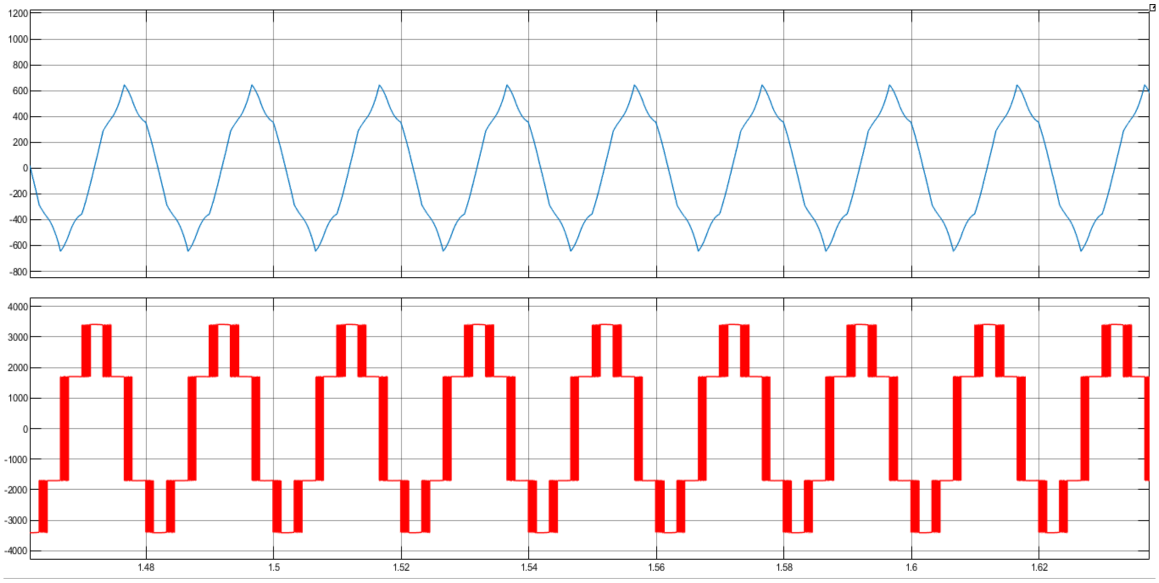
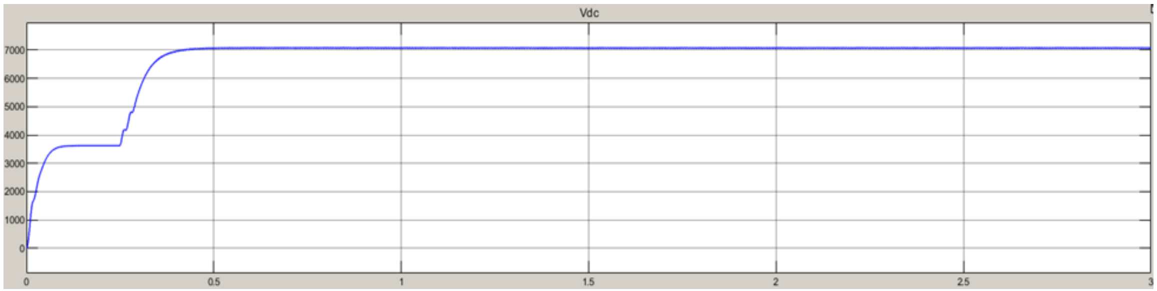


Figure 51

STATCOM Capacitor DC Voltage



After compensation, the active and reactive power delivered by the supply is depicted in Figure 42. we can see that; the supply delivers 3.094 MW active power. The reactive power delivered by the supply is very small now (0.212 MVAR) compared to 2.962 MVAR before compensation. Figure 43 shows the supply rms current and voltage after compensation. We noticed that while the supply rms voltage is always constant at 12.7 kV, the supply current magnitude has decreased from 108.7A to 83.72 A. This is because the supply does not deliver any reactive power to the load anymore.

Figure 44 shows the amount of reactive and active power the load receives. These are 2.969 MVAR and 2.969 MW respectively. Figure 45 shows the load rms current and voltage after compensation. We can see that the load rms voltage at Bus-2 has risen to 12.67 kV from 12. 4kV.This is because all of the load reactive power is being delivered by the STATCOM, and not by the supply. The supply current has decreased to 83.72A, because the load does not receive reactive power. The load current did not change much when STATCOM is connected, since the complex power of the load,3MW+j3MVAR, remains the same. The load current was 108.7A before compensation and 110A after compensation. The slight increase in the current is because of the slight decrease in the load voltage.

It can be noticed that the supply receives a small amount of reactive power, which is 0.212 MVAR. The load receives 2.969 MVAR of reactive power from the STATCOM. Figure 48 shows that STATCOM generates 3.2 MVAR. STATCOM absorbs 0.098354 MW, because the Voltage-Sourced Converter is not lossless. All the reactive power drawn by the load comes from STATCOM. from Table 6 it can be noticed that the power factor of the supply has improved from 0.6985 to 0. 9986.The power factor at the load side remains constant at 0.7071, since the complex power of the load is constant.

Table 6 shows that the load voltage at Bus-2 has risen from 12.4kV to 12.67 kV. This is because the current in the line has decreased from 108.7A to 83.72A and hence the voltage drop at the transmission line has decreased. This is the reason why the load voltage has risen to 12.67 kV. This occurred because no reactive power is delivered to the load from the supply. The transmission line voltage regulation of the line is now 0.24%, which is better than 2.4% voltage regulation in the case of no compensation. It is worthwhile to mention that the STATCOM current waveforms shown in Figure 47, Figure 49 and 50 are distorted. This is because of the switches, continuously opening and closing. This inevitably causes current harmonics to be generated. The current magnitude at the STATCOM output (Bus-4) is high at 645A, but the voltage is low at 1.904 kV.The current magnitude on the high-voltage side of the coupling transformer is low at 95.5A, but this time voltage has increased to 12.67kV.

Figure 51 shows the DC voltage across the STATCOM capacitor. It can be seen from the graph that it is 7 kV.

Table 6.

Simulation Results After Compensation for 10 km Transmission Line

12.70 kV Phase Voltage; Length 10 (km) Line resistance 1(Ω); Line reactance j3 ohm				
	Active Power (MW)	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**
SUPPLY BUS 1	3.094	0.212	12.7017	83.72
LOAD BUS 2	2.969	2.969	12.67	110
BUS 3	0.1046	3.189	12.67	95.5
STATCOM BUS 4	0.098354	3.2	1.904	645
Power Factor				
SUPPLY BUS 1	0.9986			
LOAD BUS 2	0.7071			

IV.3.2 Simulation Results for 20 km Transmission Line Before and After Compensation

IV.3.2.1 Simulation results before compensation for 20 km transmission line

Figure 52

Power System Simulation Model without Compensation

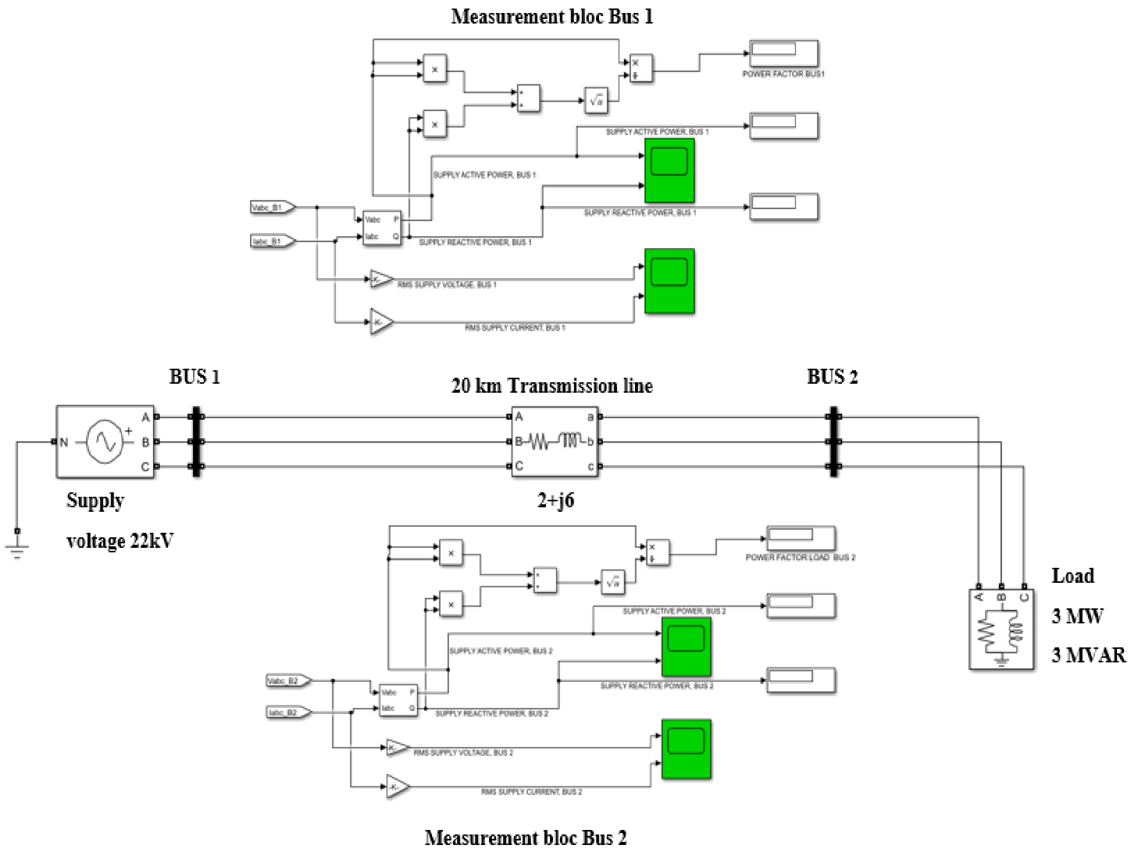


Figure 53

Active and reactive supply power at Bus-1

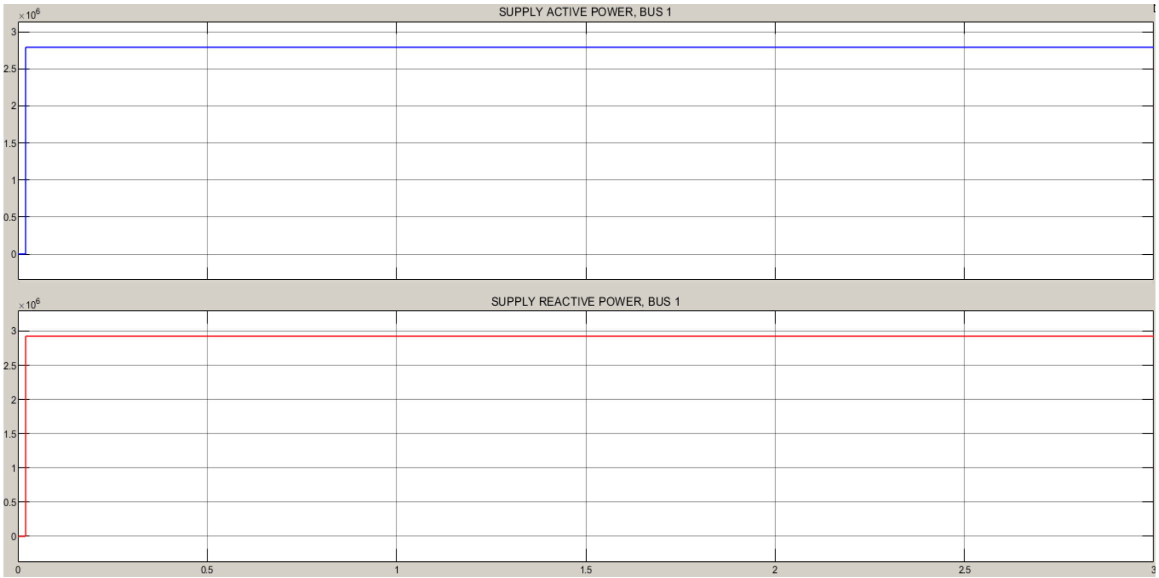


Figure 54

Supply Voltage and Current Before Compensation (Bus-1)

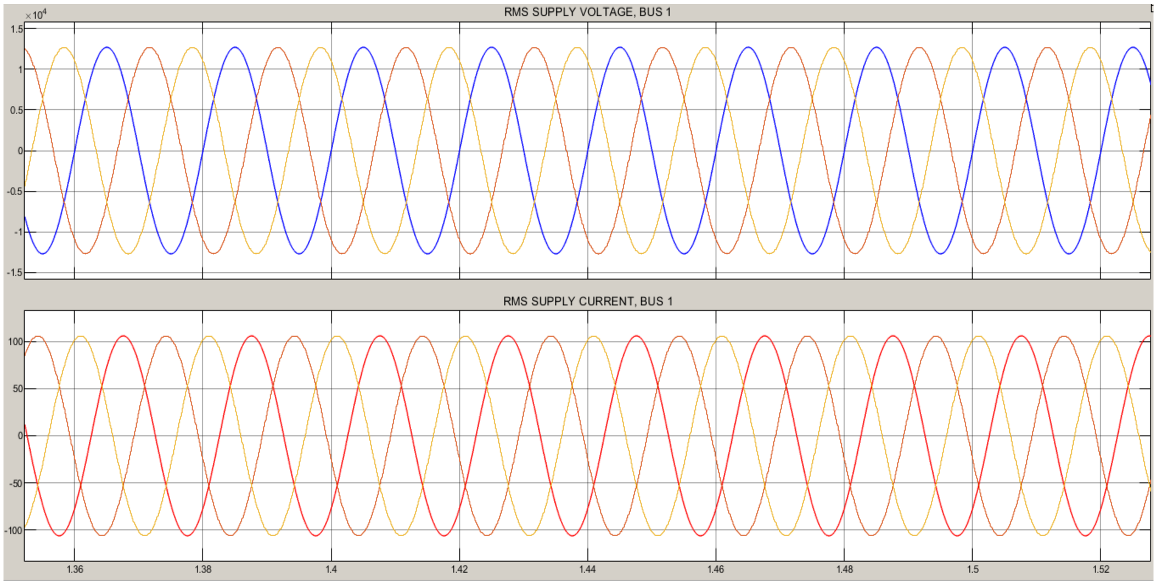


Figure 55

Active and Reactive Load Power Before Compensation

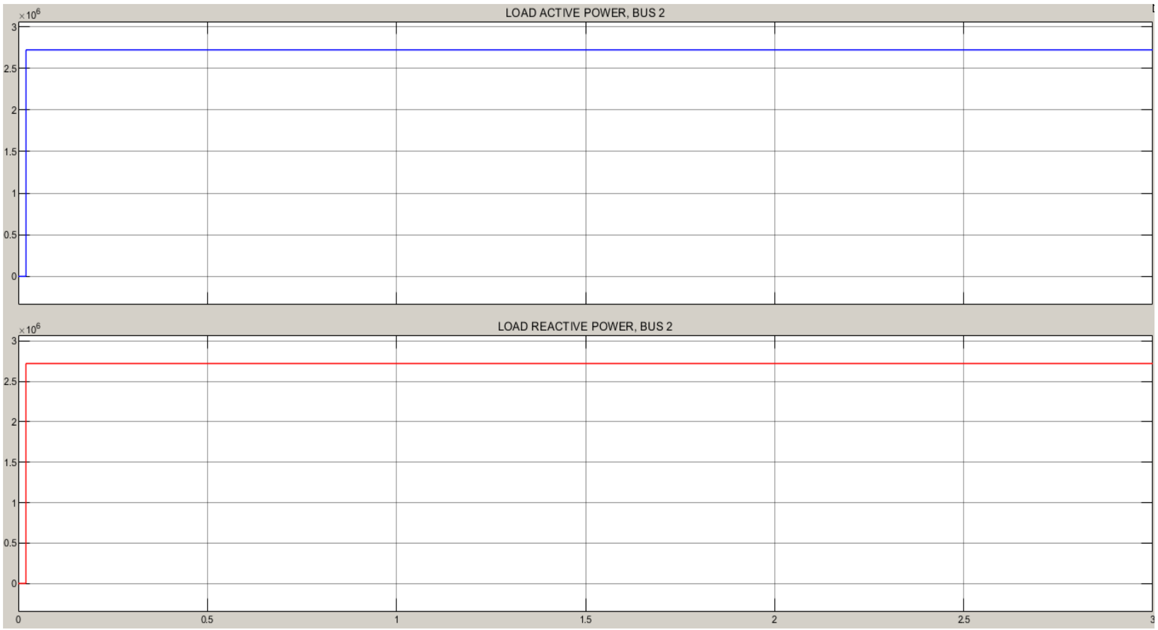


Figure 56

Load Voltage and Current Before Compensation

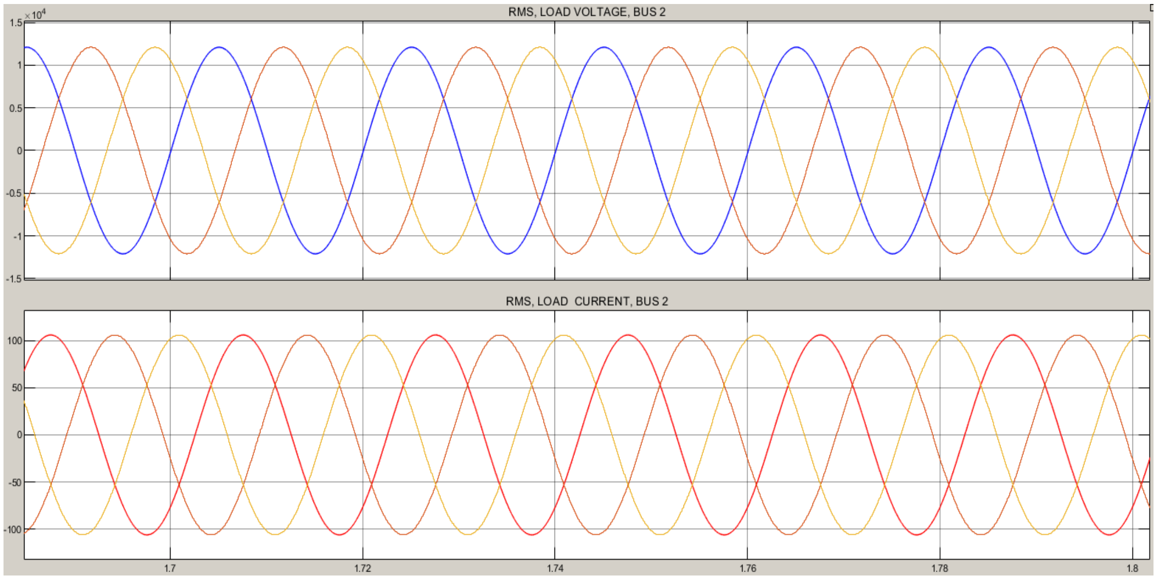


Figure 53 illustrates the reactive and active power that the supply provides to the load. As we can see, the supplying reactive power is 2.924 MVAR and the supplying active power is 2.789 MW. Figure 54 shows the supply rms current and voltage. We can see that the supply rms voltage and current at bus 1 is 12.7 kV and 106.05 A and the power factor is 0.6902.

At the load side Figure 55 depicts the amount of reactive and active power consume by the load which is 2.722 MVAR and 2.722 MW. Figure 56 shows the load rms current and voltage. It can be noticed that the load rms voltage and current at bus 2 is 12.1 kV and 106.05 A and the power factor is 0.7071.

Table 7 shows us that the voltage drops at bus 2 is 4.8% of the nominal voltage which is close to the limits of the acceptable voltage deviation according to the standards. This is due to the transmission line impedance.

Table 7.

Simulation results before compensation for 20 km transmission line

22 kV rms Line to line; Length 20 (km) Line resistance 2(Ω); Line inductance 0.019098 (H)					
	Active Power (MW)	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**	**Power Factor**
SUPPLY BUS 1	2.789	2.924	12.7	106.05	0.6902
LOAD BUS 2	2.722	2.722	12.1	106.05	0.7071

IV.3.2.2 Simulation Results for 20 km Transmission Line after Compensation

Figure 57

Power System Simulation Model after Compensation

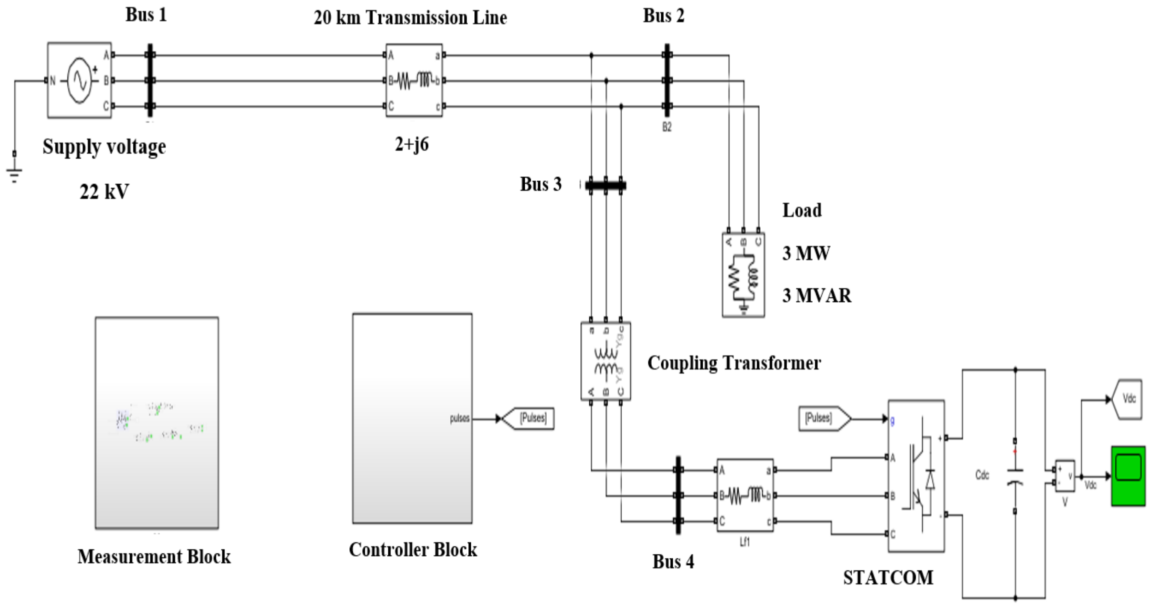


Figure 58

Supply active and reactive power after compensation

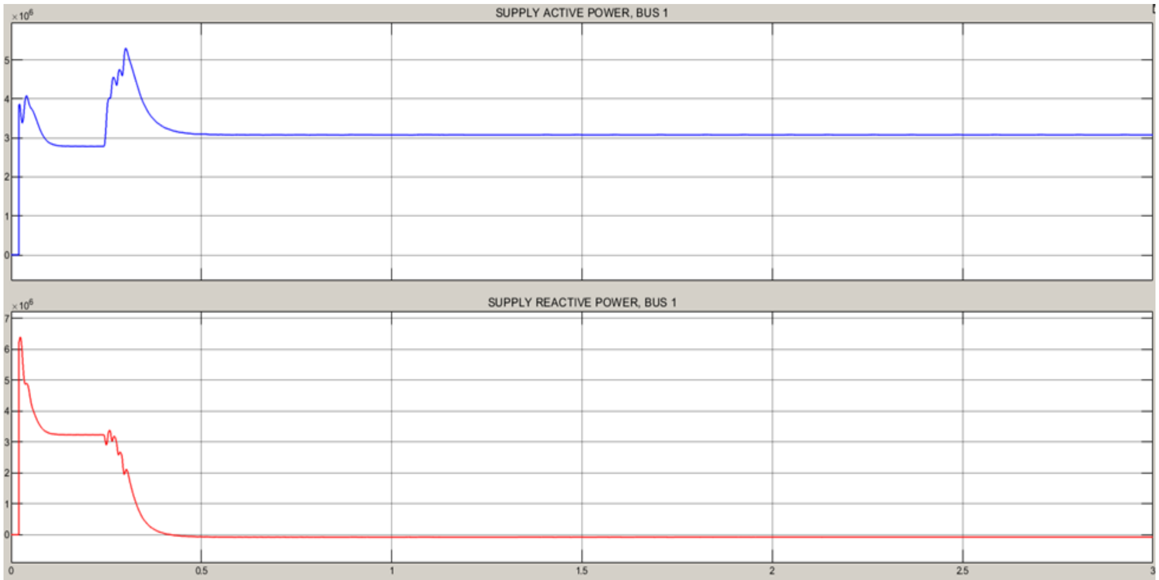


Figure 59

Supply Voltage and Current after Compensation (Bus-1)

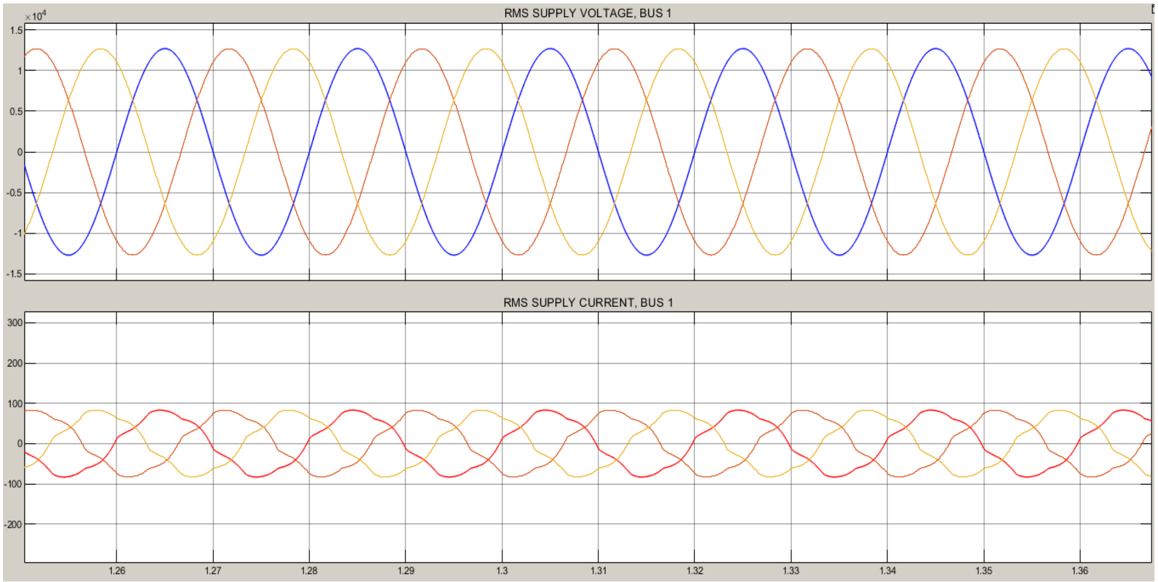


Figure 60

Active and Reactive Load Power after Compensation (Bus-2)

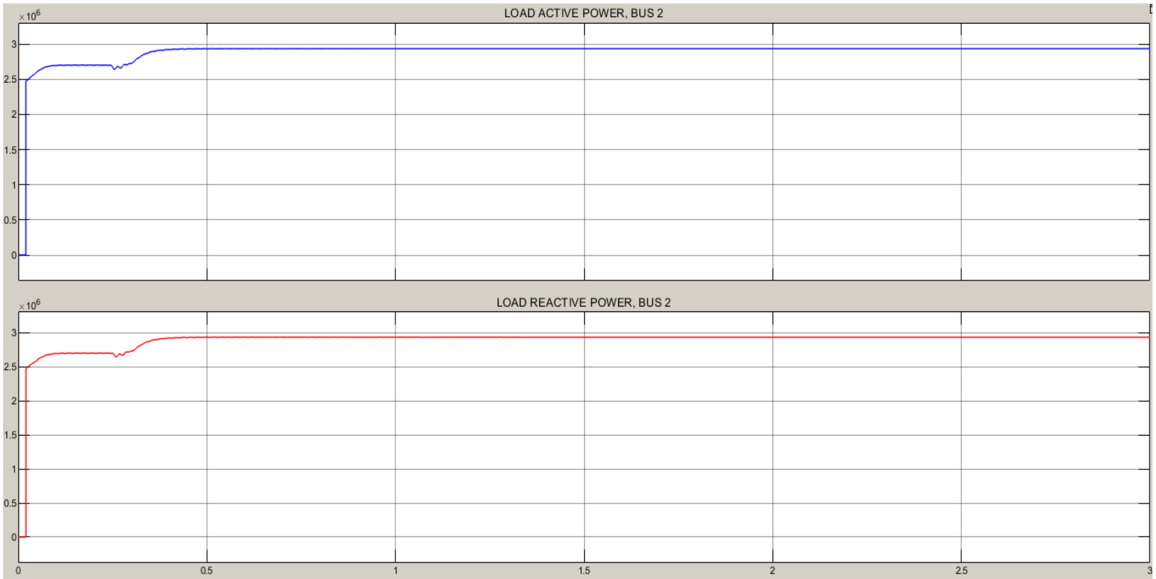


Figure 61

Load Voltage and Current after Compensation (Bus-2)

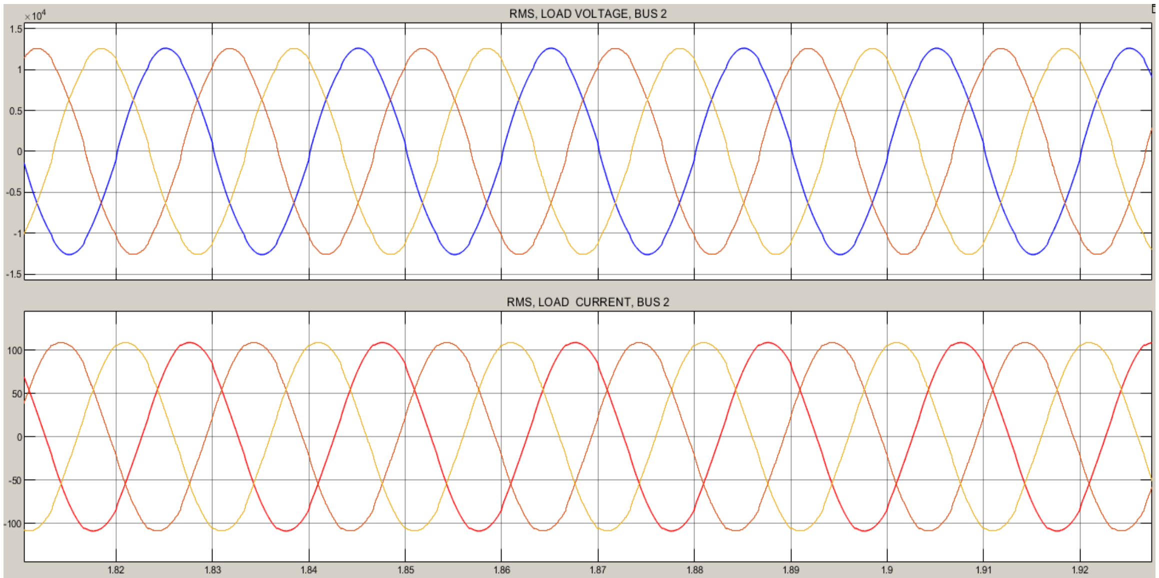


Figure 62

Active and Reactive Power at Bus-3 after Compensation

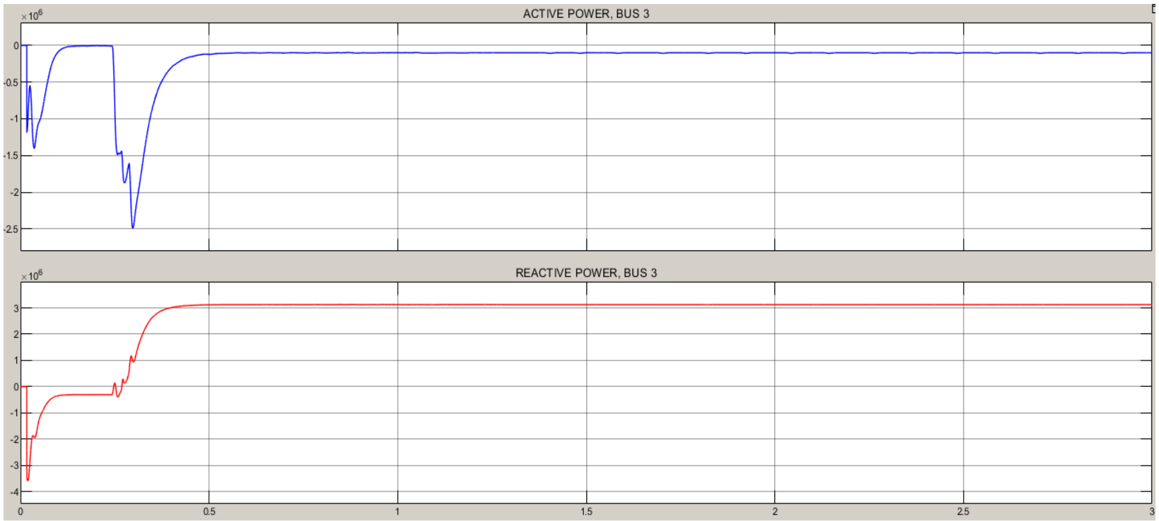


Figure 63

Voltage and Current at Bus-3 after Compensation

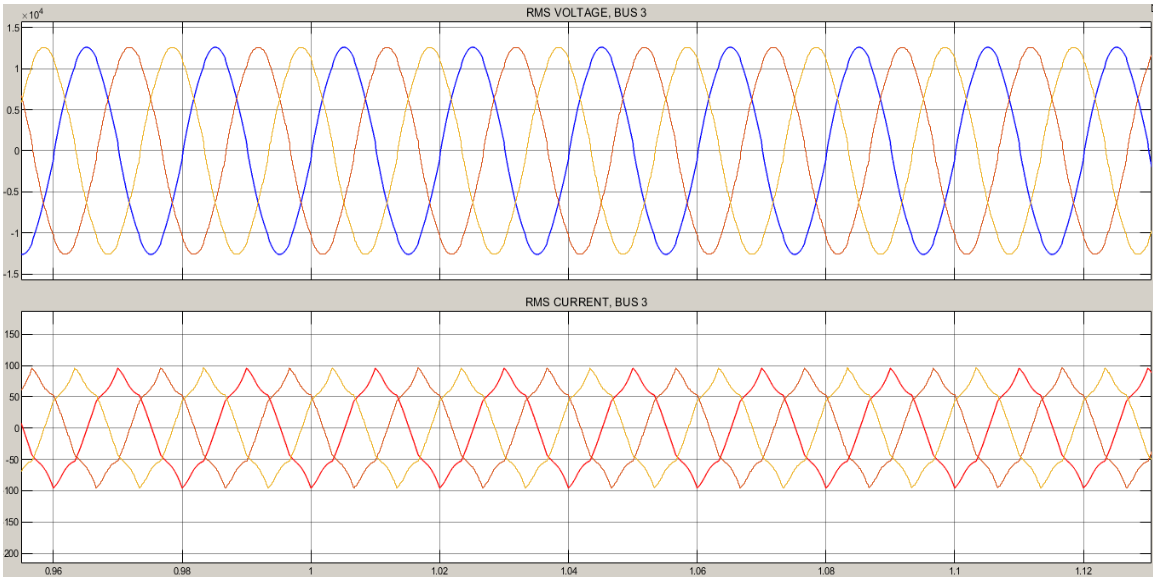


Figure 64

STATCOM Active and Reactive Power (Bus-4)

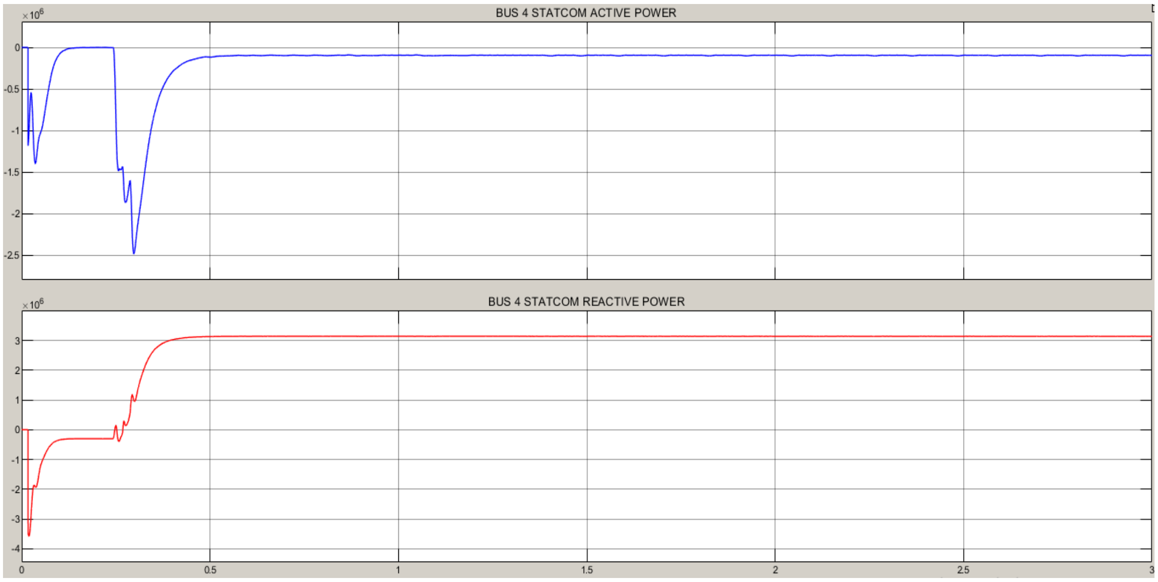


Figure 65

STATCOM Voltage and Current (Bus-4)

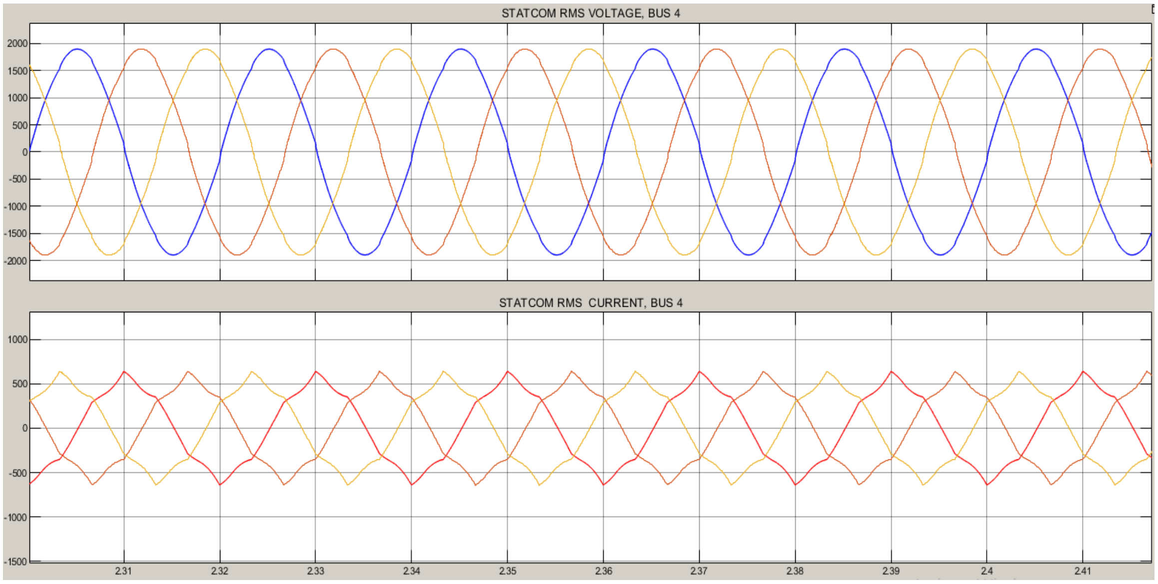


Figure 66

STATCOM output voltage and current

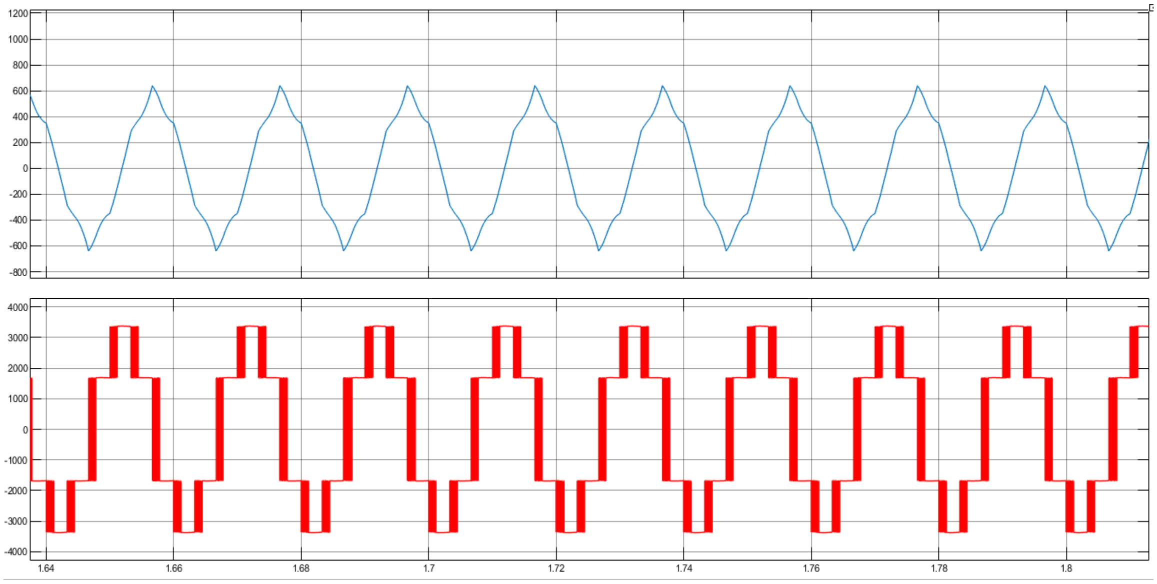
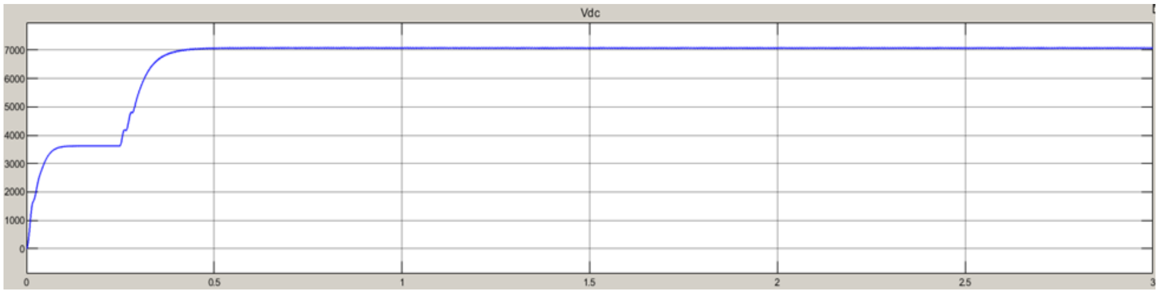


Figure 67

STATCOM Capacitor DC Voltage



After compensation the active power and reactive power delivered by the supply to the load is shown in Figure 58. We can see that the supply delivers 3.075 MW of active power and very low reactive power (0.185MVAR) compared to 2.924 MVARS before compensation. Figure 59 shows the supply rms current and voltage after compensation. It can be noticed that the supply rms voltage and current at Bus-1 is 12.7 kV and 83 A. Before compensation the supply current was 106.5A but now because the load does not receive reactive power, the supply current has reduced to 83A.The supply only provides real power to the load. Because the transmission line current has reduced, the line losses have also decreased.

Figure 60 shows the amount of reactive and active power the load receives, which is 2.934 MW and 2.934 MVAR. Figure 61 shows the load rms current and voltage after compensation. It can be noticed that the load rms voltage and current at Bus-2 is 12.62 kV and 109 A. Before compensation the load voltage was 12.1kV, but after compensation it has increased to 12.62 kV. The voltage regulation is now 0.62%, which is much better than the voltage regulation in the absence of compensation, which was 4.8%. The load current in the cases of 10 km and 20 km, after compensation is done, are more or less the same,110A and 109A respectively, because the load voltages are also very close to each other,12.67 kV and 12.62 kV respectively. This is because load power is always kept constant.

Figure 59, Figure 63 and Figure 65 shows current waveforms at the supply bus Bus-1, Bus-3 and Bus-4. These waveforms are distorted because the converter switches cause current harmonics to be generated.

The transmission line receives a small amount of reactive power which is 0.185 MVAR. The load receives 2.934 MVAR reactive power. Figure 64 shows that STATCOM generates 3.137 MVAR and consumes 0.09459 MW active power which means that the all the load reactive power is by the STATCOM. VSI converter which is not lossless, consumes some active power.

Figure 67 shows the DC voltage across the STATCOM capacitor voltage. It can be seen that it is 7 kV.

From Table 8 we can noticed that the supply power factor has improved from 0.6902 (before compensation) to 0.9997(after compensation). The load power factor remains the same at 0. 7071, because the load is kept constant at 3MW + j3MVAR.

Table 8.

Simulation results after compensation for 20 km transmission line

22 kV rms Line to line; Length 20 (km) Line resistance 2(Ω); Line inductance 0.01909 (H)				
	Active Power (MW)	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**
SUPPLY BUS 1	3.075	0.185	12.7	83
LOAD BUS 2	2.934	2.934	12.62	109
BUS 3	0.1006	3.125	12.62	95.7
STATCOM BUS 4	0.09459	3.137	1.8975	639
Power Factor				
SUPPLY BUS 1	0.9997			
LOAD BUS 2	0.7071			

IV.3.3 Simulation Results for 30 km Transmission Line Before and After Compensation

IV.3.3.1 Simulation Results Before Compensation for 30 km Transmission Line

Figure 68

Power System Simulation Model Before Compensation

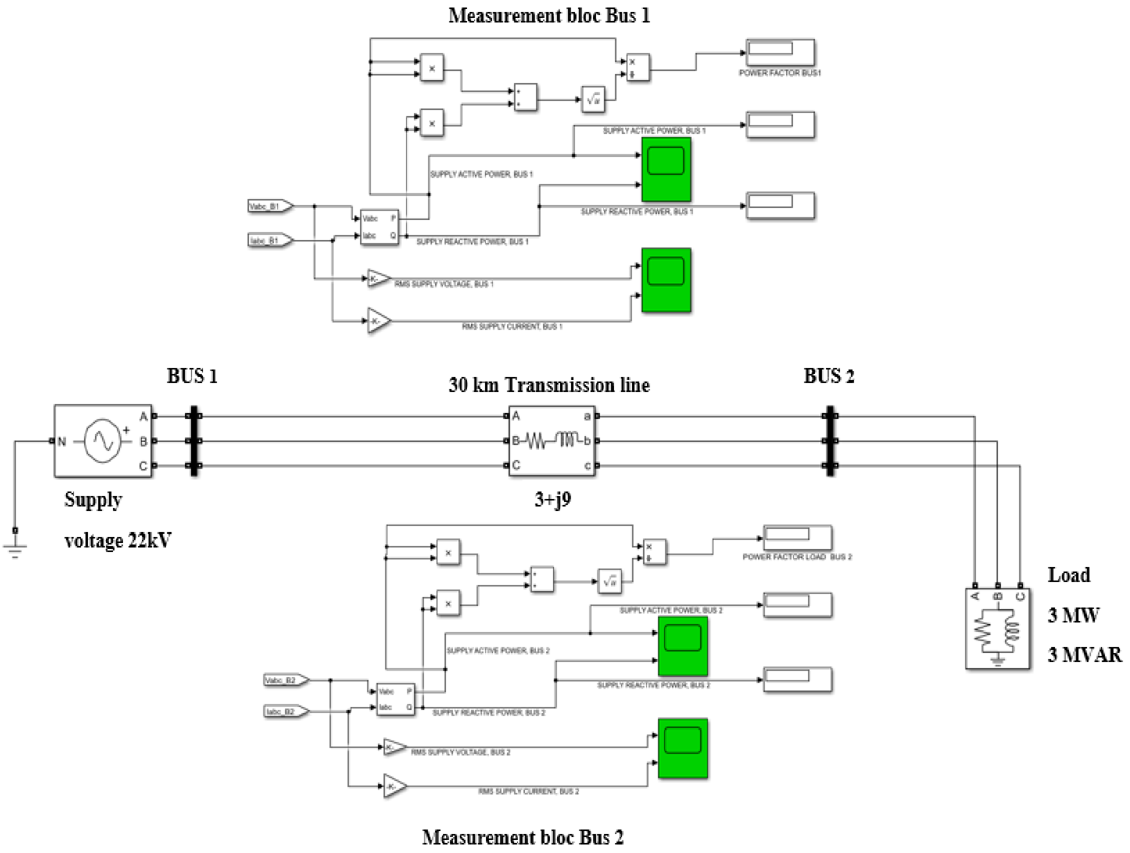


Figure 69

Active and Reactive Supply Power Before Compensation (Bus-1)

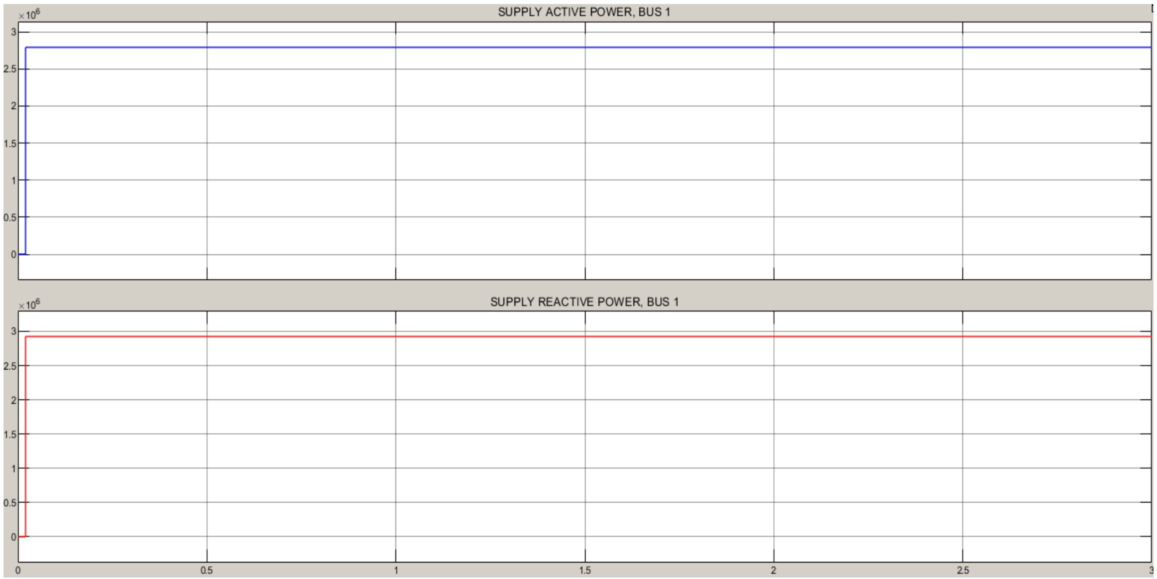


Figure 70

Supply Voltage and Current Before Compensation (Bus-1)

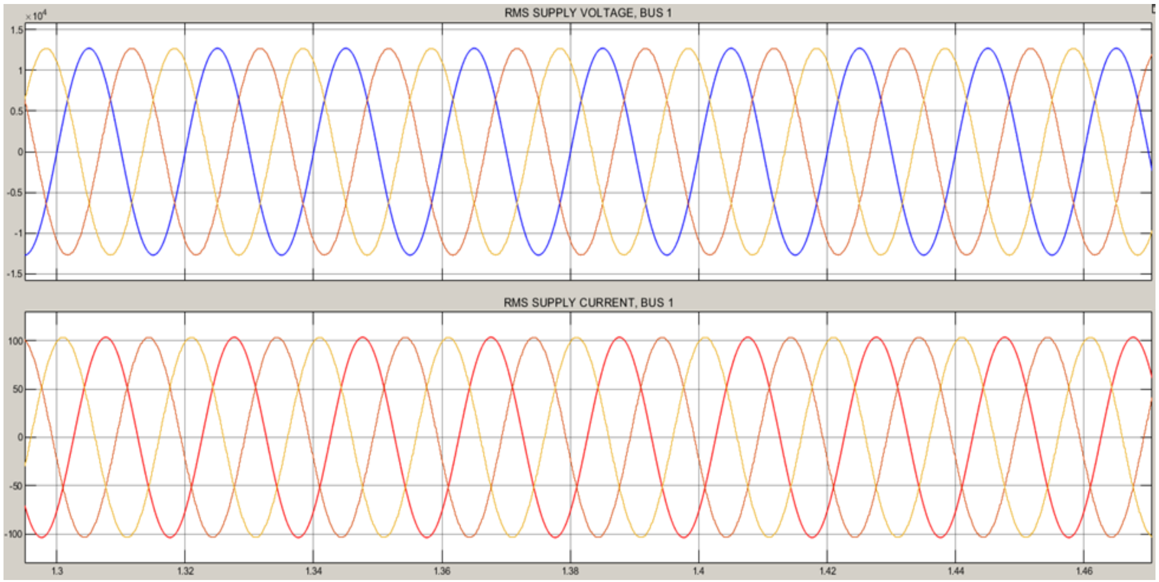


Figure 71

Active and Reactive Load Power Before Compensation (Bus-2)

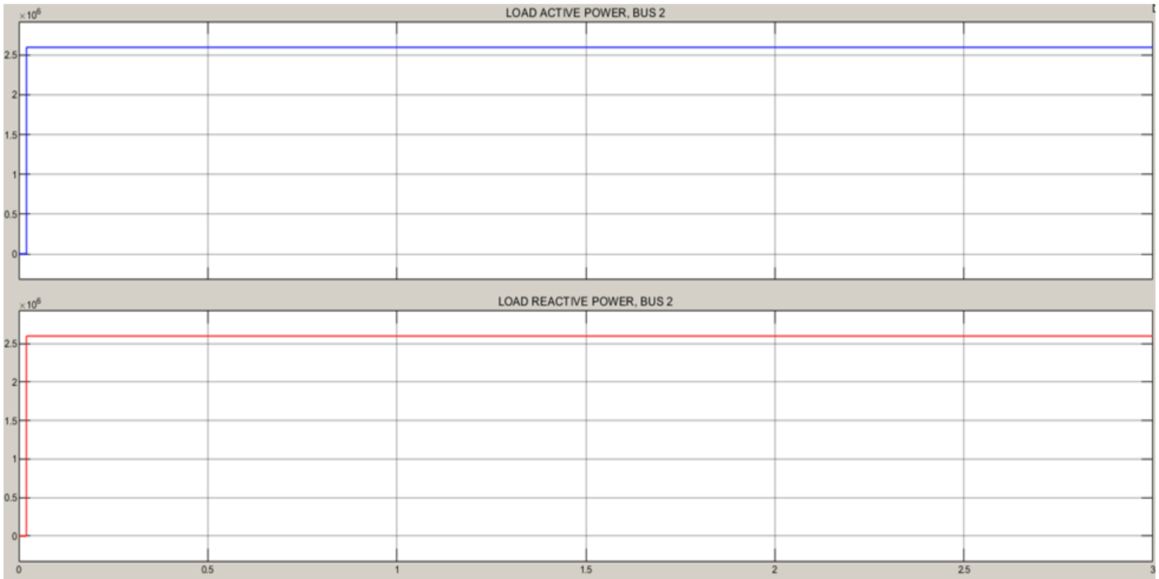


Figure 72

Load Voltage and Current Before Compensation (Bus-2)

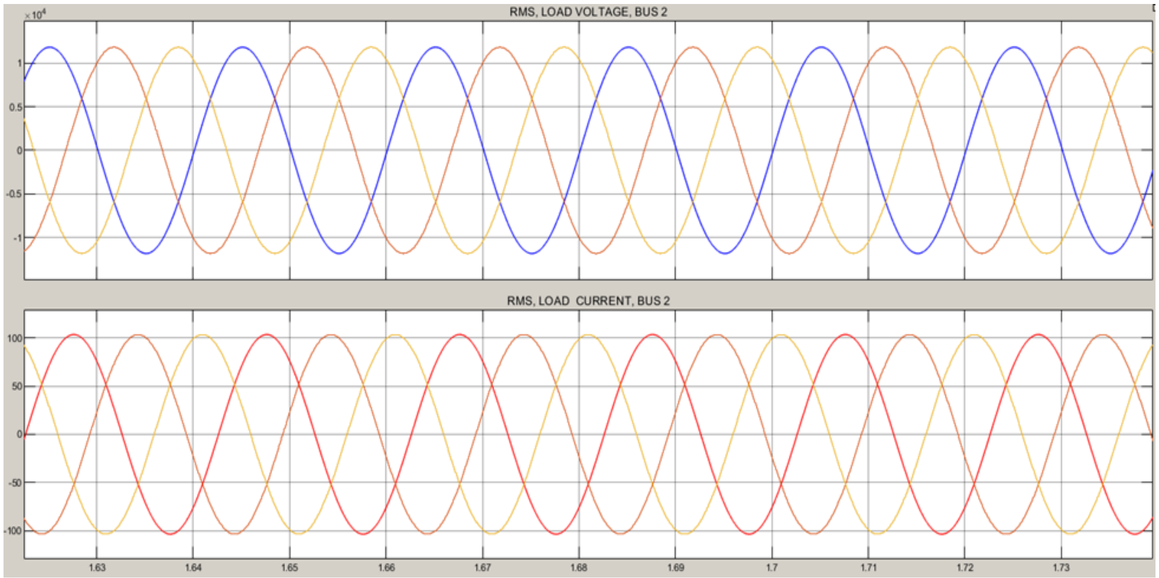


Figure 69 illustrates the reactive and active power that the supply provides to the load. As we can see, the supplying active power is 2.692 MW and the supplying reactive power is 2.886 MVAR. Figure 70 shows the supply rms current and voltage. It shows that the supply rms voltage and current at Bus-1 is 12.7 kV and 103.57 A and the power factor is 0.6822.

Figure 71 shows the active and reactive power taken by the load which is 2.596 MW and 2.596 MVAR. Figure 72 depicts the load rms current and voltage. We can see that the load rms voltage and current at Bus-2 is 11.815 kV and 103.57 A and the power factor is 0.7071.

Table 9 shows us that the voltage drops at bus 2 is 6.97 % of the nominal voltage, which is beyond the limits of the acceptable voltage deviation (5%) according to the standards. This is due to the higher transmission line impedance.

Table 9.

Simulation results before compensation for 30 km transmission line

22 kV rms Line to line; Length 30 (km) Line resistance 3(Ω); Line inductance 0.028647 (H)					
	Active Power (MW)	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**	**Power Factor**
SUPPLY BUS 1	2.692	2.886	12.7	103.57	0.6822
LOAD BUS 2	2.596	2.596	11.815	103.57	0.7071

IV.3.3.2 Simulation Results After Compensation for 30 km Transmission Line

Figure 73

Power System Simulation Model after Compensation

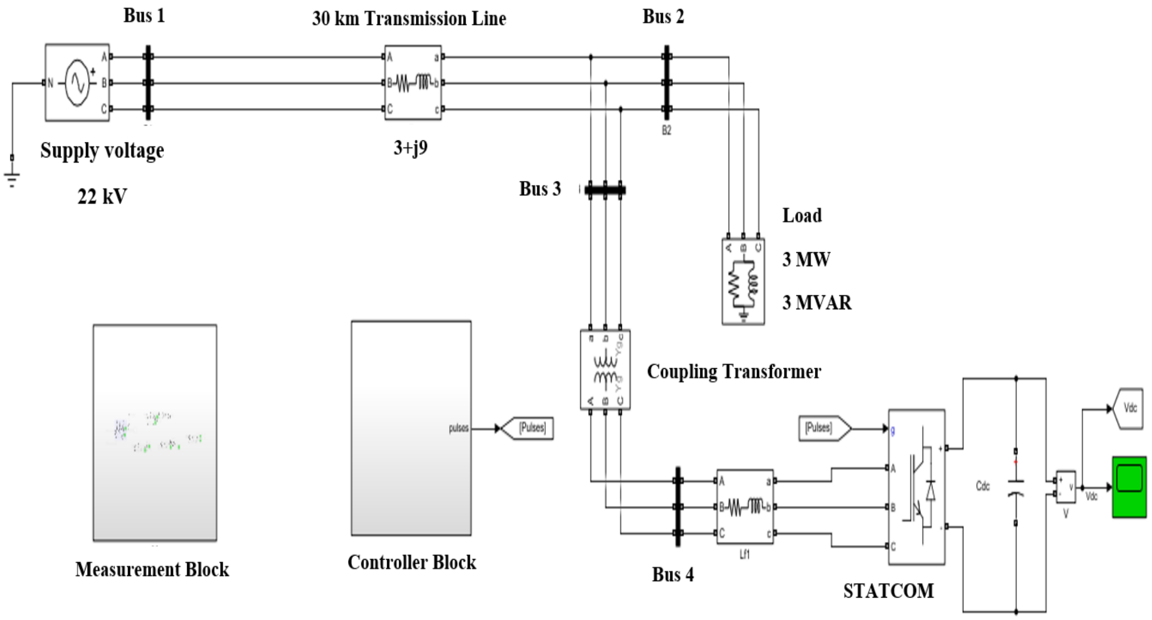


Figure 74

Active and Reactive Supply Power after Compensation (Bus-1)

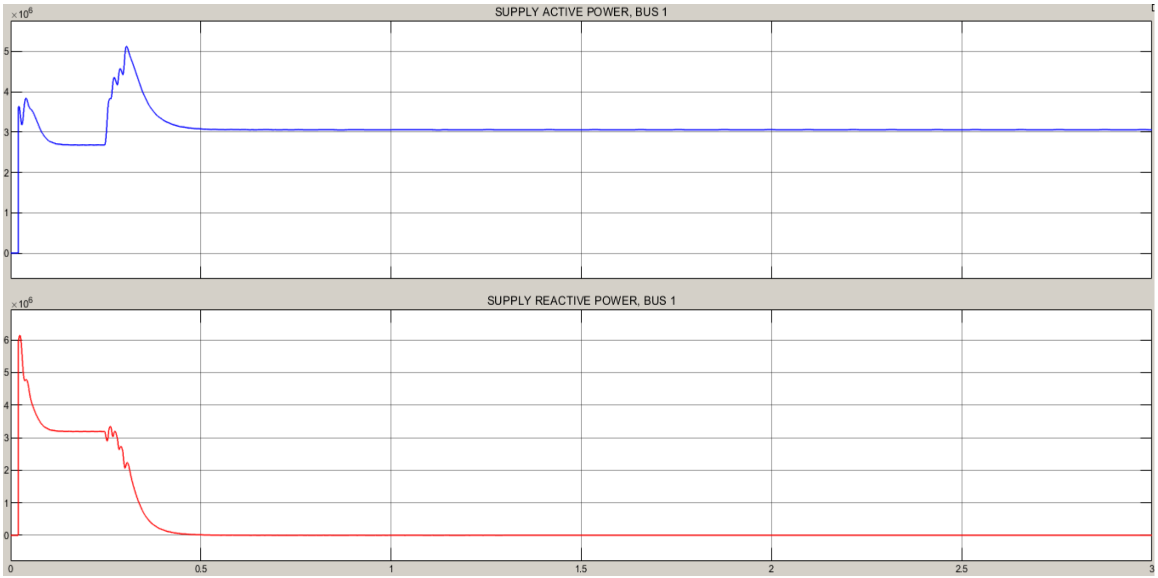


Figure 75

Supply Voltage and Current after Compensation (Bus-1)

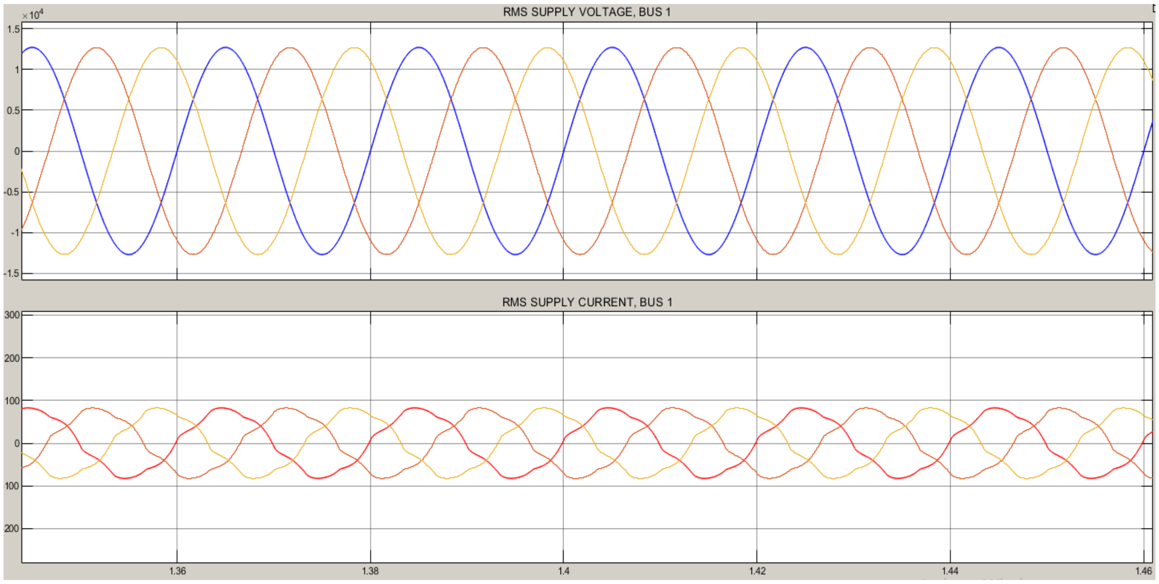


Figure 76

Active and Reactive Load Power after Compensation (Bus-2)

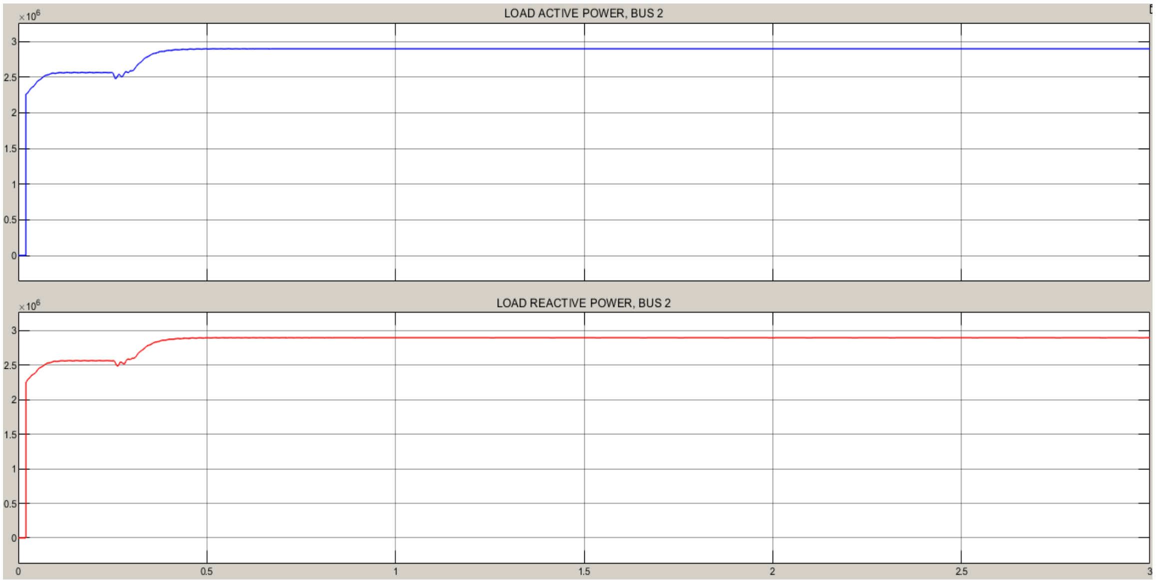


Figure 77

Load Voltage and Current after Compensation (Bus-2)

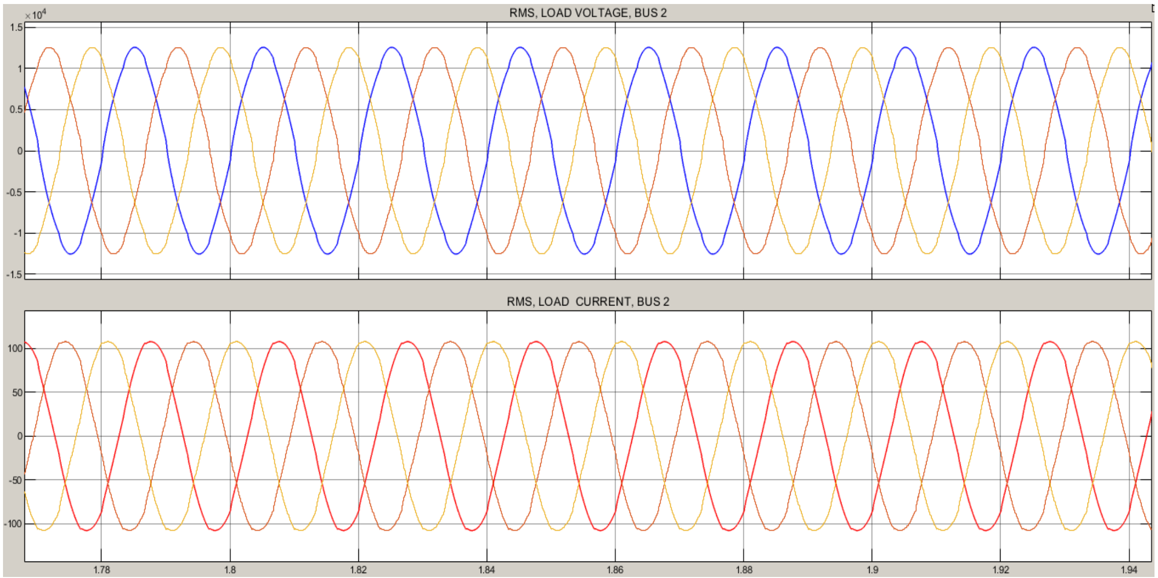


Figure 78

Bus-3 Active and Reactive Power after Compensation

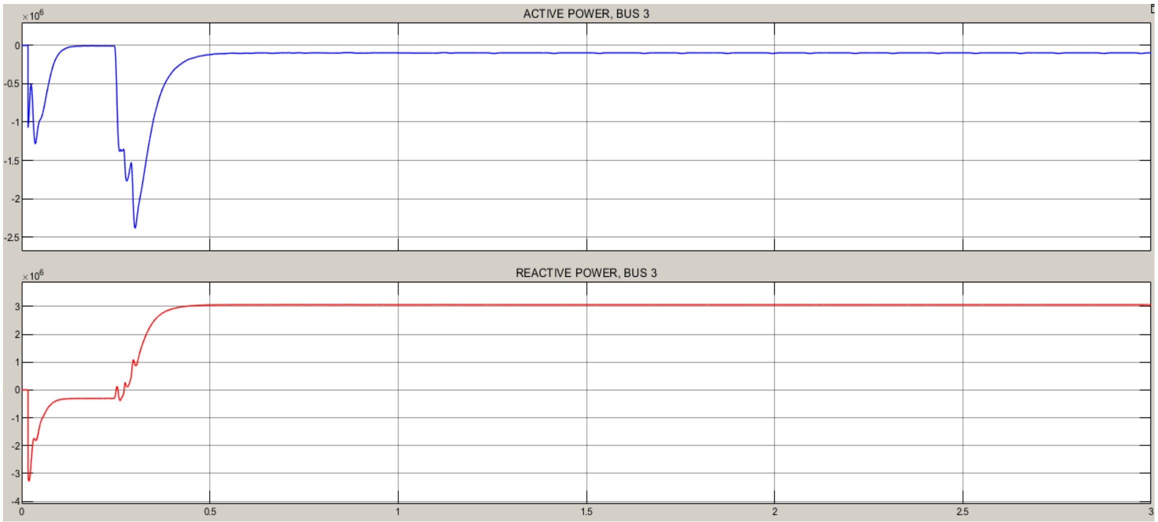


Figure 79

Bus-3 Voltage and Current after Compensation

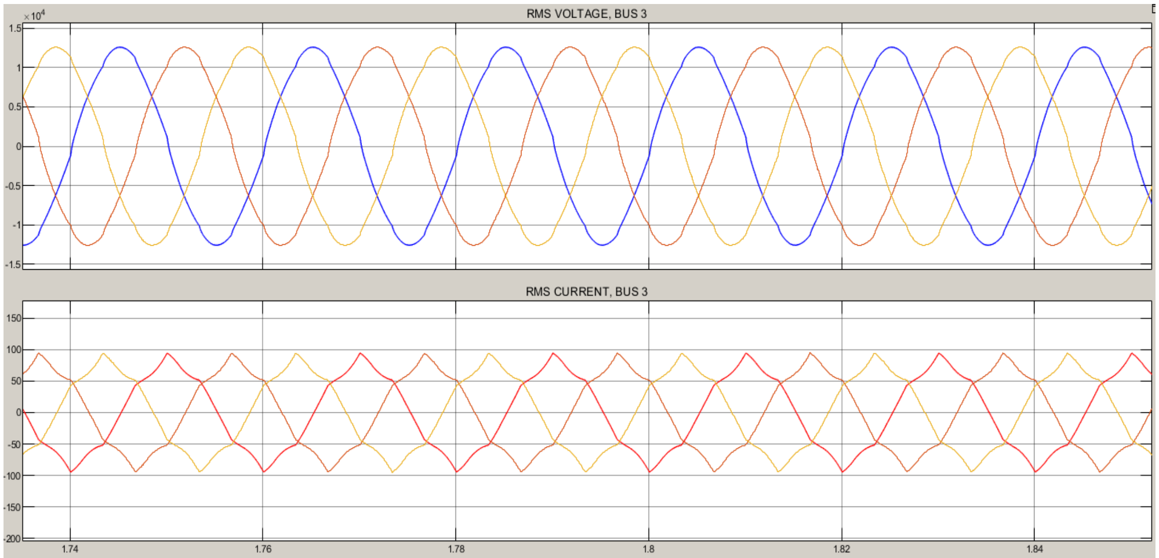


Figure 80

STATCOM Active and Reactive Power (Bus-4)

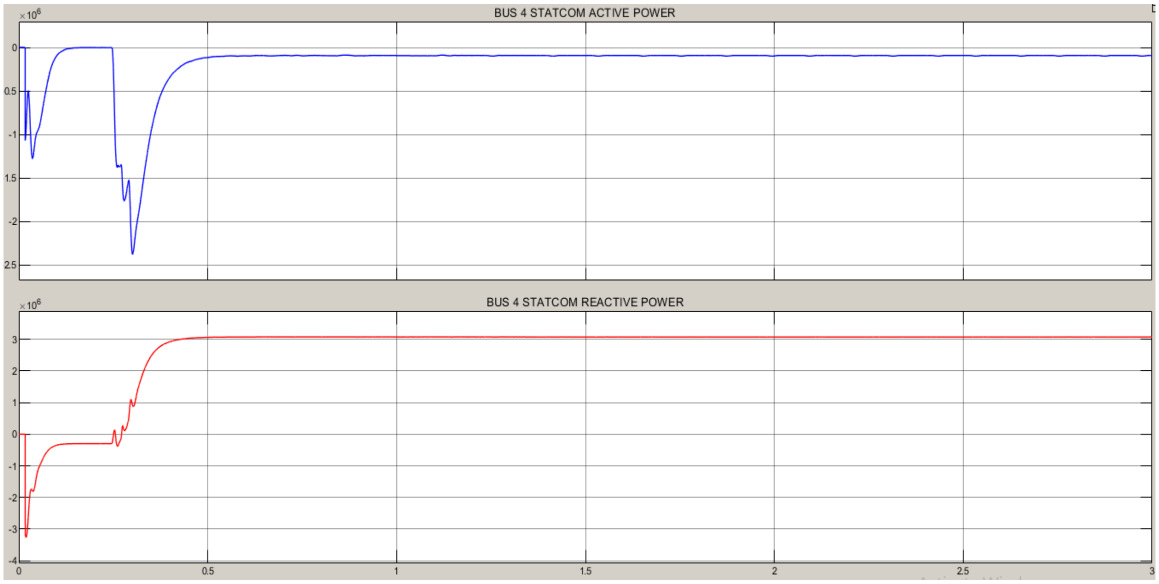


Figure 81

STATCOM Voltage and Current (Bus-4)

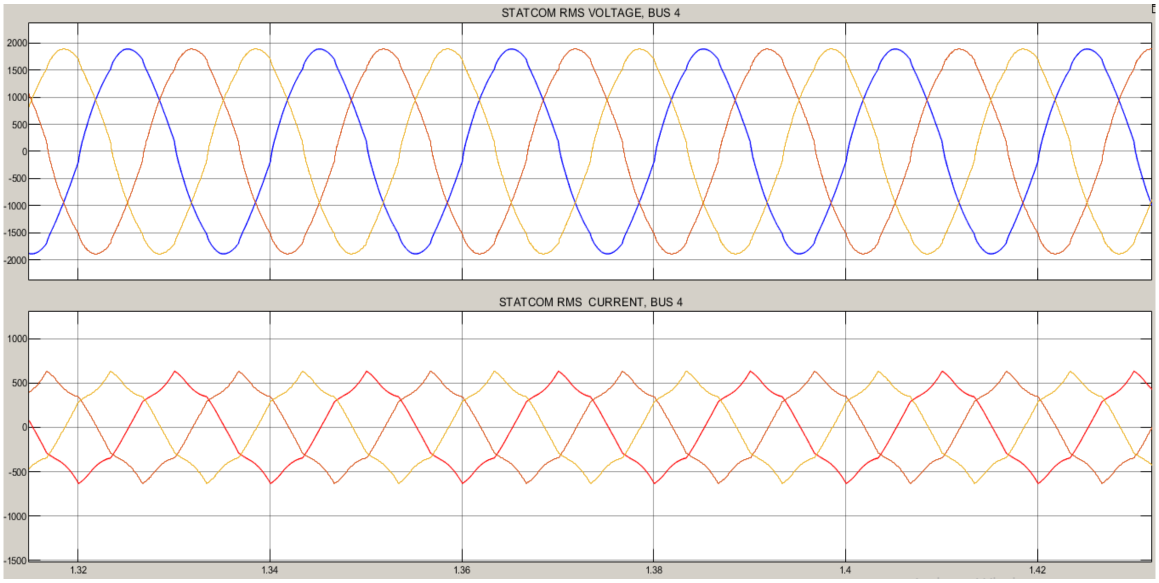


Figure 82

STATCOM output voltage and current for 30 km transmission line

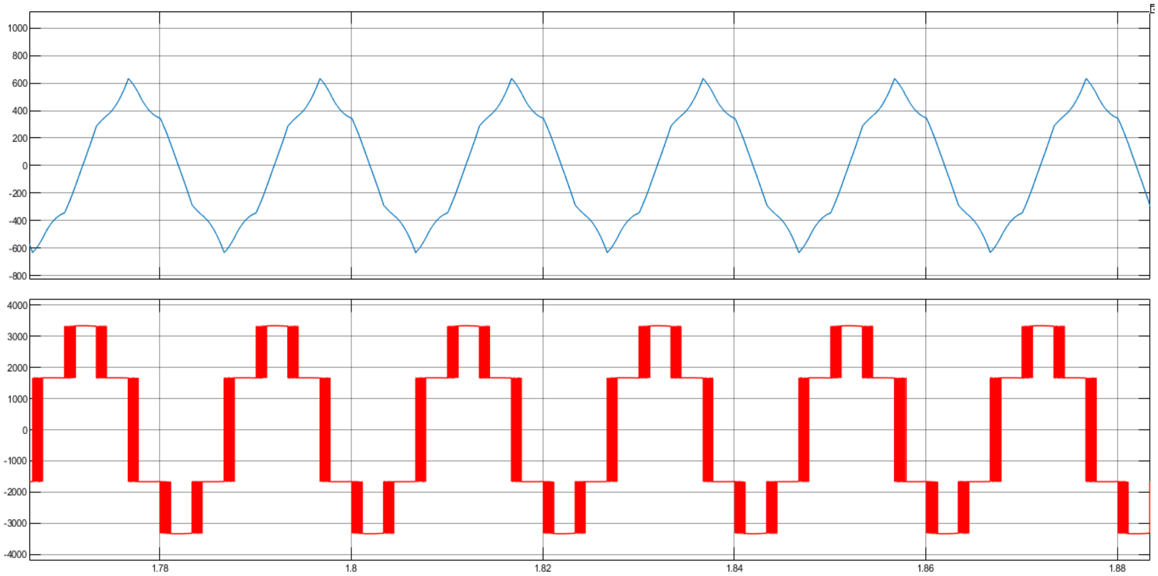
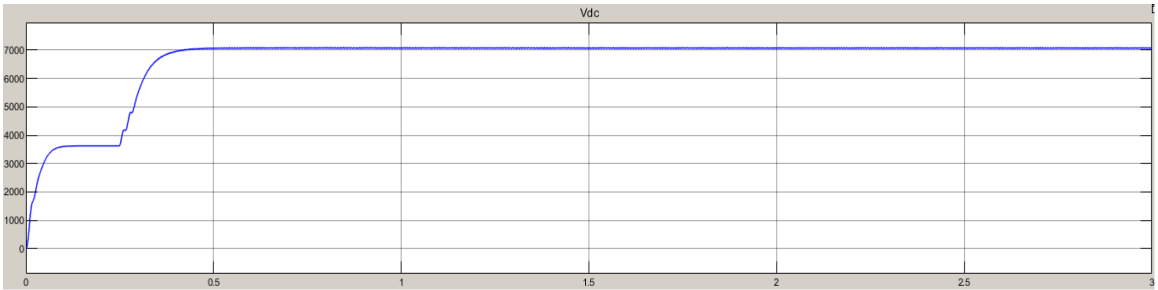


Figure 83

STATCOM Capacitor DC Voltage



After compensation for 30 km transmission line, the active power and reactive power delivered by the supply to the load is depicts in Figure 74. We can see that supply delivers 3.055 MW of active power. Reactive power delivered by the supply is very small (0.155 MVAR) compared to 2.886 MVAR before compensation. Figure 75 depicts the supply rms current and voltage after compensation. It can be noticed that the supply rms voltage and current at Bus-1 is 12.7 kV and 82.5 A respectively.

Figure 76 shows the amount of active and reactive power the load receives, which is 2.897 MW and 2.897 MVAR. Figure 77 shows the load rms current and voltage after compensation. We can see that the load rms voltage and current at Bus-2 is 12.57 kV and 107.8 A respectively. Table 10 shows us that the voltage drops at Bus-2 is 1% of the nominal voltage. This is within the limits of the acceptable voltage deviation according to the standards. The voltage regulation was 6.97% when uncompensated. When compensated it improved to 1%.

Figure 80 shows that STATCOM generates 3.075 MVAR and consumes 0.09214 MW. It is seen that all of the reactive load power comes from STATCOM.

From Table 10 it can be noticed that the power factor on the supply side is near 1 and at the load side it remains constant at 0.7071.

Table 10.

Simulation results after compensation for 30 km transmission line

22 kV rms Line to line; Length 30 (km) Line resistance 3(Ω); Line inductance 0.028647 (H)				
	Active Power (MW)	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**
SUPPLY BUS 1	3.055	0.155	12.7	82.5
LOAD BUS 2	2.897	2.897	12.57	107.8
BUS 3	0.09808	3.064	12.57	94.8
STATCOM BUS 4	0.09214	3.075	1.89	633.5

Power Factor	
SUPPLY BUS 1	0. 9999
LOAD BUS 2	0.7071

Table 11.

Simulation Results for 10 km, 20 km and 30 km Before Compensation

	22 kV rms Line to line; Length 10 (km) Line resistance 1(Ω); Line reactance j3 ohm				**22 kV rms Line to line; Length 20 (km) Line resistance 2(Ω); Line reactance j6 ohm**				**22 kV rms Line to line; Length 30 (km) Line resistance 3(Ω); Line reactance j9 ohm**			
	Active Power (MW)	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**	**Active Power (MW)**	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**	**Active Power (MW)**	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**
SUPPLY BUS 1	2.892	2.962	12.70	108.70	2.789	2.924	12.70	106.05	2.692	2.886	12.70	103.57
LOAD BUS 2	2.856	2.856	12.40	108.70	2.722	2.722	12.10	106.05	2.596	2.596	11.815	103.57

Table 12.

Power Factor Before Compensation for 10km, 20 km and 30 km

Power factor for 10 km transmission line		**Power factor for 20 km transmission line**		**Power factor for 30 km transmission line**	
Supply BUS 1	0.6985	**Supply BUS 1**	0.6902	**Supply BUS 1**	0.6994
Load BUS 2	0.7071	**Load BUS 2**	0.7071	**Load BUS 2**	0.7071

Table 13.

Simulation results for 10 km, 20 km and 30 km after compensation

	22 kV rms Line to line; Length 10 (km) Line resistance 1(Ω); Line reactance j3 ohms				**22 kV rms Line to line; Length 20 (km) Line resistance 2(Ω); Line reactance j6 ohms**				**22 kV rms Line to line; Length 30 (km) Line resistance 3(Ω); Line reactance j9 ohms**			
	Active Power (MW)	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**	**Active Power (MW)**	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**	**Active Power (MW)**	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**
Supply BUS 1	3.094	0.212	12.70	83.72	3.075	0.185	12.7	83	3.055	0.155	12.7	82.5
Load BUS 2	2.969	2.969	12.67	110	2.934	2.934	12.62	109	2.897	2.897	12.57	107.8
BUS 3	0.1046	3.189	12.67	95.5	0.1006	3.125	12.62	95.7	0.0981	3.064	12.57	94.8
STATCOM BUS 4	0.09835	3.2	1.904	645	0.09459	3.137	1.8975	639	0.09214	3.075	1.889	633.5

Table 14.

Power factor after compensation for 10km, 20 km and 30 km

Power factor for 10 km transmission line		**Power factor for 20 km transmission line**		**Power factor for 30 km transmission line**	
Supply BUS 1	0.9986	**Supply BUS 1**	0.9997	**Supply BUS 1**	0. 9999
Load BUS 2	0.7071	**Load BUS 2**	0.7071	**Load BUS 2**	0.7071

IV.4 Comparison of Transmission Line Losses Before and After Compensation

i. Before Compensation

Transmission line power loss is calculated by subtracting power taken by the load bus, Bus-2 from the power generated at Bus-1.

For 10 km transmission line the loss is equal to $2.892 - 2.856 = 0.036\ MW = 36\ kW$

For 20 km transmission line the loss is equal to $2.789 - 2.722 = 0.067\ MW = 67 kW$

For 30 km transmission line the loss is equal to $2.692 - 2.596 = 0.096\ MW = 96 kW$

Now let us calculate the power loss by using the line current and the line resistance.

For 10km transmission line power loss $= 3 \times (108.7^2) \times 1 = 34.45\ kW$

For 20km transmission line power loss $= 3 \times (106.5^2) \times 2 = 67.48\ kW$

For 30 km transmission line power loss $= 3 \times (103.57^2) \times 3 = 96.54\ kW$

It can be noticed that the simulation results and theoretical calculations match.

ii. After Compensation

Transmission line power loss is calculated by subtracting power taken by the load bus Bus-2 and by Bus-3, from the power supplied by Bus-1.

For 10 km transmission line the loss is equal to $3.094 - 2.969 - 0.1046 = 0.0204\ MW = 20.4\ kW$

For 20 km transmission line the loss is equal to $3.075 - 2.934 - 0.1006 = 0.0404\ MW = 40.4\ kW$

For 30 km transmission line the loss is equal to $3.055 - 2.897 - 0.09808 = 0.05992\ MW = 59.92\ kW$

Now let us calculate the power loss by using the line current and the line resistance.

For 10km transmission line power loss $= 3 \times (83.72^2) \times 1 = 21.03\ kW$

For 20km transmission line power loss $= 3 \times (83^2) \times 2 = 41.33\ kW$

For 30 km transmission line power loss $= 3 \times (82.5^2) \times 3 = 61.25\ kW$

It can be noticed that the simulation results and theoretical calculations match

iii. Percentage Reduction in Transmission Line Losses After Compensation

For 10 km transmission line: After compensation line losses decreased by $36 - 20.4 = 15.6\ kW$,which is 43.34%.

For 20 km transmission line: After compensation line losses decreased by $67 - 40.4 = 26.6\ kW$,which is 39.7%.

For 30 km transmission line: After compensation line losses decreased by $96 - 59.92 = 36.08\ kW$,which is 37.58%.

IV.5 Improvement of the Power Transfer Capability of Transmission Lines

Figure 84

power System Simulation Model showing the Improvement of the Power Transfer Capability

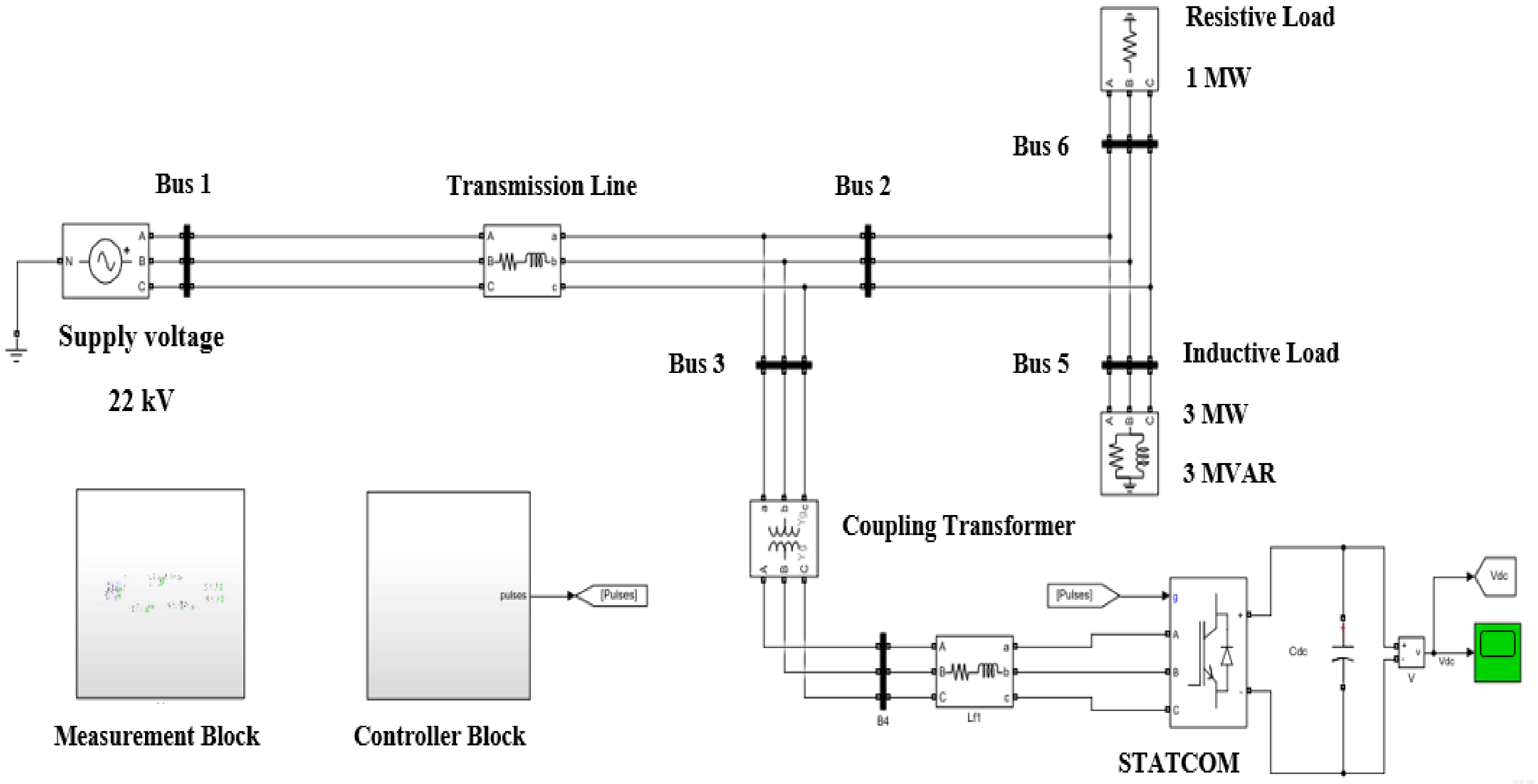


Table 15.

Transmission Line Power Transfer Capability Improvement

22 kV rms Line to line; Length 10 (km) Line resistance 1(Ω); Line reactance j3 ohms				
	Active Power (MW)	**Reactive Power (MVAR)**	**rms Voltage (kV)**	**rms Current (A)**
SUPPLY BUS 1	4.078	0.1104	12.7	109
BUS 2	3.941	2.956	12.64	130
BUS 5 Inductive Load	2.956	2.956	12.64	109.8
Bus 6 Resistive Load	0.985	-	12.64	26.12

It can be easily noticed from Table 11 that, in the absence of reactive power compensation by STATCOM, the supply currents are 108.7 A, 106.05 A and 103.57 A, for 10 km, 20 km and 30 km long transmission lines. It is well-known that inductive loads with low power factors draw higher currents from the supply, compared to the loads with higher power factors. The supply current can be reduced by doing reactive power compensation. In this thesis STATCOM is used compensate for reactive power. Table 13 shows that the supply currents are reduced to 83.72 A, 83 A and 82.5 A respectively when compensated by the STATCOM, for 10 km, 20 km and 30 km long transmission lines. The meaningful reductions in the supply currents came about because the load receives its reactive power requirement from the STATCOM only. The supply does not deliver any reactive power to the load. It only delivers the real power requirement of the load. This causes the supply currents to reduce from 108.7 A, 106.05 A and 103.57 A to 83.72 A, 83 A and 82.5 A respectively. This can be turned into an advantage. The question is this: Can we draw more active power from the supply, until the supply current becomes 108.7A,106.05A and 103.57A in the presence of compensation? The power system operated safely when the supply current was around 108A.

We added a resistive load parallel to the existing 3MW+j3MVAR load, until we obtained a supply current of magnitude 109A.It was found that when 1MW resistive load is connected parallel to the existing inductive load, the supply current becomes 109 A. The real power supplied by the supply becomes 4 MW. Table 15 shows the power transfer capability of the existing line has increased approximately 33 %. The current received by the 3MW+j3MVAR has not changed. It is 109A. This was done for 10 km transmission line but we have got similar results for other transmission line. From the table it can be noticed that the summation of real powers (2.956MW + 0.985 MW) taken by the inductive load and the resistive load is equal to 3.941 MW, which is equal to the real power supplied by bus 2 in Figure 82.

This is one of the main reasons why we make use of FACTS devices like STATCOM. We can carry more active power in the existing transmission lines and there is no need to spend money to build new transmission lines.

IV.5 Conclusions

In this thesis, we have made simulations on a 2-bus power system which consisted of a supply feeding an inductive load having a low power factor, via a transmission line. Because the load is highly inductive it draws higher currents from the supply and causes high transmission line losses and bad voltage regulation at the load bus. This has been averted by using a STATCOM, which is a powerful reactive power compensator. Reactive power compensation decreased the supply current, which in turn decreased the line losses by 40%, which then increased the efficiency of the line. The voltage drop on the line has decreased, causing the load voltage to increase close to its rated value. In this way the voltage regulation improved. The power transfer capability of the transmission line is also increased by doing reactive power compensation using STATCOM. The power factor of the supply bus has improved as well.

CHAPTER V

Conclusion And Recommendations

V.1 Introduction

Reactive power in power systems is a very important matter and it can be detrimental unless kept under strict control. Reactive power control gains importance especially with inductive loads, having low power factors. Inductive loads draw higher currents from the generators and hence increase the line losses, increase line voltage drops and hence decreases the load voltages. These problems can be mitigated by exercising reactive power compensation. Several FACTS devices are used to accomplish the compensation reactive power compensation, as explained extensively in Chapter 2. STATCOM is one of the most popular FACTS device that is being used frequently nowadays and for this reason STATCOM is used in this thesis for compensation.

It will be the first time that a master thesis is being done on reactive power compensation by using a FACTS device, in the Electrical & Electronic Engineering Department here at Near East University. For this reason, we initiated this study by using the simplest 2-bus power system. We studied a 2-bus power system which supplies power through a short transmission line to an inductive load having a nominal real power of 3 MW and nominal reactive power of 3 MVAR. The nominal powers are so chosen to make the power factor of the load low at a value of 0.7071 lagging. We especially choose a low power factor load so that the supply current would first increase and then made to decrease by doing reactive power compensation by using STATCOM.

V.2 Conclusion

2 sets of simulations were done on the power system by using MATLAB/Simulink software. In the first simulation STATCOM was not connected, whereas in the second simulation STATCOM was connected. The active and reactive power of the load was always kept constant at 3 MW+j3 MVAR. The simulations show that when uncompensated the supply and load currents are the same. For 10 km transmission lines this current is 108.7 A, for 20 km 106.5 A and for 30 km 103.57 A. When compensated supply current reduces

sharply to 83.72 A, 83A and 82.5 A for 10 km, 20 km and 30 km lines respectively. It can be seen that the supply currents are very close to each other. When compensated the load currents become 110 A, 109 A and 107.8 A, for 10 km, 20 km and 30 km lines respectively. We can notice that these load currents are very close to load currents before compensation. This is natural because the load power is always constant.

The load voltages before compensation are 12.4 kV, 12.1 kV and 11.815 kV respectively for 10 km,20 km and 30 km. The load voltages after compensation are 12.67 kV, 12.62 kV and 12.57 kV respectively, for 10 km, 20 km and 30 km. The load voltage regulations are 2.4%, 4.8% and 6.97% before compensation, for 10 km, 20 km and 30 km lines. After compensation the load voltage regulations improve to 0.24%, 0.62% and 1% respectively. We have shown from the above data that reactive power compensation by STATCOM improves voltage regulation. Similarly, the power factors of the supply, before compensation are 0.6985, 0.6902 and 0.6994 for 10 km, 20 km and 30 km respectively. After compensation the power factors improved to 0.9986, 0.9997 and 0. 9999.This occurred because the supply does not deliver reactive power to load anymore. Load receives its reactive power from the STATCOM. By simulations we have noticed that when reactive power compensation is done, the supply power factor has also improved.

The simulation results for 10 km transmission line before compensation show that the active and reactive supply powers are 2.892 MW and 2.962 MVAR respectively. The active and reactive load powers, before compensation, are respectively 2.856 MW and 2.856 MVAR. The supply and load currents are same at 108.7 A. The supply voltage, before compensation, is 12.7 kV and the load voltage is 12.4 kV. After compensation the active supply power has increases to 3.094 MW and the supply reactive power practically reduced to zero. All the reactive power needed by the load is provided by STATCOM. This causes the supply current to decrease from 108.7 A (before compensation) to 83.72 A (after compensation). The active power before compensation was 2.892 MW and after compensation it has risen to 3.094 MW.

For 20 km transmission line, we have noticed the same improvement as for 10 km transmission line. At the supply side the active power was 2.789 MW before compensation and 3.075 MW after compensation. The active load power was 2.722 MW before compensation and 2.934 MW after compensation. Because all load reactive power comes from the STATCOM, the supply current before compensation,106.05 A, reduces to 83 A, after compensation.

For 30 km transmission line, active supply power was 2.692 MW before compensation and 3.055 MW after compensation. The active load power was 2.596 MW before compensation and 2.897 MW after compensation. All load reactive power is now provided by the STATCOM and because of this, the supply current before compensation,103.57 A, reduces to 82.5A, after compensation.

Reactive power compensation causes the supply current to reduce. This provides an opportunity to increase the active power. We have shown in this thesis that, after compensation based on table 15, it has been possible to increase the transmission line's power transfer capacity by around 35%.

The results obtained in this thesis showed that the compensation of reactive power using STATCOM enhances the power system voltage profile and decreases the power losses in the transmission lines, enhances the supply power factor and improves the power system stability. The burden on grid is decreased, which provides an opportunity to increase the transfer capability of transmission lines.

V.3 Recommendations

For future work, we recommend the following:

(1) The number of buses in the power system can be increased to simulate more complex power systems.

(2) In this thesis, the lengths of transmission line were kept short(<30km) so that we could use the simple transmission line equivalent circuit (series R-L) to represent the line in the simulations. We can repeat the simulations for ‘medium’ size transmission lines, whose equivalent circuit becomes more complex, with shunt capacitances.

(3) In this thesis, we make used of STATCOM for reactive power compensation only. We can repeat the simulations for both reactive and active power compensation, by using STATCOM.

(4) In this thesis PI-Controllers were used. In a new study, Fuzzy Logic Controllers may be utilized instead.

(5) It will be useful to do harmonic analysis of the current waveforms, especially that of STATCOM.

(6) In a new study we can keep the length of the transmission line the same and vary the load complex power.

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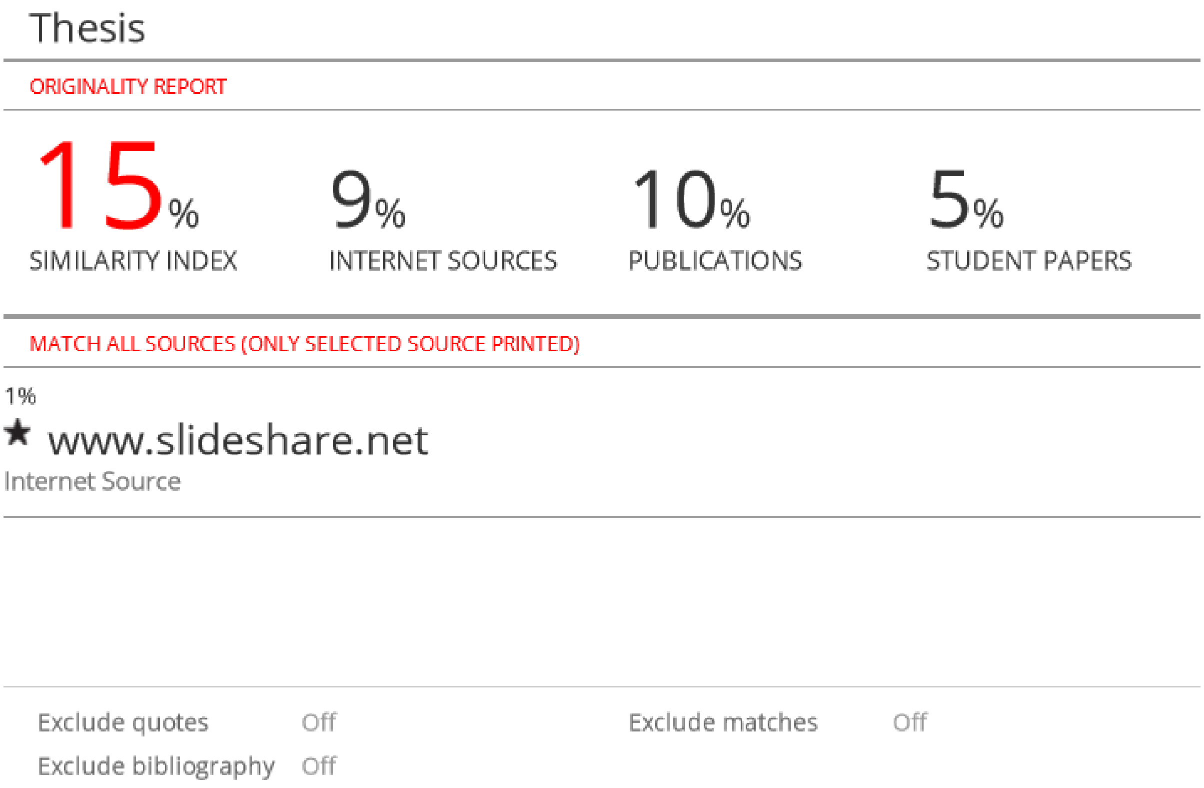
Appendices

Appendix A

Turnitin Similarity Report



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