DURBAN UNIVERSITY OF TECHNOLOGY

INVESTIGATING THE APPLICATION OF STATIC SYNCHRONOUS COMPENSATOR (STATCOM) FOR MITIGATING POWER TRANSMISSION LINE LOSSES

By

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Declaration

This dissertation is the candidate's own work except where indicated in the text. It has not been submitted in part or in whole, at any other University.

This research was conducted at the Durban University of Technology under the supervision of Mr. K.T Akindeji and Professor. Pat Naidoo.

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Dedication

This study is dedicated to God Almighty who has given me life and a sound mind to be able to begin and bring to completion this phase of my life, to Him only be all the glory and praise.

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Abstract

Voltage instability and increased power loss on transmission lines are major challenges in power transmission due to ever increasing load growth. This work investigates the effect of Static Synchronous Compensator (STATCOM) to mitigate power losses and enhance the voltage stability of a transmission system. STATCOM, a shunt-connected power electronic device, operate as a Voltage Source Converter (VSC) to improve power transfer capacity of transmission lines by injecting a set of three-phase balanced sinusoidal current with controllable magnitude and phase angle into the transmission lines to regulate the line voltage and compensate for reactive power at the Point of Common Coupling (PCC).

To validate the capacity of STATCOM in this light, a modified model of IEEE 14 bus test system was simulated using DIgSILENT PowerFactory v15. Four different load profiles were included by increasing the base load in a step of 10%. In each case, power flow was run with and without STATCOM incorporated in the network with a view to determine the impact of STATCOM on bus voltage and transmission line losses.

The simulation results are obtained were recorded and analyzed. It is noted that there was sufficient improvement in the new voltage profile obtained for the weak buses of the system, the active and reactive power losses were mitigated by 17.73% and 24.80% respectively when STATCOM was incorporated at normal load.

The results showed that STATCOM could give quick voltage support to reduce the likelihood of voltage collapse and mitigate power losses along the transmission lines. Reduction of reactive power losses along the lines is higher than the active power losses resulting in the improvement of the voltage profile as the device is connected to the system.

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Acronyms

AC	Alternating Current
CSI	Current Source Inverter
DC	Direct Current
DIgSILENT	Digital Simulation and Electrical Network Calculation
DSSC	Distributed Static Series Controller
D-STATCOM	Distribution Static Synchronous Compensator
DVR	Dynamic Voltage Restorer
E-STATCOM	Energy Storage Static Synchronous Compensator
EMT	Electromagnetic Transients
FACTS	Flexible Alternating Current Transmission System
GCT	Gate Commutated Turn-off
GTO	Gate Turn-off
GUPFC	Generalized Unified Power Flow Converter
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
IEGT	Integrated Enhanced Gate Transistor
IGBT	Integrated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
IPFC	Interline Power Flow Controller
LFO	Low Frequency Oscillation
MATLAB	Matrix Laboratory
MVAr	Mega Volt Ampere Reactive
PCC	Point of Common Coupling

PLC	Power Line Communication
PSB	Power System Blockset
PSC	Permanent Split Capacitor
PSO	Particle Swarm Optimization
PSS	Power System Stabilizer
PST	Phase Shifting Transformer
PWM	Pulse Width Modulation
RMS	Root Mean Square
SPWM	Sinusoidal Pulse Width Modulation
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
STS	Static Transfer Switch
SVC	Static Var Compensator
TCR	Thyristor Controlled Reactor
TCR-FC	Fixed Capacitor Thyristor Controlled Reactor
TCSC	Thyristor Controlled Series Controller
TSA	Trajectory Sensitivity Analysis
TSC	Thyristor Switched Capacitor
TSSC	Thyristor Switched Series Controller
UPFC	Unified Power Flow Controller
UPS	Uninterrupted Power Supply VAR
VSC	Voltage Source Converter
VSL	Voltage Stability Limit

CHAPTER ONE: Introduction

1.1 Background

In recent years, electric power transmission lines have become more constrained due to continuous load growth. There is an urgent need to increase the power carrying capacity of the power transmission lines in order to mitigate losses and reduce voltage instability, thereby maintaining reliability and security of the power system as a whole. Power generating stations are mostly situated far away from the load center due to environmental challenges such as pollution, hazard to human and regulatory policies. With a specific objective to meet the perpetually increasing power demand, utilities depend on the existing arrangements of power generation and transmission lines as opposed to building new transmission lines that are subject to economic and environmental issues. Also, certain transmission lines are well operating below their rated thermal limit, some other lines are over loaded, resulting in voltage collapse thereby reducing the system reliability and stability. This general circumstance requires the investigation of different methods or techniques of reducing transmission line losses and the application of available methods, which would allow the existing transmission lines function up to their full capacity without reducing the power system security, stability, and power transfer. It is imperative to note that the increase of reactive power in the system causes power losses and reduces the transmission line power transfer capacity. It also brings about a large voltage amplitude variation at the consumer's end. Compensating reactive power is thereby important in controlling and mitigating losses in the electric power system [1].

This research focus is on investigating the effect of Static Synchronous Compensator (STATCOM) in mitigating power transmission line losses. STATCOM is a Voltage Source Converter based Flexible Alternating Current Transmission System (FACTS) controller that offers support to power system by providing rapid voltage control and reactive power compensation on power transmission system. STATCOM increases the line transmission capacity, enhances the voltage, angle stability and dampens the oscillation mode of the system [2]. A modified model of IEEE 14 bus test system was built on DIgSILENT PowerFactory v15 to validate the Voltage Source Converter (VSC) based STATCOM capacity to mitigate power losses on power transmission lines. Power flow study using the Newton Raphson algorithms was adopted with and without STATCOM incorporated into the power system while considering four different loading scenarios. It is observed that there was satisfactory change in the new voltage profile obtained for the weak buses of the system, the active and reactive power losses was diminished by 17.73% and 24.80% respectively when STATCOM was connected at base load. From the results, it is established that STATCOM could give swift voltage support to lessen the probability of voltage collapse and mitigate power losses along the transmission lines. Reduction of reactive power losses along the lines is higher than the active power losses, resulting in improvement of the voltage profile as the device is connected to the system.

1.2 Aim and objectives

The aim of this research is to investigate the effect of applying STATCOM on a transmission system with respect to power losses mitigation and improvement of voltage stability. The following are research objectives:

- Modelling of the case study, IEEE 14 bus test system in DIgSILENT PowerFactory v15 to validate the performance of STATCOM.
- Study the performance of the system without the application of STATCOM.
- To study the performance of the system with the application of STATCOM on voltage variation, active and reactive power and compare results obtained for the different loading scenarios of the power system with and without STATCOM.

The software DIgSILENT PowerFactory v15 was used to simulate and analyze the steady state operation of an electric power transmission system. A test system which consists of 5 generators, 14 buses, 16 lines and 11 non-linear loads was studied. The system was first simulated and analyzed without STATCOM and then with STATCOM; thereafter, the loads were increased in steps of 10% up till 40% load increase without STATCOM and then with STATCOM, to examine the effect of sudden load on power transmission line losses. Newton Raphson power flow algorithms were used [3] to investigate the voltage stability and power transfer of the system before and after the STATCOM device was incorporated in the system.

1.3 Problem statement

Electric power systems play important roles in the industrial and socioeconomic development of any nation. Electrical energy is generated and transported from remote generating stations to the load centers through transmission lines. These transmission lines are susceptible to losses, which affect the ability to deliver the same amount of power generated at the receiving end. This has become a problem that needs to be solved through research. This motivates the idea of investigating the effect of application of STATCOM in mitigating the transmission line losses by studying the IEEE 14 bus test system. Power flow calculation is key to evaluating the operational state of any power system, therefore a power flow study using the Newton-Raphson algorithms was adopted with and without STATCOM placement in the power system, while different loading factor scenarios were considered to understand how sudden load increase contribute to power losses on a transmission network..

1.4 Need for reactive power compensation

Voltage and reactive power control are two major features of power system support for reliability and transaction across transmission systems, because active power cannot flow if system voltage is not high enough, and a controlled reactive power is vital to active power transfer through the transmission and distribution lines to the load centers. At low system loading, the system produces reactive power that must sink, while at dense system loading the system uses a lot of reactive power that must be replaced. Therefore, system reactive power requirement per time as load levels change needed to be studied and applied [4]. Reactive power compensation is mainly voltage support and load compensation. In voltage support, reactive power compensation is employed to bring the voltage fluctuation to barest minimum at a particular bus of a transmission or distribution line, while for load compensation, the aim is to improve the power factor of the system, provide voltage regulation, balance the per phase real power consume from the AC supply and mitigate voltage flicker caused by large nonlinear industrial load. When reactive power in transmission system is compensated, it helps to increase the transmittable active power, thereby improving the stability of the system. At all levels of transmission and distribution, it maintains a substantial level of voltage profile, improves the efficiency of the transmission line, controls temporary overvoltage, and it reduces the occurrence of blackouts. Also, there is need for dynamic reactive power compensation to limit the slow increase or decline of voltage, limit rapid increase or decline of voltage and to limit overvoltage caused by switching transient [5].

1.5 Impact of reactive power on power system

One of the significant impact of low reactive power in power system is blackout (power outage). Blackout could mean a temporary or long term loss of electric power supply to a particular section of the power system network. Blackouts, evaluated by the interruption duration, seems to be similar in different countries of the world. In the United Kingdom, power interruption that last more than three minutes is defined as power cut while in Sweden and United States a power cut last for one and five minute respectively. There is no official definition regarding the size of a blackout [6]. Most large transmission blackouts are caused by a single event which leads to cascading outages and eventual total collapse of the system. Engineers and researchers alike have tried to mitigate the initial event over the years to avoid the risk of ensuing line and generation trips. It may not be possible to eliminate system blackout, considering the modern power system enormity and complexity, but there are ways to minimize the risk of blackout based on the knowledge of the root cause and nature of events. Human error, a single transmission line, or generator outage can cause blackouts. However, the timely intervention of the operator or proper automatic control can prevent the single event from leading into a large blackout [7]. Figure 1.2 below illustrates the events that lead to power blackout. In the case where proper automatic control or operator intervention is not readily available, it can lead to:

i) Transient angular instability: The fault in the transmission system will cause the generator rotor angle to deviate, which will lead to loss of synchronization of all generators in the system, thereby depressing the voltage in the system. This event occurs within a few seconds [8].
ii) Voltage collapse: Voltage collapse is the loss of voltage due to instability in the system, which cuts off a considerable portion of a power system

If any of these instability phenomena is not checked, it may split the system into smaller segments of load and generator. Another cause of blackout is the inability to control reactive power. The unusual increase of inductive reactive power demand due to high electrical energy consumption stresses the transmission line and reduces the voltage at the load centre. Voltage collapse caused by insufficient reactive power has been a factor in major blackouts throughout the world. The major blackout in the United State on July 2, 1996 and August 14, 2003 affecting about 50 million people in the US and two provinces in Canada was reported in the IEEE Power Engineering Society Power System Dynamic Performance Committee as being caused by insufficient reactive power, leading to voltage collapse [9]. With emerging technology, various means to mitigate the occurrence and impact of blackouts include:

i) FACTS devices
ii) Coordinated emergency control
iii) Real-time monitoring and control

FACTS devices, when incorporated into a power system at strategic points, provides reactive power compensation, changes the obvious impediments across the grid, and shifts the voltage-power angle to improve system voltage stability [10].

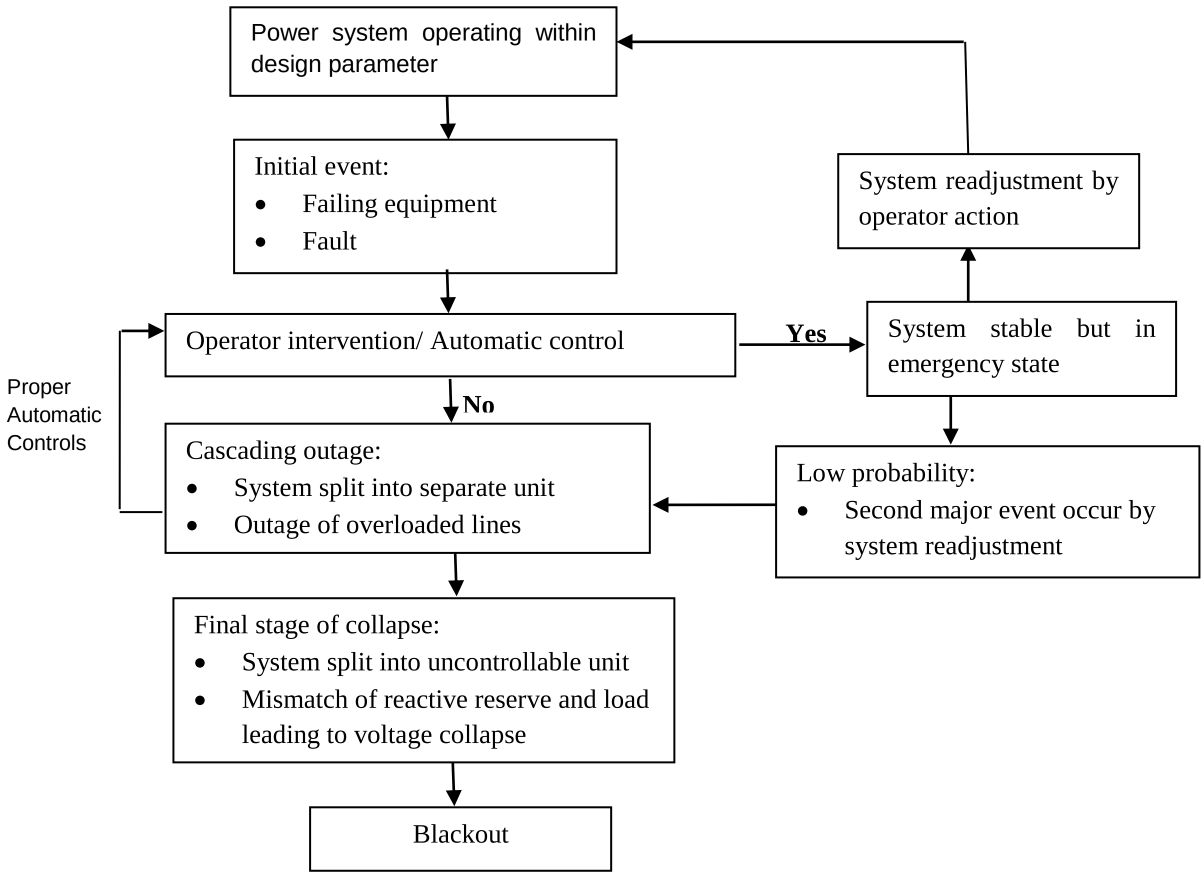

Figure 1.1: Illustration of events leading to a blackout [11]

1.6 Structure of dissertation

Chapter one gives a general introduction of the study, statements of the problem and the objectives. Chapter two focuses on the literatures reviewed. Chapter three presents the system model development and simulation, while chapter four discusses simulation results, including comparing the results to determine the effect of application of STATCOM for mitigating transmission line power losses. Chapter five presents the conclusions based on the work carried out.

CHAPTER TWO: Literature Review

2.1 Electrical power systems

For a very long time, there has been a significant increase in demand for electrical power energy, and as a result electrical power transmission networks are experiencing limitation in power transmission [12]. These limitations are due to balancing supply, allowed level of voltage, and maintaining the network stability. These have resulted in lesser practical operational capacity of the power systems compared to the full capacity. The consequence is non-optimal operation of the power transmission systems. Among the many options to solve the increasing problem of power transmission capacity is to construct brand new transmission lines, which is not practical nor economically viable. Researchers have worked in the last two decades to develop models and new algorithms for power system stability incorporating Flexible AC Transmission System (FACTS) devices for a reliable, fast, and continuous control of power flow in the transmission system. These devices have been applied in different areas of power system studies, including power quality, voltage stability, optimal power flow, power system security, improvement in the dampening ratio of power system and economic power dispatch so that power may be made available without violating system constraints to the consumers [13]. This chapter collates information from previous scholarly reviewed work by other researchers with a view to further the study of application of FACTS devices to enhance power system stability and mitigate power losses.

2.2 Configuration of electrical power systems

Generally the goal of an electrical power system is to transport electrical energy to the load, in a secure, economical, and reliable manner. Before the loads can consume this energy, electrical power must be generated and then transported. There are two different ways to transport electric power: transmission, and distribution. The primary task of a power system is the generation, transmission, and distribution of electrical power. There is a secondary task apart from the three main functions; this includes metering and protection. These tasks are carried out by the primary and secondary systems respectively. The primary configuration of an electrical power system is illustrated schematically in figure 2.1

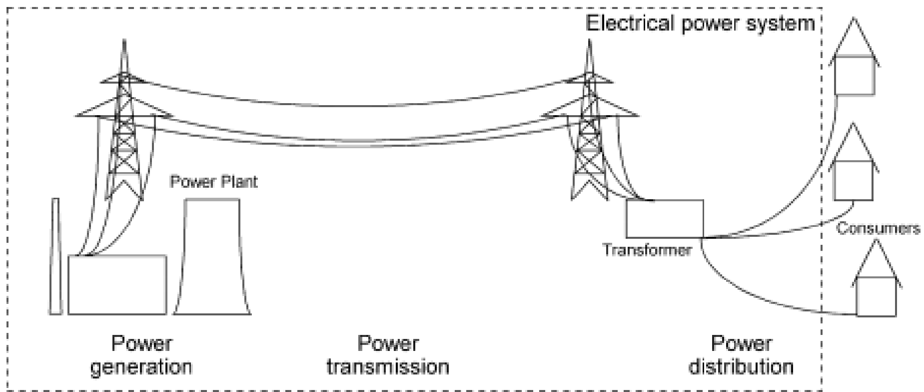

Figure 2.1: Schematic diagram of a primary configuration of an electrical power system [14]

Electrical power systems are much more complex than the graphic illustration in the figure above, because they consist of a network of meshed transmission lines that cut across regions and to which a great number of power plants and loads are connected. The followings are the advantages of transmission networks in the power system [15]:

- Economies of scale in electrical power generation
- A strong reduction of the required reserve margins at the level of the individual plant, because the outage of one unit can be compensated for by all other plants connected to the system, which hence only have to supply a relatively small amount of extra power
- A flattening of the load curve, enabling a more effective use of the generation equipment
- The possibility to minimize the cost of electrical power by shifting generation between units using different prime movers (such as oil, coal, and gas), dependent on the prices of these primary energy sources [16].

These are the reasons that justify the financial viability of connecting huge power plants by a transmission and distribution system in order to secure the movement of power generated to load, instead of having a disperse power generating station at every load centre.

2.2.1 Power generation

For electrical power generation, there is always a source that produces the energy. In a fossil fuel powered electrical power generating station, coal, oil, and gas are fired to produce thermal energy that goes through a steam cycle process to produce electrical energy. Atomic nuclei serve as the primary source of energy to generate electrical power in a nuclear power plant; the nuclei are subjected to nuclear fission to free their energy. The energy released is used to generate high pressure steam that drives a prime mover. In both cases, a synchronous prime mover, generator, or turbine is utilized to convert mechanical energy into electrical energy [17]. The generated electrical power energy is delivered to the loads by the transmission network. Figure 2.2 depicts a fuel and nuclear power generating station process.

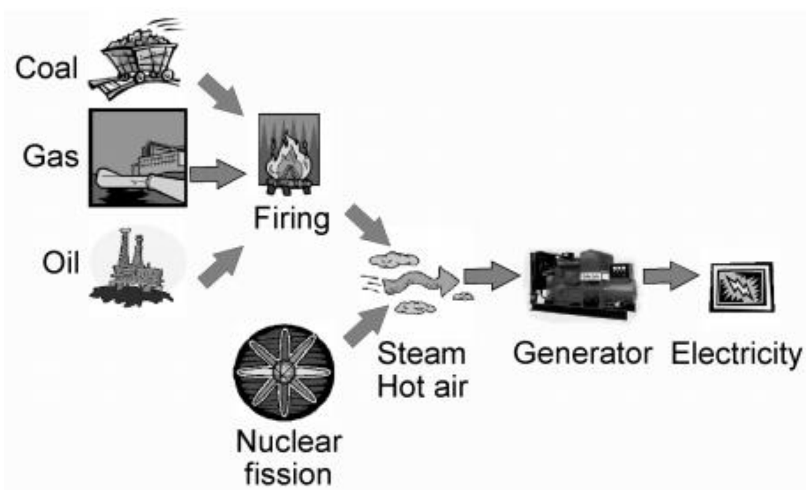

Figure 2.2 Fuel and nuclear power generating station process [17].

The primary source of both modes of power generation presented in figure 2.2 is limited and they are not environmentally friendly. Therefore, we need to consider renewable electrical power generation which has an unlimited primary resource, with the advantage of being environmentally friendly.

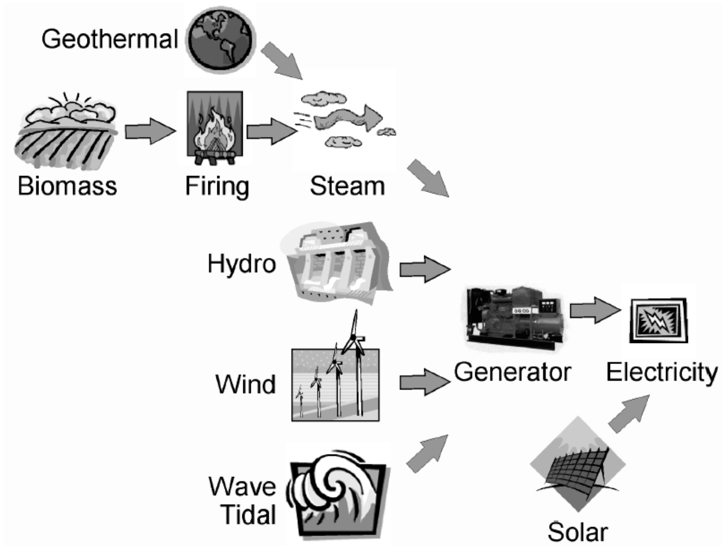

Figure 2.3 Renewable electrical power generating process [17].

A graphical representation of how renewable power is generated is shown in figure 2.3. A synchronous prime mover connects the renewable power plants and is used to convert the generated energy to electrical power.

2.2.2 Power transmission and distribution

The transmission of electrical power is carried out at high voltages and often over long distances, whereas the distribution is carried out at lower voltages and usually over short distances [18]. This difference is caused by the fact that the amount of power transmitted is dependent on both voltage and current, whereas the losses are mainly dependent on the current and the distance to be covered. Hence, the power losses over distance and the amount of power to be transmitted can be minimized by reducing the current and increasing the voltage of the line. On the other hand, the higher the voltage, the more expensive and bulky the components will be. As a result, power loss minimization comes at a cost. Therefore, there exists an option of capital expenditure for equipment to minimize losses for efficient power transfer.

2.3 Application of power electronics in power system

The use of power electronics devices has grown significantly in the last decade. Its use has significantly increased both in the transmission and the distribution system. Power electronics devices used in the transmission system are: High

Voltage Direct Current (HVDC) links and Flexible Alternating Current Transmission Systems (FACTS). The HVDC links serve as an alternative means of transmitting electrical power, while the FACTS devices are applied to compensate and improve the AC systems. The devices used in the distribution system are employed to improve the system power quality and they are usually referred to as custom power devices, while the devices on the transmission system are optimized to reduce losses by balancing the reactive power [19]. The next section below detailed this assertion.

2.3.1 Transmission level

The HVDC transmission system is the first power electronics device to be used on a transmission line [20]. The HVDC finds more use in long distance overhead and underground transmission systems, as an alternative means to transport power. It is also used to connect AC systems of different frequencies [21]. FACTS devices are applied to compensate and improve on an existing AC transmission system where there is a need to enhance the capacity of the system on power delivery. It has been proven that there is a significant increasing demand for electrical power leading to the complexities of the transmission system [22]. Considering the time and cost to build a new transmission line, FACTS comes in as a viable and attractive alternative. FACTS devices can be connected in series, shunt, or combined mode.

2.3.2 Distribution level

The focus of this dissertation is on the implementation of a power electronics device on transmission system, but a few custom power devices used on the distribution system will be highlighted briefly below. As power electronics devices are used to control power flow and enhance voltage stability on the transmission system, likewise are the custom power devices used to improve power quality within the distribution system. Problems with harmonics, damages related to transient over-voltages, or tripping of equipment caused by voltage dips have attracted attention to dynamic and adjustable devices to mitigate such problems [20]. Similar to FACTS devices, custom power devices are either connected in series, shunt or combined.

2.3.2.1 D-STATCOM

Distribution STATCOM (D-STATCOM) is the adaptation of STATCOM used in the distribution system; figure 2.4 depicts a D-STATCOM connected to a distribution system. It is a shunt connected VSC that only injects reactive power into the system [23]. The major function of a D-STATCOM on a distribution grid is to control voltage during transient and voltage dip, filter the system to reduce the level of current harmonics, and for load balancing.

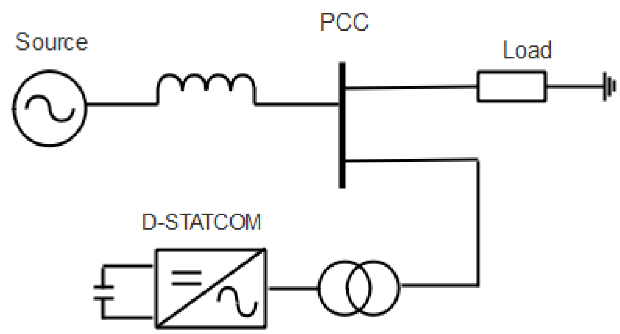

Figure 2.4 D-STATCOM on a distribution system [23]

2.3.2.2 Energy Storage Static Synchronous Compensator (E-STATCOM)

E-STATCOM has a similar use to D-STATCOM, with the exception of its energy storage capacity which exchanges active power with the system. Shown in figure 2.5 is the energy storage static synchronous compensator.

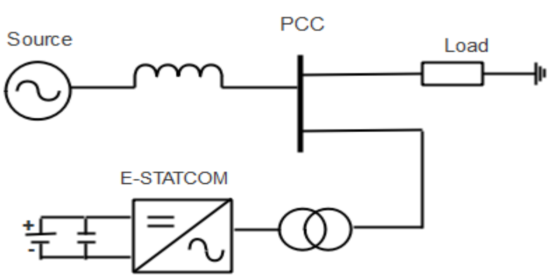

Figure 2.5 E-STATCOM on a distribution system [24]

2.3.2.3 Dynamic Voltage Restorer (DVR)

The DVR is a VSC usually connected in series; this mode of connection allows it to spontaneously mitigate voltage dip, since it can inject voltage directly whenever there is voltage drop [23]. Figure 2.6 shows the connection of a DVR to a distribution system. The major advantage of the use of the DVR to mitigate the voltage drop is its dynamic performance, which is not dependent on the source impedance. Likewise, it can be deployed to compensate for unbalanced voltage and filter voltage harmonics. The only disadvantage of the device is the increase in cost due to the requirement of an advanced protection system in case of a short-circuit fault further down the device.

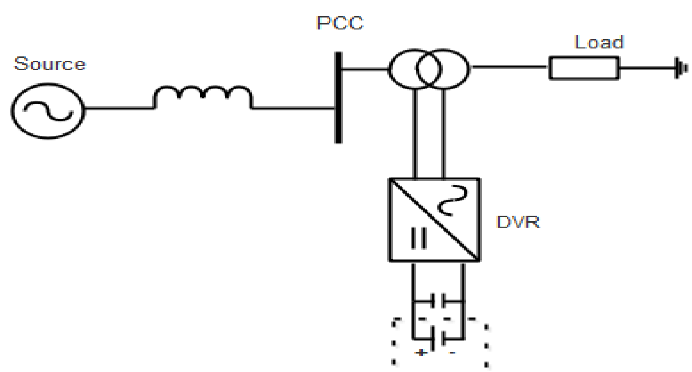

Figure 2.6 DVR connected to a distribution grid [23].

2.3.2.4 Uninterrupted Power Supplies (UPS)

UPS of about 5000 kVA can be deployed for low power equipment that is sensitive, such as computers and servers [25]. UPS come in various structures but the common denominator of all UPS is that its energy storage can supply active power. The size of the UPS energy storage determines its capacity to mitigate power interruption, voltage drop, and other power quality problems. UPS connection to a system is shown in figure 2.7.

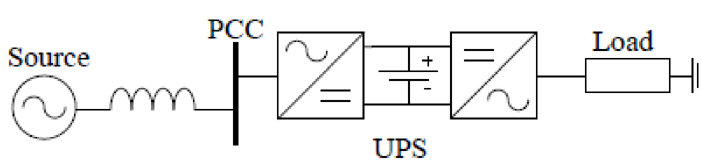

Figure 2.7 UPS on a distribution system [25].

2.3.2.5 Static Transfer Switch (STS)

STS is another means of protecting a sensitive load from voltage dip; its connection is shown in figure 2.8. Either the primary or secondary feeder can feed a load with static transfer switch. The thyristor switches the device from the primary feeder to the secondary feeder in cases of voltage dip. The STS only protects equipment in the distribution system; if there is a voltage dip in the transmission system, both feeders of this device will be affected.

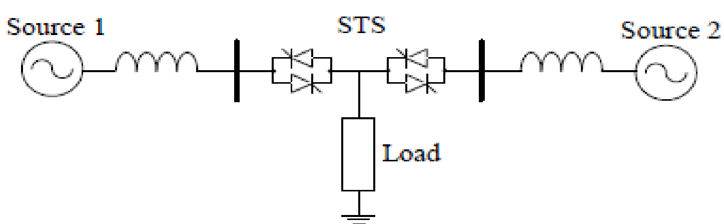

Figure 2.8 STS on a distribution system [25]

2.4 Overview of major FACTS devices

The two categories of power flow control devices are the conventional (mechanically switched) and power electronics-based devices. Regarding the mode of placement of this technology in the network; we have shunt, series, and combined as shown in figure 2.9.

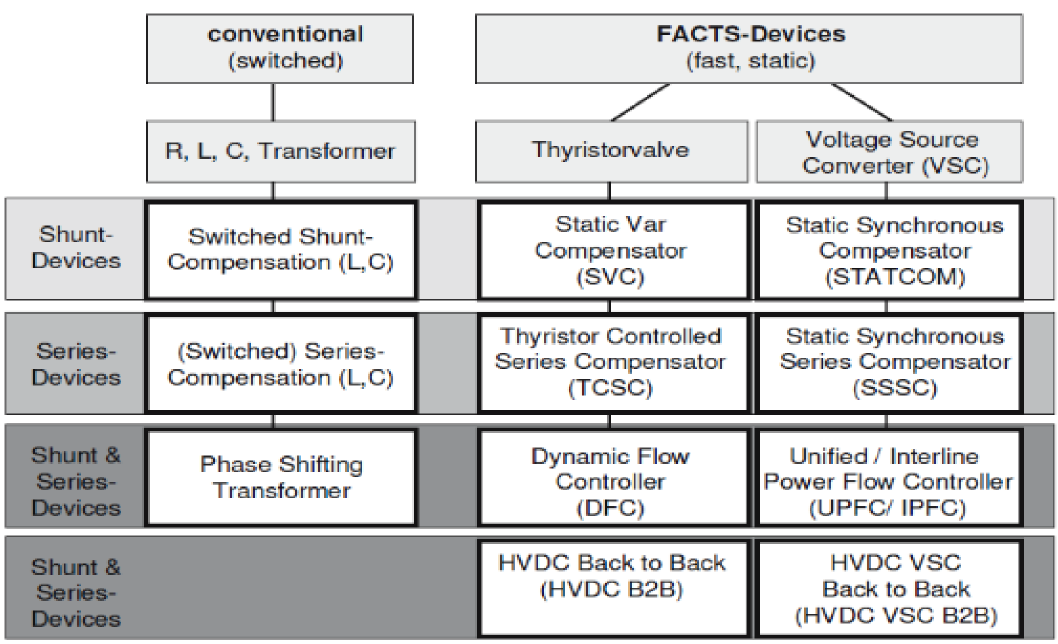

Figure 2.9 Overview of major FACTS Devices [26].

2.5 Types of FACTS devices

There are two types of reactive power compensating device [21, 27]. The first type engage conventional thyristor switched reactors and capacitors, while the other type engages a Gate Turn-Off (GTO) thyristor, Integrated Gate Bipolar Transistor (IGBT), Integrated Gate Commutated Thyristor (IGCT), Injection Enhanced Gate Transistor (IEGT) converters as voltage source converters (VSC) [28]. The idea of FACTS and its controllers was defined in [29] as an alternating current transmission system made up of power electronic-based static controllers to improve the control of system parameters and power transfer ability of an electric power transmission system. Electronics-based FACTS devices have replaced many mechanically controlled reactive power compensators; more importantly, they are playing a major role in the operation and control of modern power systems. FACTS devices can be grouped into four categories:

- i) Series devices
- ii) Shunt devices
- iii) Combined Series-Series devices
- iv) Combined Series-Shunt devices

i) **Series devices:** These devices could be a variable impedance such as thyristor switched, capacitor, reactor or a power electronics based variable source that injects voltage in series with the line as shown in figure 2.10. The injected variable series voltage in the line is represented by the variable impedance multiplied by the current flowing through it. In this case, the device requires an external energy source. This device either supplies or absorbs variable reactive power when the voltage is more or less than 90^0 out of phase with the line current.

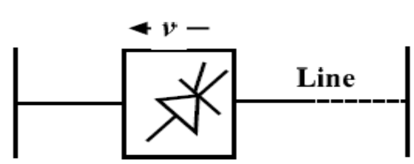

Figure 2.10 Basic Series FACTS device [21].

ii) **Shunt devices:** The shunt devices can have variable impedance, variable current or voltage source, capacitor, reactor, or a power electronic based variable source that is connected in shunt to the system so as to inject variable current into the line as shown in figure 2.11. The shunt device either supplies or absorbs variable reactive power when the injected current is more or less than 90^0 out of phase with the line voltage.

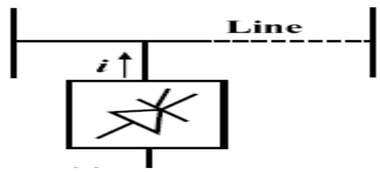

Figure 2.11 Basic shunt FACTS device [21]

iii) **Combined Series-Series devices:** These devices combine two or more separate series devices controlled in a coordinated manner. These devices have the capacity to balance both real and reactive power flow in the line via the DC link whereby the transmission system is maximally utilized. For real power transfer, the DC terminal of all the device converters is connected together, therefore it is called Unified Power Flow Controller (UPFC).The series-shunt device is shown in figure 2.12.

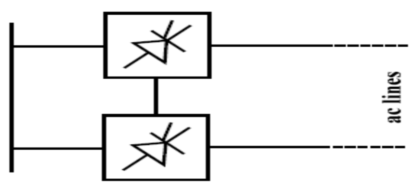

Figure 2.12 Basic series-series FACTS device [21]

iv) **Combined Series-Shunt devices:** These are devices that combine separate series and shunt controllers in a coordinated manner. The combined series and shunt controllers inject voltage in series in the line with the series part, and current into the system with the shunt part. The series-shunt device is shown in figure 2.13.

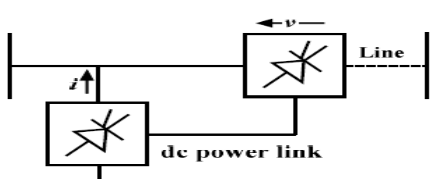

Figure 2.13 Basic Series-Shunt FACTS device [21].

2.6 Operational principle of shunt devices

The operational principle of a shunt device is to supply reactive power that is required at the load, by varying its impedance, to inject reactive current I_{sh} thereby it indirectly control the line current I. By Ohm's law, the difference between the sending end voltage and the receiving end voltage (i.e. V_s-V_r) being the voltage drop across the transmission line correlate to the line current I. We can assume the voltage at the sending end (V_s) to be a constant value, the magnitude of voltage at the receiving end |Vr| can be controlled by a shunt device [30].

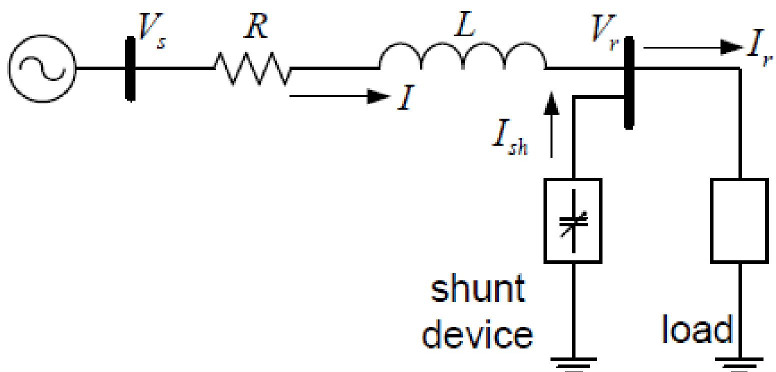

Fig. 2.14 Shunt device operating principle [30].

The link between the injected current I_{sh} by the shunt device and the voltage at receiving end V_r can be found in the equation below:

$$V_r = V_s - IZ \qquad (2.1)$$

$$= V_s - (I_r - I_{sh})Z$$

Where $Z = R + j\omega L$

As seen in equation (1), the shunt device can control the voltage magnitude by varying it impedance. The line current I in heavy load condition leads to a voltage drop and is reduced by the shunt current I_{sh} partial compensation for the large load current I_r. The three types of shunt controllers are: switched shunt inductor and capacitor devices, Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM).

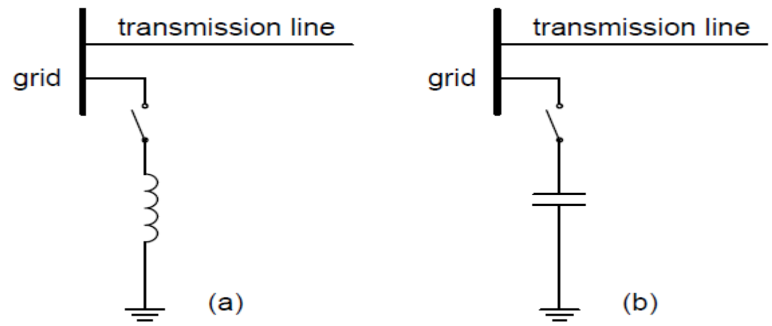

Figure 2.15: Configuration of Switched shunt inductor and capacitor:
(a) inductor; (b) capacitor [30].

2.6.1 Review of Static Var Compensator (SVC) application

As defined in [21] *a static var compensator is a static var generator whose output is varied so as to maintain or control specific parameters (e.g. voltage or reactive power of bus) of the electric power system*. The device is shunt connected and its output is designed to exchange inductive or capacitive current to maintain and control typically the terminal bus voltage of an electrical power system. The device is made up of a bank of Thyristor Switched Capacitors (TSC) and Thyristor-Controlled Reactors (TCR) [31-33]. Figures 2.16 and 2.17 show the basic configuration and terminal characteristics of a SVC respectively.

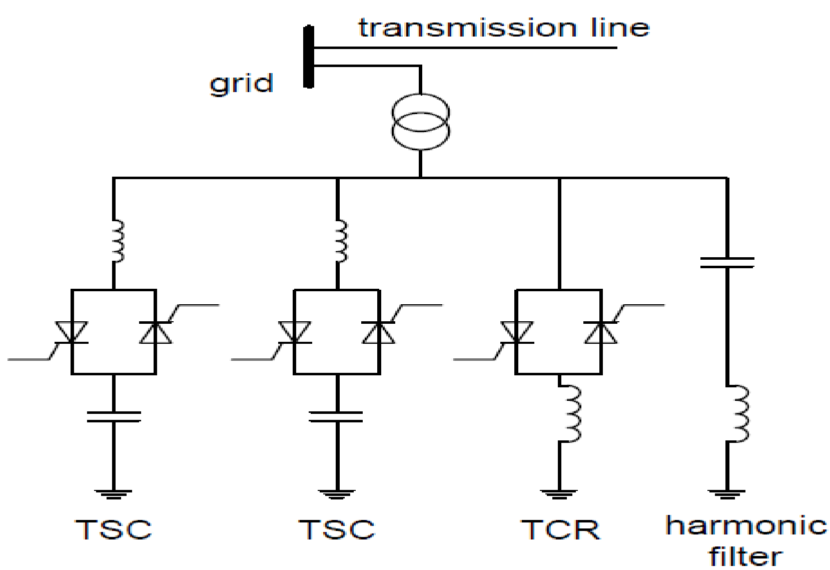

Figure 2.16: A typical SVC configuration [30].

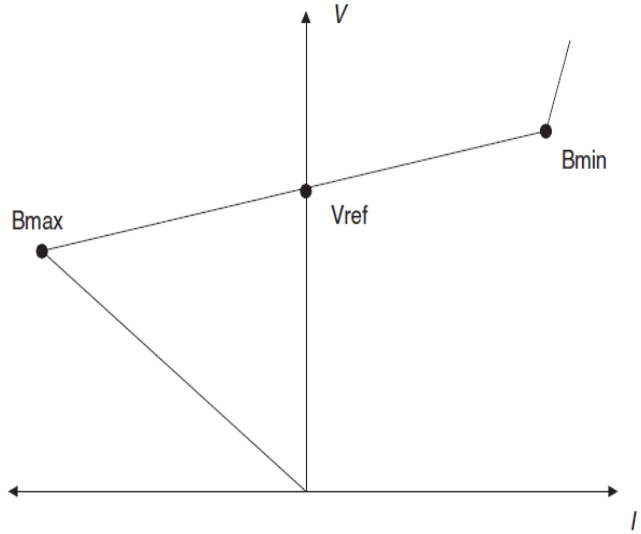

Figure 2.17: Terminal characteristic of SVC [26]

The TCR consists of a fixed reactor in series with a bi-directional thyristor valve. The inductance in each phase is divided in such a way that half of the inductance is on each side of the thyristor valve. The TSC consists of a capacitor in series with a bi-directional thyristor valve and a damping reactor. The thyristor switch connects or disconnects the capacitor for an integral number of half-cycles of the applied voltage. The reactor in the TSC serves to limit inrush current when severe transience occur [34, 35]. In a Fixed Capacitor Thyristor Controlled Reactor (TCR-FC), the current in the reactor is controlled by varying the firing angle of the thyristor valve thereby controlling the shunt reactance [21, 36].

In [37, 38] a comprehensive examination of the use of Static Var Compensator (SVC) to support damping of low frequency inter-area oscillations in a large interconnected power system is presented. Modal analysis of a linearized model of the power system was used to study inter-area oscillation and design of controls. This approach allows the identification of the nature of oscillation pattern and presents important information needed in the application of Static Var Compensators (SVC). Simultaneous coordinated designing of power system stabilizer and Static VAR Compensator damping controller was studied in [39], by introducing disturbance, particle swarm optimization (PSO) is used to get the optimal controller parameters. The result of the study shows that the proposed coordinated controllers have excellent capability in damping inter-area oscillations. SVC has been analyzed to enhance the damping of low frequency oscillation. In [40] fuzzy logic and genetic algorithms based approaches was proposed for Static Var Compensators (SVC) control of nonlinear modal interaction in stressed power systems with multiple Static Var Compensators (SVC). A sensitivity model for Var dispatch to restore the var reserve of Static Var Compensator (SVC) was proposed in [41] by keeping desirable voltage profile and the control capability of SVCs, defined by the available control margin, the reference voltage, the slope, and the static voltage characteristic of the system.

In [42] a new method was proposed for optimal placement of Static Var Compensator (SVC) to improve voltage profiling, reduce power losses, minimize the voltage derivations in power system using Voltage Stability Limit (VSL) and to increase the efficiency of power system. A study on voltage stability in power systems was conducted, examining the incorporation and effects of Static Var Compensator (SVC). The model was based on setting the controller as variable impedance that change with the firing angle of the Thyristor Controlled Reactor TCR [43, 44]. The Coordinated Transformation method is recommended for the voltage regulator of the SVC controller. To explain the design and operation of this method, a MATLAB simulation of SVC controller was used to analyze the response of SVC controller when connected to a transmission line. The result shows that the method is cheap, better, and accurate with quick response [45]. SVC was applied to a power system in [46] to examine its performance enhancement on real power transfer capability in f cv a grid. As observed, after fault clearance by time domain analysis, the stability analysis of the system shows an improvement in bus voltage profile and increase in power flow.

2.6.2 Static Synchronous Compensator (STATCOM)

The Static Synchronous Compensator (STATCOM) is a Synchronous Voltage Generator (SVG) that is power electronics based. It is a shunt connected

FACTS device that provides capacitive or inductive output current for reactive power compensation to solve a variety of power system voltage stability and fluctuation conditions independent of the AC system voltage [21, 34, 47]. STATCOM is a shunt VSC that is connected to the grid as shown in figure 2.18. The device controls the line reactive power via the output reactive current without interfering with the AC voltage. It control line voltage, increases the power delivery capacity of the transmission lines, and improves the voltage stability angle [48]. The device consists of a DC Voltage Source Converter, self-commutated converters using a Gate Commutated Turn-off (GCT) thyristor and step-up transformer [21]. From the DC capacitor; it generates a three-phase voltage in sync with the grid voltage via a coupling transformer, it improves the static and dynamic voltage stability of bus on power network, and keeps the voltage of the electric system in receivable operating mode [49]. Figures 2.18 and 2.19 show the configuration and terminal characteristic of STATCOM.

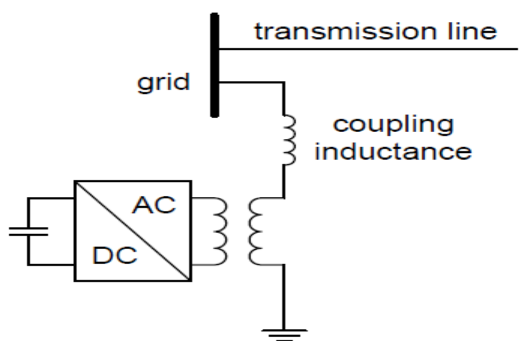

Figure 2.18: The configuration of STATCOM [30].

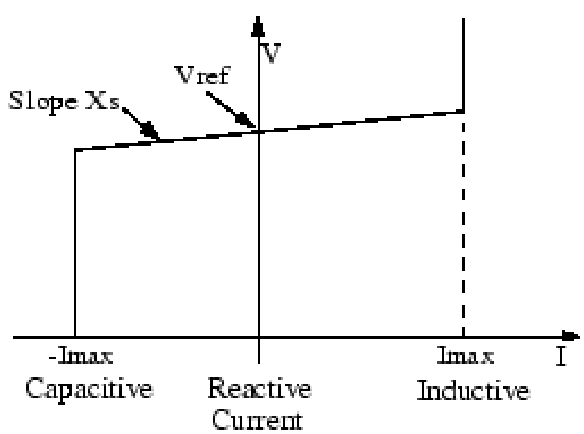

Figure 2.19: Terminal characteristic of STATCOM [32]

The injected AC current of this device is either leading or lagging with grid voltage and it acts as an inductive and capacitive impedance at the point of connection [50]. If the voltage generated by the STATCOM is lesser than the transmission line voltage, it will emulate an inductive load and withdraw reactive power from the system. On the other hand, when the device voltage is higher than the transmission line voltage, it will emulate a capacitive load and provide reactive power to the transmission line [51, 52]. The DC VSC is the most common type of converter that is used for the STATCOM, where the DC voltage source can be a capacitor. By using a Multi-phase, Multi-level or Pulse-Width Modulated (PWM) converter, the output current distortion of STATCOM can be sufficiently reduced. The reactive power produced by STATCOM is independent of the actual transmission line voltage magnitude [53, 54].

The application of STATCOM to improve power system stability has been studied in [13, 55]; the coordination between the STATCOM damping stabilizers and its internal voltage controller is taken into consideration to improve the system dynamic stability and voltage regulation. STATCOM containing Insulated Gate Bipolar Transistor (IGBT) based VSC optimized by Genetic Algorithm is used for voltage stability and compensation of reactive power in [56]. The simulation results when compared with the system without STATCOM compensation for inductive and capacitive load condition show that STATCOM tuned with Genetic Algorithm has the best performance closest to the nominal value of the voltage of 1 per unit.

The dynamic operation of a novel control scheme for STATCOM and SSSC was investigated in [57] based on a new model of a 48-pulse GTO voltage source converter for combined voltage stability and reactive power compensation of an electric transmission line network. STATCOM and SSSC digital simulation was carried out in MATLAB/Simulink environment with the Power System Blockset (PSB). Two novel controllers based on a decoupled current control strategy is proposed for the STATCOM and SSSC while the performance of both devices connected to a 230kV line was evaluated. In both capacitive and inductive mode, the operation of STATCOM and SSSC is validated using the sample power transmission system. The controllers verified high efficiency for voltage regulation and reactive power compensation when the system was subjected to load disturbance.

A new coordinated voltage control scheme was presented in [58] for improving network voltage profile and to minimize the steady-state loading of STATCOM to efficiently support the system contingencies. A new approach was presented in [59] for the dynamic control of Current Source Inverter (CSI) based STATCOM. For the design, the steady state and d-q frame model uniqueness of the CSI STATCOM are projected as a basis for control design. This approach comprises a fast AC current control inner loop and a slower DC current control outer loop. To validate this proposed control design and the simulation result, experiments were conducted on a 5-kVA laboratory current source inverter STATCOM, setup to confirm the control design. The simulation results obtained shows that STATCOM improved the system voltage profile and minimized losses.

The ability of a STATCOM to deliver reactive power required at a wind farm under various conditions is studied in [60] with results from the studies; it is noted that it improves the steady-state stability limit of the system. STATCOM also improved transient and short-term generator stability conditions when incorporated into a system as an active voltage or VAR supporter [61-65]. The compensating current of STATCOM is not dependent on the voltage level at the point of connection, that is, the compensating current is not lowered when the voltage drops; this the advantage of STATCOM over thyristor-based SVC [32, 66, 67]. The usual applications of STATCOM are stability improvement and active power compensation [68], low frequency oscillation (LFO) damping [69, 70], enhancement of transient stability [71], voltage flicker control [72, 73], and power quality improvement [74, 75].

2.7 Operational principle of series devices

The series FACTS devices are used to enhance power system stability and loadability; it operates as a variable capacitive or inductive impedance that can be adjusted in series with the transmission line to damp oscillation in the system as shown in figure 2.21. This is accomplished by injecting a proper voltage phasor in series with the transmission line and is seen as the voltage across an impedance in series with the line. In the event that the line voltage is in phase quadrature with the line current, the controller sink or generate reactive power, otherwise the devices sink or produce active and reactive power. The power flow is controlled according to equation (2) and (3) below.

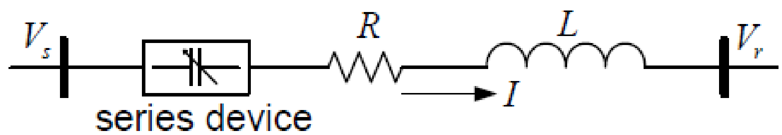

Figure 2.21: Series FACTS device operating principle [30].

$$P_r = \frac{|V_r||V_s|}{X}\sin\theta \tag{2.2}$$

$$Q_r = \frac{|V_r||V_s|}{X}\cos\theta - \frac{|V_r|}{X} \tag{2.3}$$

When the device acts in capacitive mode, it balances a fraction of the transmission line reactance. In the case of an inductive mode, the reactance will be increased to limit the power flow [76].

2.7.1 Thyristor Controlled Series Capacitor (TCSC)

Thyristor Controlled Switched Capacitor (TCSC) is defined by IEEE as "*A capacitive reactance compensator which consists of a series capacitor bank shunted by thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance"* [29]. TCSC use inverse-parallel thyristors to control the Thyristor Controlled Reactor (TCR) branch reactance, with the fixed capacitor, the total impedance of TCSC is adjusted [34, 77]. TCSC adjusts line impedance in one cycle [78], thus providing a faster system control than a mechanically switched device. The figure below shows TCSC configuration. Trajectory Sensitivity Analysis (TSA) techniques were proposed and investigated in [79] to assess the transient stability of a power system with TCSC at various operating conditions.

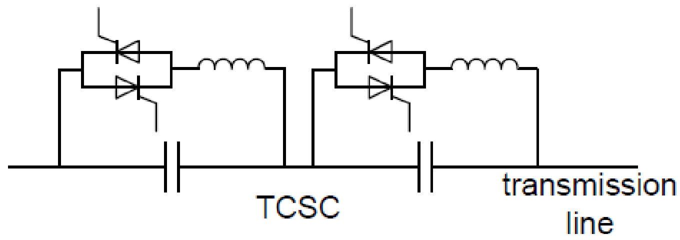

Figure 2.22. TCSC configuration [30].

2.7.2 Thyristor Switched Series Controller (TSSC)

A Thyristor Switched Series Capacitor (TSSC) is "*a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor switched reactor to provide a step-wise control of series capacitive reactance*" [29]. The TSSC utilize the thyristor to switch the capacitor bank and it has a faster response than compensators that are mechanically switched. The TSSC as shown in the figure below can only inject capacitance into the lines; it cannot limit the line current.

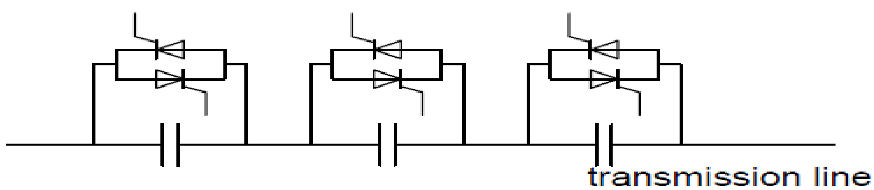

Figure 2.23. TSSC configuration [30].

2.7.3 Static Synchronous Series Compensator (SSSC)

The Static Synchronous Series Compensator (SSSC) is connected in series with transmission line. It injects a controlled voltage magnitude at an angle into the line. The voltage injected is dependent on the mode selected for the SSSC to control the transmitted electric power. "The SSSC operates without an external energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current. The purpose of this is to increase or decrease the overall reactive voltage drop across the line, thereby controlling the power flow" [29]. Figure 2.24 shows a SSSC line configuration.

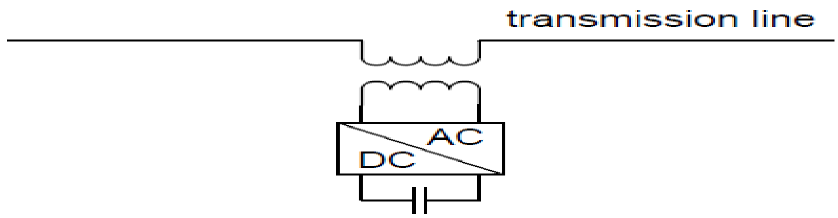

Figure 2.24 A SSSC line configuration [30].

Different power system studies on SSSC have been carried out to improve power system performance. An active approach to series line compensation was described in [80-84], where a synchronous voltage source, implemented by a gate turn-off thyristor (GTO) based voltage-sourced inverter was used to provide series compensation control. SSSC provides controllable voltage compensation independently of the magnitude of the line current over an identical capacitive and inductive range. A new method - non-linear control of SSSC to significantly improve the stability region of a power system - was proposed in [85]. It was observed that this method yields better result than that of linear control as used in previous research.

2.7.4 Distributed Static Series Controller (DSSC)

Distributed Static Series Compensator is a multiple low-rated, single phase VSC that is attached to the grid by single-turn transformers. The transformer uses the transmission line as its secondary winding, and it injects a controllable amount of voltage directly into the line. The voltage injected by this device is in quadrature with the current, to imitate capacitive and inductive impedance [86]. The DSSC is remotely controlled through wireless communication or by Power Line Communication (PLC) [87]. DSSC has a high reliability and its cost is relatively low. DSSC is a single phase device floating on transmission lines; it can be applied at any transmission voltage level since it does not require supporting phase-ground isolation, and requires no additional land for installation since the device is clamped onto the transmission lines. Figures 2.25 and 2.26 below show the configuration of a DSSC.

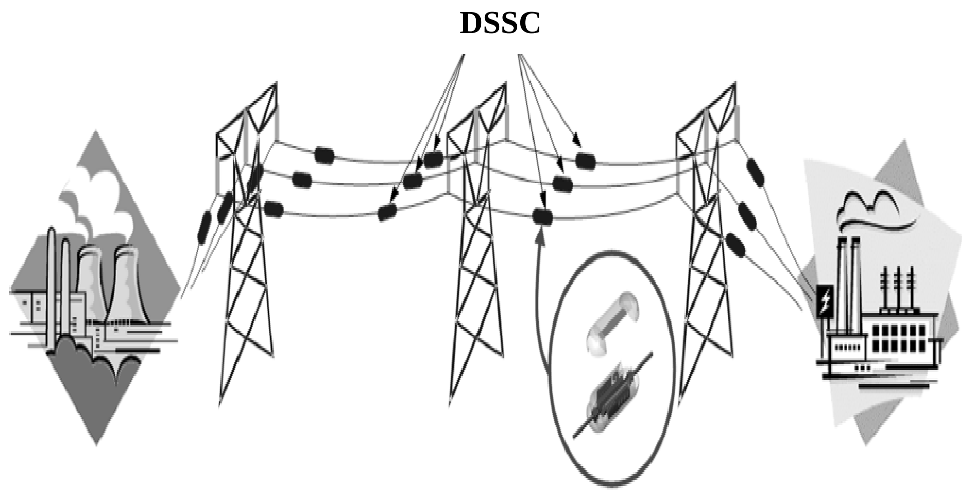

Figure 2.25 The DSSC modules clamped on a power line [87]

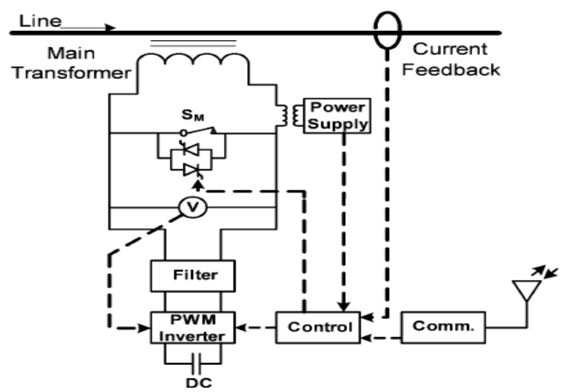

Figure 2.26 Circuit schematic of a DSSC [87]

2.8 Combined devices

Three devices are introduced in this section: the Phase Shifting Transformer (PST), the Unified Power Flow Controller (UPFC) and the Interline Power Flow Controller (IPFC).

2.8.1 Phase Shifting Transformer (PST)

The PST is a specialized transformer used to control the flow of active power in a three-phase electric power transmission network. Power flow through the grid in an AC transmission line is proportional to the sine of the difference in the phase angle of the voltage between the sending and receiving ends of the line. By connecting the transformer in a proper way, phase shift is obtained between the power source and the load [14]. Figure 2.27 below illustrates a simple circuit diagram of a PST constructed with two separate transformers; a variable tap exciter that controls the voltage amplitude and the other, a series transformer that insert voltage in the right phase angle thereby allowing division of power flow between lines and preventing overload [88].

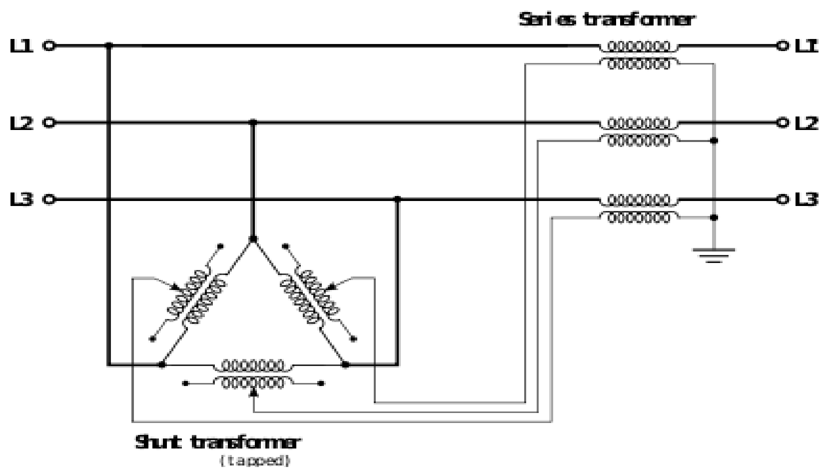

Figure 2.27 Simplified circuit diagram of a PST [88].

2.8.2 Unified Power Flow Controller (UPFC)

The Unified Power Flow Controller is a combination of Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC) which are linked by a common DC-link; this allow bi-directional flow of active power between the series and shunt output terminals of the SSSC and STATCOM respectively, and are controlled to provide real and reactive series line compensation concurrently without an external electric energy source [50]. The device with two converters of shunt and series transformer operates from a DC link provided by a DC storage capacitor as represented in figure 2.28.

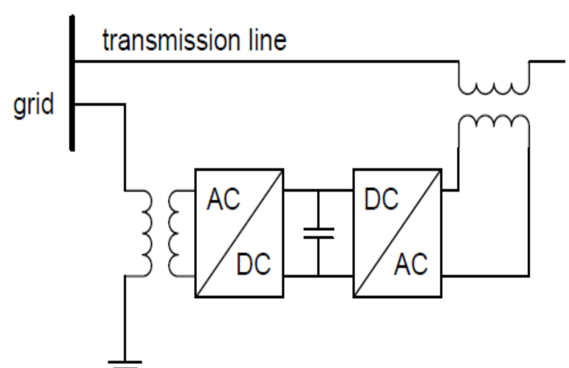

Figure 2.28 A simplified circuit diagram of UPFC [30].

The first converter provides the real power demand of the second converter at the common DC link from the AC power system. It can also generate or absorb reactive power at its AC terminal, which is not dependent on the active power that it transfers to the DC terminal. With proper control, it can execute indirect voltage stability at the input terminal of the UPFC by providing reactive power compensate for the transmission line. Converter two generates a voltage source at the basic frequency with variable amplitude and phase angle, which is injected into the AC transmission line by the series connected booster transformer. Therefore, the converter voltage output added in series with the line can be used for direct series compensation, voltage control, and phase shift. It has been experimentally proven that the UPFC can regulate the three control parameters of active power flow, reactive power flow, and voltage magnitude [89]. Two UPFC models were developed which have been linearized and incorporated into the Phillips-Heffron model [90]. It was observed that the UPFC needs to be equipped with a damping controller, otherwise the voltage control of the DC link capacitor may interact negatively with PSS system [91]. An intelligent damping controller for UPFC was developed to damp inter-area and local modes of oscillation for a multi-machine system. The controller effectiveness was demonstrated and its satisfactory success was reported in [92-94]. The use of supplementary controller of a UPFC to damp low frequency oscillation and enhance the dynamic stability in a weakly connected system was investigated in [95]. Two objective functions were proposed for the controller design problem, eigen-value based and time domain-based using PSO technique. Through non-linear time simulation, the effectiveness of the controller to damp low frequency oscillations was demonstrated and tested where it was concluded that the time domain based design improves the system greatly to respond under fault disturbance. It was demonstrate in [96] that UPFC has the capability to regulate power flow and minimize losses on transmission lines but due to its protection requirement and high voltage VSCs, UPFC is relatively expensive, which limits its practical application.

2.8.3 Interline Power Flow Controller (IPFC)

The Interline Power Flow Controller (IPFC) consists of two series converters in different lines that are inter-connected by a common DC link. Unlike other FACTS controllers that control the parameter of a single transmission line, the IPFC controls and compensates power flow in a multiple line transmission system as shown in figure 2.29.

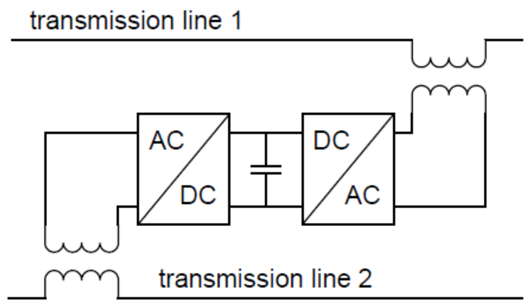

Figure 2.29 Interline Power Flow Controller configuration [30].

Both converters have the capacity to provide series reactive compensation on their line as a SSSC [97, 98]. The converters can provide active compensation just as they can exchange active power through a common DC link. This allows the controller to provide both active and reactive compensation for the transmission lines and thereby optimize the operation of a multi-line transmission system [99, 100]. Mathematical models of the IPFC and GUPFC (Generalized Unified Power Flow Controller) and their implementation in Newton Raphson power flow are reported in [101]. Numerical results based on the IEEE 30-bus, 118-bus and 300-bus systems were presented to demonstrate the performance of the Newton power flow algorithm with incorporation of the IPFC and GUPFC. In [102] a single machine-infinite bus model integrated with IPFC is used to investigate the damping control function of an interline power flow controller installed in a power system. It was concluded that IPFC provided perfect control of the system.

2.9 Power system stability

Power system stability can simply be defined as the ability of the system to maintain equilibrium under normal operating conditions, and also to return to the required state of equilibrium after it has been subjected to a high or low disturbance. A system can be said to be stable if the force of synchronization is able to overcome the force of disturbance; that is, system instability is the state of loss of synchronism. It has been established that stability is one of the major concerns when planning a power system, because as the load demand increases with time coupled with the ever growing size of interconnected systems in the region, it may become more difficult to maintain synchronism within the power system. Due to the expanding demand on the existing transmission network, in the absence of fresh investment to build new lines, there is ever increasing stress on the network. One of the consequences of this condition is the threat of instability following a disturbance or sudden load increase. It has been found that FACTS devices can effectively manage a stressed transmission network without forfeiting the system stability margin for better utilization. To analyze power system stability, the instability has been categorized into three main types – steady state stability, dynamic stability and transient stability.

i) Steady-state stability: This refers to the ability of a power system to return to a state of equilibrium after being subjected to disturbance. It is the maximum limit of the system to which power can be transferred without losing synchronism. Steady state stability is affected by the total load angle, the summation of the generator load angle, and the line load angle. If the load angle goes beyond 90^0, there will be instability in the system. So to prevent steady-state instability, the power system must be operated without excessive load angles to avoid the system from reaching its stability limit, even under disturbance.

ii) Dynamic stability: Dynamic stability refers to the ability of a power system to return to a state of equilibrium under operating conditions after experiencing a small disturbance for a short duration of time. The rotor of a machine tends to go out of step if dynamic instability is ignored.

iii) Transient stability: Transient stability of a power system is the ability of the system to attain synchronism when subjected to a severe transient disturbance. The disturbance may include a sudden load change in large loads, sudden line outage, or system fault.

2.10 Reasons for choosing STATCOM

It is a well-known fact that shunt compensator can be used to provide reactive power compensation on the grid. The shunt capacitor or shunt FACTS devices serve this purpose. These devices are very expensive [103, 104] as seen in Table 1 below. Comparing the cost of the shunt capacitor to the other shunt FACTS devices, it becomes apparent that it is relatively cheap to install and maintain and when it is connected to the grid, it provides the needed voltage stability, but it has a demerit of poor voltage regulation - voltage regulated by the shunt capacitor can become higher than the allowable voltage limit of 1.05 pu. STATCOM, being a VSC based device, converts input DC voltage into an output of AC voltage, by which means it compensates the active and reactive power needs of the system. One of the reasons for using STATCOM is that its compensating current does not depend on the voltage level of the transmission network at the point of connection, unlike SVC that experience lower compensating current as the voltage dips. It exhibits constant current characteristics when the voltage is less than the prescribed limit. [105]. To maintain the proper voltage level of a system, reactive power compensation is required, since imbalance reactive power can cause breakdown of the power system. STATCOM operation advantage can be applied to minimize and compensate for such reactive power imbalances. Due to its fast switching times offered by the IGBTs (self-commutating power semiconductor) of the VSC, STATCOM responds faster than SVC and its harmonic emissions are lower. STATCOM requires less space because of its elimination of large passive components; it requires less maintenance without the problem of loss of synchronism. In this dissertation, a STATCOM based on the VSC PWM technique is proposed to mitigate power loss.

Table 1: Cost comparison of shunt devices [105]

Shunt device	Cost (US $)
Shunt capacitor	8 / kvar
SVC	40 / kvar
STATCOM	50 / kvar

In this dissertation, a voltage source converter (VSC) PWM technique based STATCOM is proposed to mitigate power losses on a power transmission line. Although SVC and STATCOM seem similar in their fundamental basic operational principles, table 2 below show the different basic operational principles of both devices.

Table 2: Different basic operational principles of SVC and STATCOM [105]

SVC (Thyristor based shunt compensator)	STATCOM (VSC based shunt compensator)
SVC operates as a shunt connected to control reactive admittance	STATCOM functions as a shunt connected synchronous voltage source.
SVC does not provide active power compensation	STATCOM provide active power and reactive power compensation.

These differences account for STATCOM's superior functional characteristics for better performance and greater application flexibility than SVC. STATCOM increases flexibility and boosts power system performance, provides instant detection of voltage disturbance, and rapidly compensates by injecting leading or lagging reactive power. STATCOM helps utilities recover from system voltage collapse events and eliminates stability-related power transfer limitations, with advanced controls. More importantly, it is a cost effective solution with minimal footprint.

CHAPTER THREE: Modelling and Simulation

3.1 Test system description

This section presents the model and simulation of the case study, IEEE 14 bus test system. The IEEE 14-bus test system represents a simple estimation of the American Electric Power System [106]. It has 5 generators, 14 buses, 16 lines and 11 loads.

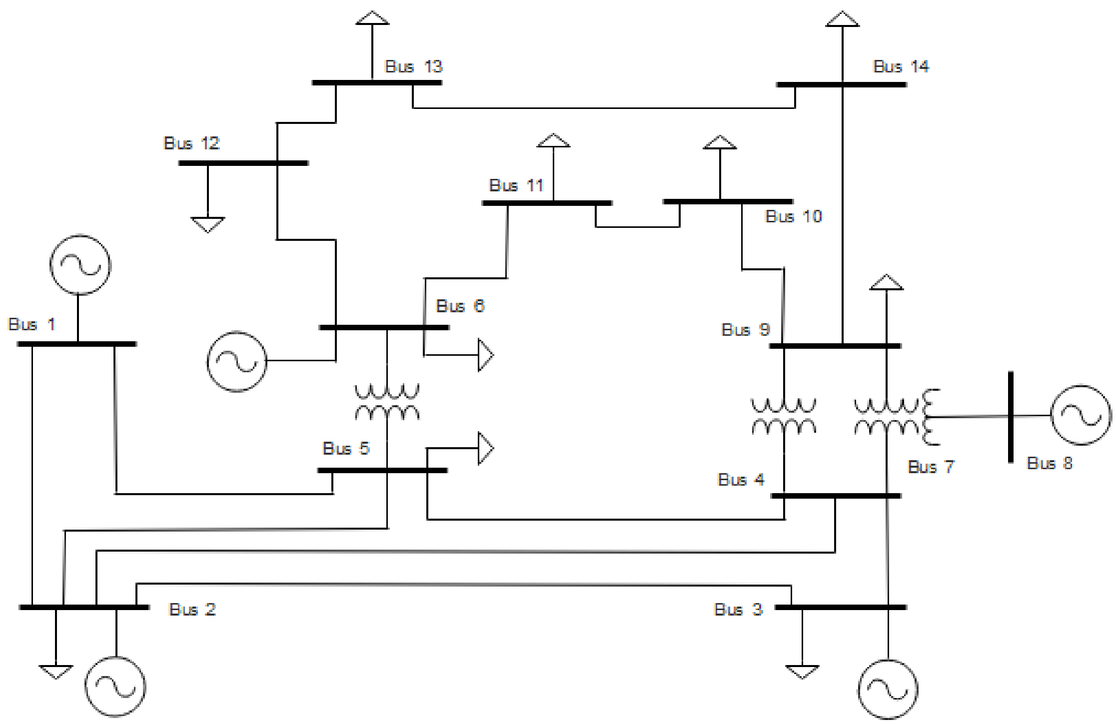

Figure 3.1 IEEE 14 bus test system model in PowerFactory

A brief introduction to the tool used for the modeling and simulation, DIgSILENT PowerFactory 2016 is given; thereafter the schematic diagram of the case study is presented with explanations of the associated consoles of the software. The power system is made of more than a few parts: generators, transmission lines, transformers, loads, and shunt components. These various parts of the power system will be implemented by way of modelling, simulation, and optimized for power flow calculation using DIgSILENT PowerFactory tool. The software is developed by DIgSILENT GmbH, a company in Germany; it is a time domain

Root Mean Square (RMS) and Electromagnetic Transients (EMT) simulation tool used in analyzing and controlling electrical power transmission and distribution in industrial power systems [107]. It is a computer system based engineering tool with an integrated and interactive interface used for optimal control and planning for power systems. The software provides an environment to implement operations of a real-life power system with all the calculations. Its huge single database support all power system functions – load flow, modal analysis, fault calculation/analysis (IEC, ANSI, VDE), protective relay coordination reliability, etc. – to be executed. The RMS simulation is centered on simplified electrical transient models, while EMT is based on extensive electromagnetic transient models. In RMS simulation, voltages and currents are defined as phasors, characterized by the magnitude and phase angle of the steady-state sinusoidal waveforms. Along these lines, currents and voltages in the system are found from algebraic equations as opposed to the EMT differential equation [108].

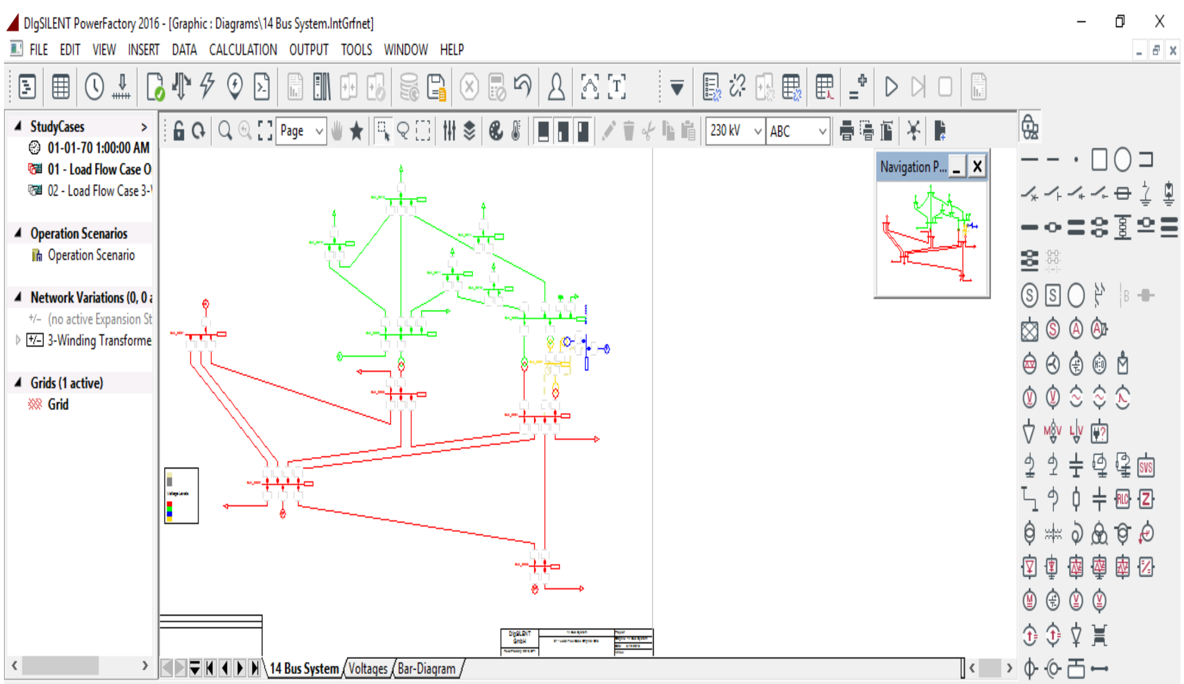

Figure 3.2 Screen grab for PowerFactory software

In RMS simulation voltage and current is found with this equation:

$$v = j\omega Li \qquad and \qquad i = j\omega Cv \tag{3.1}$$

The main differential equations that are considered are for the dynamic conduct of controllers also, mechanical transience, is the swing equation:

$$\omega J \frac{d\omega}{dt} = P_{mesh} - P_{el.} \tag{3.2}$$

In PowerFactory, RMS simulations can be performed in two diverse ways, utilizing either a symmetrical steady-state system model suitable for balanced system conditions, where the system is simplified to one phase, or a three-phase model suitable for unbalanced conditions. In EMT simulation, voltages and currents are denoted by their instantaneous values, and the dynamic behaviour of system components is additionally represented. As opposed to equation 4 above, the voltage and current in an EMT simulation would be connected as[107].

$$v = L\frac{di}{dt} \quad and \quad i = C\frac{dv}{dt} \tag{3.3}$$

To study transient stability and assessment of control frameworks, the RMS simulation mode is the best as the improved system models consider shorter computational times.

3.2 Modeling of power plant elements in PowerFactory

Electric power plants are equipped with synchronous generators, which are fitted with excitation regulators, speed governors, and a power system stabilizer (PSS) which is used for damping oscillations [109]. Power plants are connected directly to the transmission system via transformers with their control system, which are represented by standard models (synchronous generator models). PowerFactory was fundamentally developed to be utilized and operated in a graphical environment, where data is entered to draw the system elements. Access to the data is done from the design page by double-clicking on an object. An information dialog is shown and the user may then alter the information for that object. Normally when managing power systems, it is helpful to convert the values to the per-unit classification; in this study, per unit system is utilized.

3.2.1 Transmission lines

A transmission line is a constituent which is designed to convey electrical power from the power source over a long distance with minimum losses. To set up transmission lines for load flow investigation purposes, four parameters are required; resistance, inductance, capacitance, and conductance, these are the parameters which influence the transmission line capacity as a part of the power system. Resistance, inductance, and capacitance are only considered in this section while the conductance is dismissed on the grounds that its contribution to shunt admittance is negligible [110, 111]. Resistance or effective resistance represents the power losses in a conductor. The effective resistance of a conductor is the result of power losses (W) in the conductor divided by the current (A) square [112].

$$R = \frac{P_{losses}}{I^2} = \frac{\rho l}{A}\,[\Omega] \tag{3.4}$$

Where

R: Resistance of a conductor [Ω]

P: Resistivity of the conductor [Ωm]

ℓ: Length of the conductor [m]

A: Cross section of the conductor [m^2]

The inductance of the line is measured by the induced electrical voltage compared to the rate of electric current change [112]. It is an electrical property which represents the flux linkage in conductors.

$$L = \frac{\lambda}{I} \tag{3.5}$$

Where:

L: Inductance [H]

I: Current [A]

λ: Instantaneous flux linkages [Wb]

The line capacitance is characterized as the charge on the conductors which is the result of the voltage difference between the conductors of the transmission line and to ground [112]

$$C = \frac{q}{v} \tag{3.6}$$

Where:

C: Capacitance [F]

q: Charge on the conductor [C]

v: Potential difference between conductors [V]

These three basic line parameters are measured based on unit length, Ω/km for resistance, mH/km for inductance and μF/km for capacitance. The parameters are implemented within the PowerFactory tool based on the lumped parameter model which reduces a transmission line to a number of discrete 'lumps' and assumes that electrical differences inside each lump are neglected. This is an estimation method to represent its parameters (R, L, C) for load flow and transient analysis, as shown in figure 3.3.

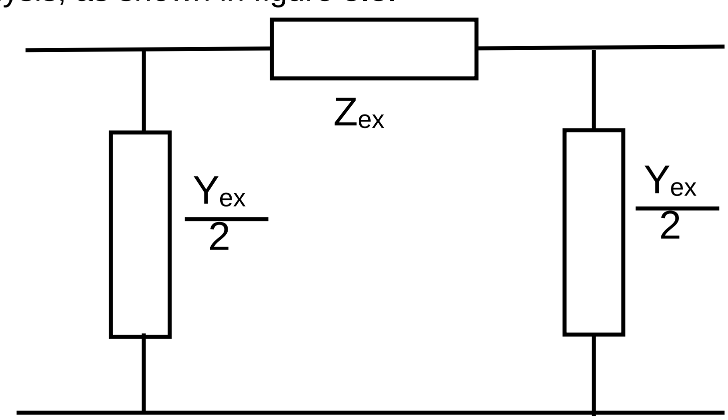

Figure 3.3 PowerFactory π-equivalent circuit for a transmission line [113]

The impedance Z_{ex} and Y_{ex} of the PowerFactory π-equivalent used are calculated according to equations 3.7 and 3.8. Both equations are derived from the matrix representation of the current and voltage magnitudes at the sending and receiving end of the line shown below in equation 3.9.

$$Z_{ex} = z_s \sinh \gamma L \tag{3.7}$$

$$Y_{ex} = \frac{2}{z_S}\tanh\frac{\gamma L}{2} \tag{3.8}$$

Where:

Z = the series impedance,

Y = the shunt admittance and

L = the length of the line.

Propagation constant: $\gamma = \sqrt{ZY}$ and

Surge impedance: $Z_S = \sqrt{\frac{Z}{Y}}$

$$A = \cosh\gamma L$$

$$B = -Z_S \sinh\gamma L$$

$$C = \frac{-1}{Z_S}\sinh\gamma L$$

$$D = \cosh\gamma L$$

$$\begin{bmatrix} v_r \\ i_r \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} v_s \\ v_r \end{bmatrix} \tag{3.9}$$

Figure 3.4 presents the equivalent circuit of a lumped parameter model of a balanced three-phase line in PowerFactory.

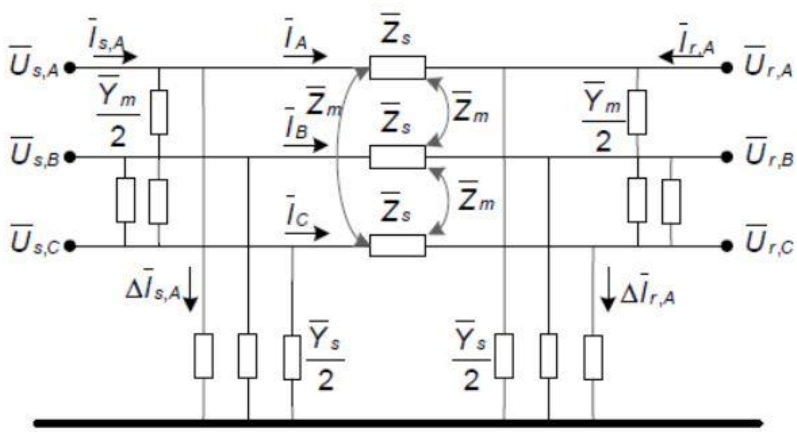

Figure 3.4 Equivalent circuit of a lumped parameter model of a balanced three-phase line in PowerFactory.

Where a, b and c represent the three-phase of the sending and receiving end of the line and Y_s and Y_m is the total of the admittance connected to the corresponding phase and negative value of admittance between two phases respectively. The data for the line model are presented in Table 3.

Table 3: IEEE 14 bus test system line data

Line number	From Bus	To Bus	Resistance (pu)	Reactance (pu)	Half susceptance (pu)	Transformer Tap
1	1	2	0.01938	0.05917	0.0264	1
2	1	2	0.09498	0.0219	0.25581	1
3	1	5	0.05403	0.22304	0.0246	1
4	2	3	0.04699	0.19797	0.0219	1
5	2	4	0.05811	0.17632	0.0187	1
6	2	5	0.05695	0.17388	0.017	1
7	3	4	0.06701	0.17103	0.0173	1
8	4	5	0.01335	0.04211	0.0064	1
9	6	11	0.09498	0.1989	0	1
10	6	12	0.12291	0.25581	0	1
11	6	13	0.06615	0.13027	0	1
12	9	10	0.03181	0.0845	0	1
13	9	14	0.12711	0.27038	0	1
14	10	11	0.08205	0.19207	0	1
15	12	13	0.22092	0.19988	0	1
16	13	14	0.17093	0.34802	0	1

3.2.2 Power transformers

The power transformer is the linkage between the generators and the transmission lines in a power system; likewise it links the transmission and distribution systems by transforming the system voltage level. There are two categories for system analysis, that is, two winding and three winding transformers with tap changer. To actualize transformer models in PowerFactory, nine parameters are required to model it; nominal voltages at primary and secondary side (V_1, V_2), rated power (S), operation frequency (f), connection configuration, short circuit voltage, copper losses, no load current and no load power losses.

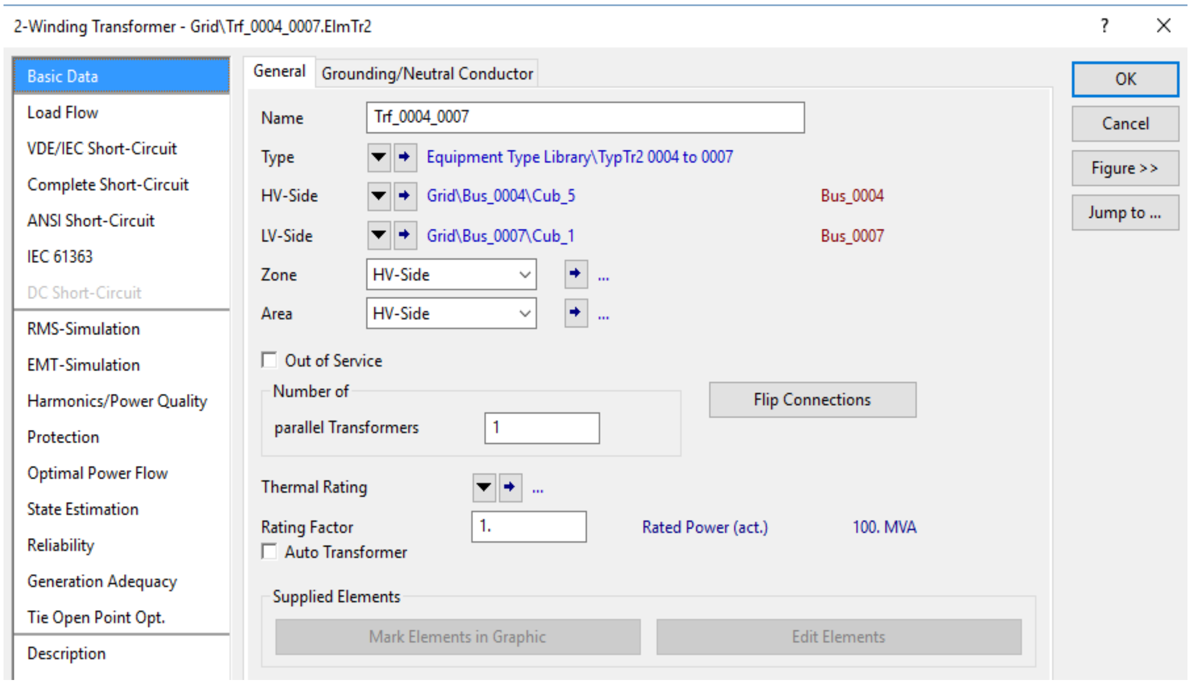

Figure 3.5 Power Transformer model in PowerFactory

3.2.3 Loads

In power system, loads characterize the electric energy consumed by the end users and the losses in the system. This can be Y- load (unbalanced or star-connection load), I- load (balanced current load) or P-Q load (constant active and reactive power load). For complex load models, Y- and I- loads are considered, which are not utilized in this case study. In a power system, electrical loads comprise of different diverse sorts of electrical devices, from lamps and room heaters to extensive arc furnaces and motors. PowerFactory utilizes a general load model and a complex load model. The complex load model is fundamentally made to be utilized as an industrial load where induction motors are utilized.

$$P = P_0\left(a_P\left(\frac{v}{v_0}\right)e^{a1} + b_P\left(\frac{v}{v_0}\right)e^{b1} + (1 - a_P - b_P) * \left(\frac{v}{v_0}\right)e^{a1}\right) \qquad (3.10)$$

$$Q = Q_0\left(a_Q\left(\frac{v}{v_0}\right)e^{a2} + b_Q\left(\frac{v}{v_0}\right)e^{b2} + (1 - a_P - b_P) * \left(\frac{v}{v_0}\right)e^{c2}\right) \qquad (3.11)$$

The general load model for load flow calculation is characterized by the equation (3.10) and (3.11). The equations portray the load as voltage dependent. The parameters are characterized as $1-a_P-b_P=c_P$ and $1-a_Q-b_Q=c_Q$. Where a and b are the load transfer fraction. Figure 3.7 presents the load model used in this dissertation for the balanced load-flow analysis. The loads were populated with data on appendix 4.

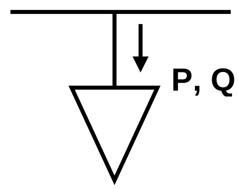

Figure 3.6 Symbol of the Load model used for balanced load flow in PowerFactory

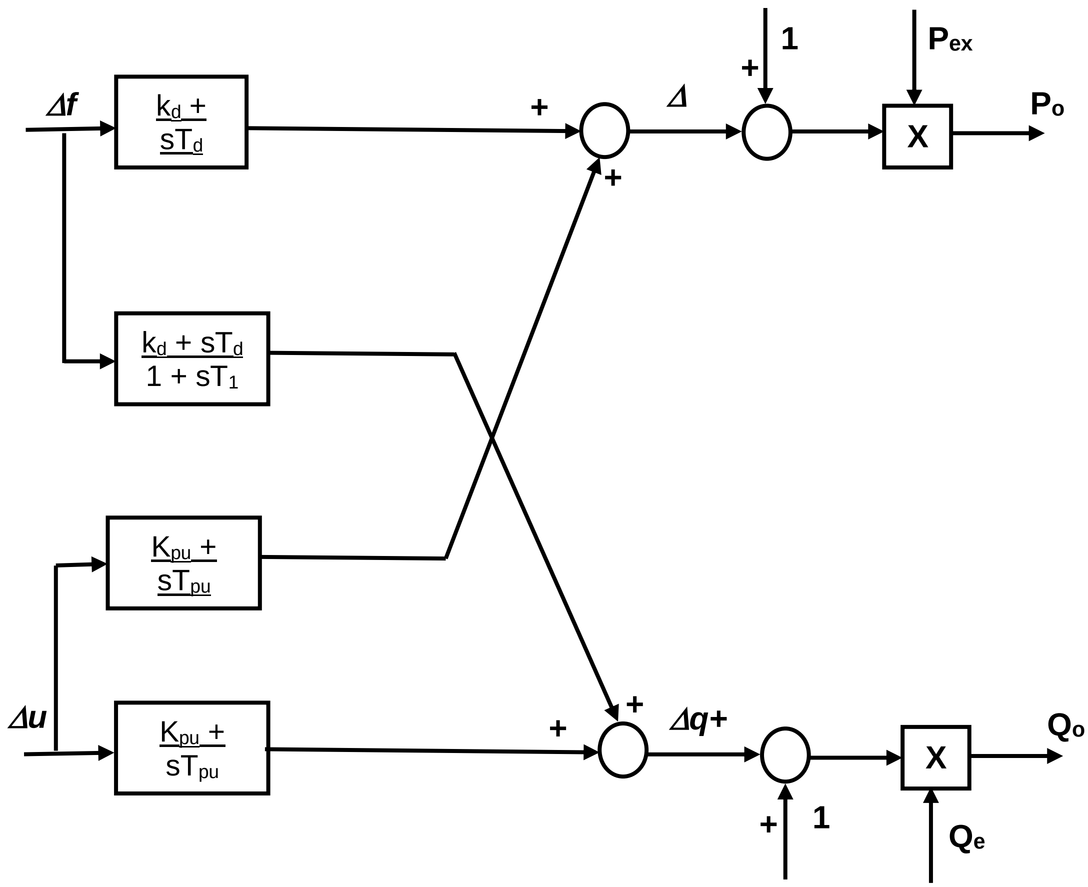

Figure 3.7 Signal block diagram of the load model.

3.2.4 Generators

There are usually several generators in a power plant, which inject electrical power into the power system. Synchronous and asynchronous generators are utilized for three phase power generation. Generators transform the mechanical energy generated by the turbine to electrical energy [9]. Asynchronous generators are usually utilized for small scale power generation, such as wind power transformation systems, while synchronous generators are utilized for huge power plants like conventional power plants. PowerFactory has an inbuilt model of generators; for synchronous and asynchronous mode, the primary parameters required are: nominal generation voltage (V), nominal power (P), operation frequency (f) and its arrangement configuration. Moreover, turbine parameters like time constant, saturation and impedances are likewise required for the modelling [10]. The generators were populated with data on appendix 5.

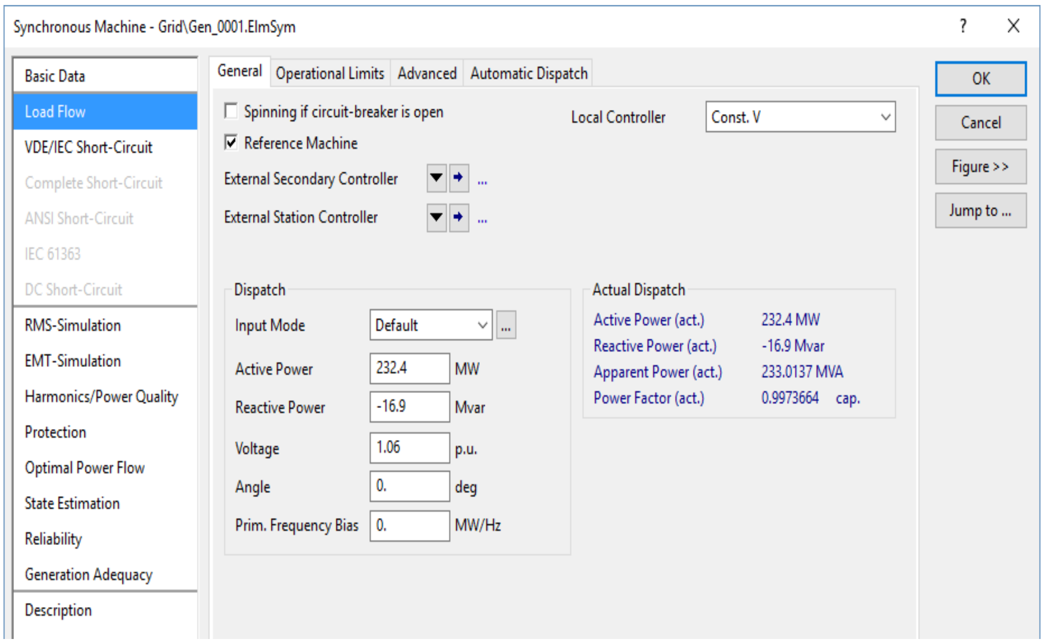

Figure 3.8 Generator model in PowerFactory

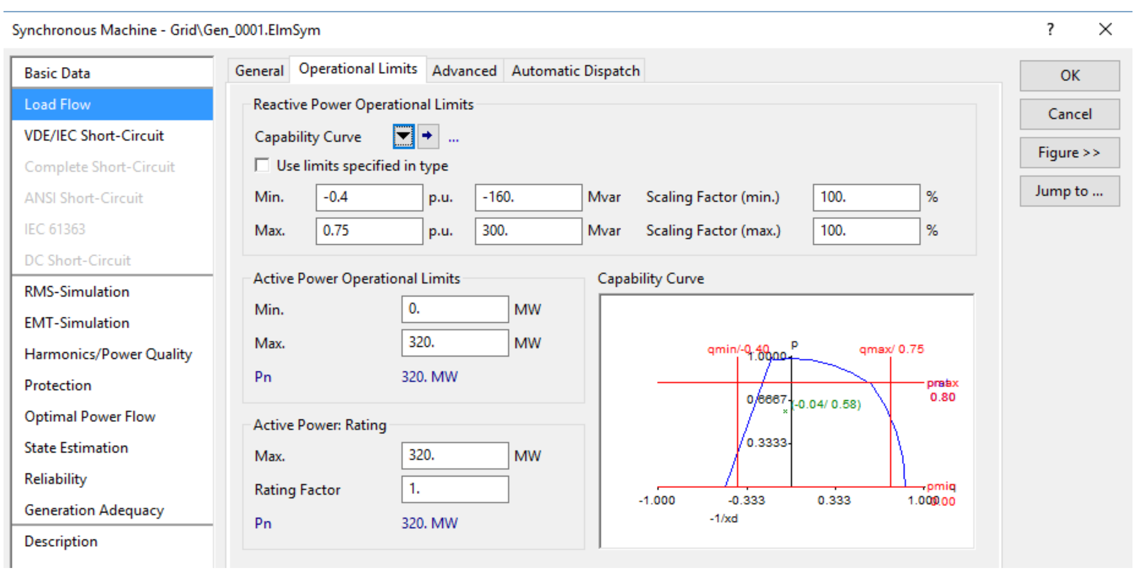

Figure 3.9 Generator load flow data in PowerFactory

3.3 Selection criteria and model of overhead lines and cables

In modeling the transmission line with PowerFactory v15, international standards and recommendations were selected on the Basic Options page of the software, then configured by defining the safety margin for the cable current capacity in a percentage. Similarly, overhead lines were utilized for various factors such as costs and capacity to convey more power in contrast to cables that have the same diameter. The determination of transmission line cross segment relies upon several few criteria: To start with, the chosen transmission line must have the capacity to convey at any rate maximum current that could flow at the nominal operating condition, with consideration given to safety factors. Also, the determination ought to fit to global benchmarks and be accessible. Costs and lifespan are additionally vital for expensive and long life time applications like a power transmission system. Equation 3.12 is considered in the selection of a transmission line cable. Figure 3.10 below is the system interface used for modeling the transmission line cable.

$$l_l = \frac{S}{\sqrt{3} * V_{l-l}} \tag{3.12}$$

Where:

I_l: line current [A]

V_{l-l}: line to line voltage [V]

S: Apparent power [VA]

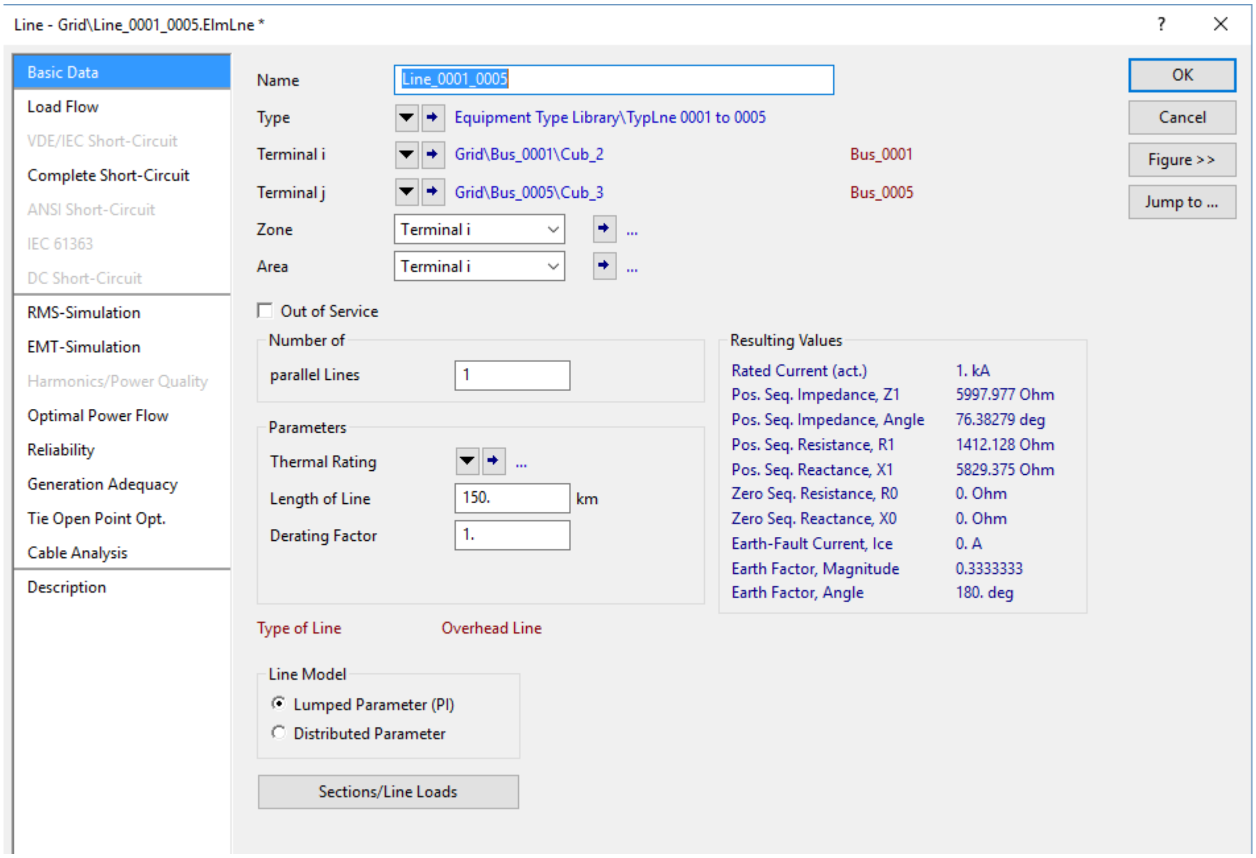

Figure 3.10 Grid line model in PowerFactory

3.4 Modeling STATCOM and its controllers

A ±50 Mvar STATCOM was modeled for this project. The size of the STATCOM device was determined based on different parameters which is governed by the amount of reactive power to be injected into the system. The grid summary of the case study obtained on PowerFactory was used to determine the capacity of STATCOM to be incorporated on the transmission system is presented in Appendix 1. A Voltage Source Converter (VSC) STATCOM was modeled for this project with its decoupled control of active and reactive power switch between the VSC and the power system. This is essential to control the DC capacitor voltage for the duration of transients, for the exchange of reactive power. The figures below illustrate a STATCOM connected to a power system, it is made up of a shunt converter that is modeled as a controllable voltage source (e), a connection filter (l) and a coupling transformer (T), which was modeled as a resistance and inductive impedance respectively. The current injected into the system is controlled by the converter.

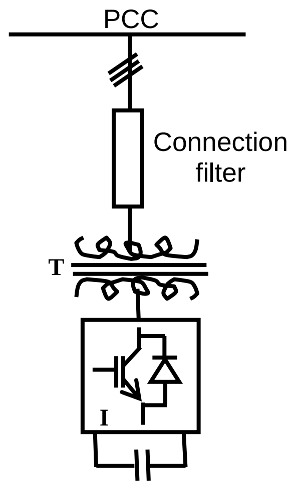

Figure 3.11 Configuration of a STATCOM

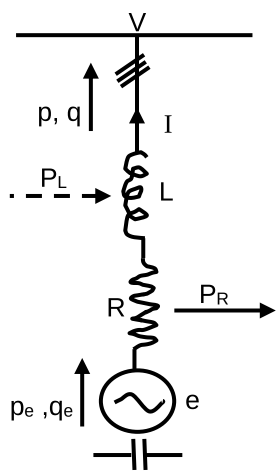

Figure 3.12 Simplified model of STATCOM connection to AC system in PowerFactory

From figure 3.12, p and q are the active and reactive power interchange by the STATCOM at the point of common coupling (PCC). P_R is the power loss in the filter resistance. P_L is the power consumed in the filter and transformer inductance while p_e and q_e are the active and reactive power exchanged by the converter with the AC system. The DC output power of the converter feeds the PWM-VSC where it is transformed to AC power before it is injected into the transmission system. The d-q transformation reference frame performs device control by utilizing Park's transformation, which defines the three phase variable of the modeled STATCOM. The PowerFactory equation for the controller is in Appendix 2. Taking the d-axis voltage vector $\underline{v}_d$ to match with the positive sequence voltage vector $\underline{v}$, considering a balanced three-phase operation makes equation 3.13 and 3.14 valid.

$$v_d = |v_d| = |v| = v \tag{3.13}$$

$$v_q = |v_q| = 0 \tag{3.14}$$

Where v_d, v_q and v are the d-axis, q-axis and terminal voltage magnitudes [pu], respectively and v_q is the q-axis voltage vector. Usually, active and reactive power exchanged at the grid side of the converter is described by equation 3.15 and 3.16.

$$P = V_i\ (i_d\ cos\theta_i + i_q \sin\theta_i) = v_d i_d + v_q i_q \tag{3.15}$$

$$Q = V_i\ (i_d\ sin\theta_i + i_q \cos\theta_i) = -v_d i_q + v_q i_q \tag{3.16}$$

In the equation above, i_d and i_q are the controller d-axis and q-axis output current [pu].Relating equation (3.13) and (3.14), equation (3.15) and (3.16) can be rationalized to:

$$P = v_d i_d \tag{3.17}$$

$$Q = -v_d i_q \tag{3.18}$$

Therefore, by controlling the d and q components of the current injected into the transmission network i_d and i_q, active and reactive power (P and Q) were controlled independently. The controllable reactive power of STATCOM allows for a rapid control of bus voltage and power factor at the load end of the system. The STATCOM control strategy considered as far as Pulse Width Modulation (PWM) control of VSC in this project, dependent on multi-pulse VSC. The efficiency of a VSC relies on upon the best possible control strategy; that is the most vital parameter to reduce the switching losses. The control strategies applied in this VSC is sinusoidal PWM (SPWM), which is a subordinate of standard PWM strategy [114]. STATCOM essentially comprises of a three-phase step-down transformer and a three-phase PWM rectifier/inverter; that is, a three-phase bridge, a three-phase filter, line inductors, a controller, and a DC link capacitor is utilized as a DC power source for the three-phase PWM rectifier/inverter. PWM Voltage Source Converter (VSC) offers several great features, for example, power factor correction, bi-directional power flow, and DC voltage regulation capabilities. Figure 3.13 show the circuit model of PWM.

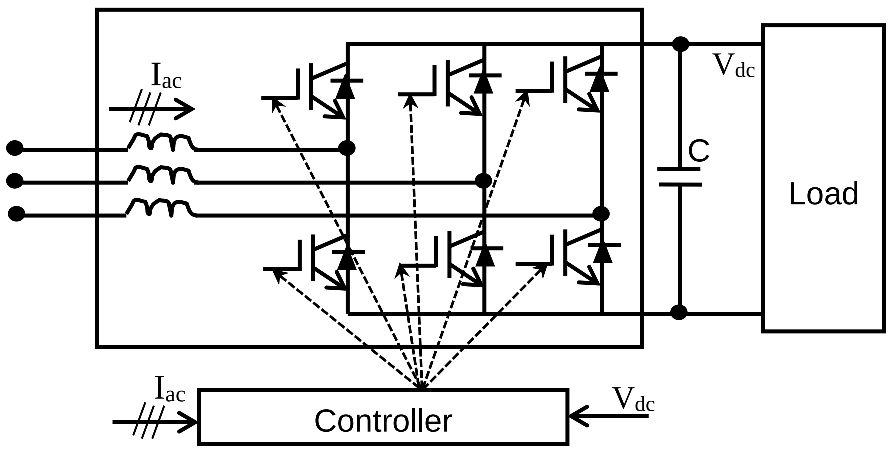

Figure 3.13 Three phase PWM Rectifier/Inverter

The block diagrams for the controllers and the model interface are presented in the figures below.

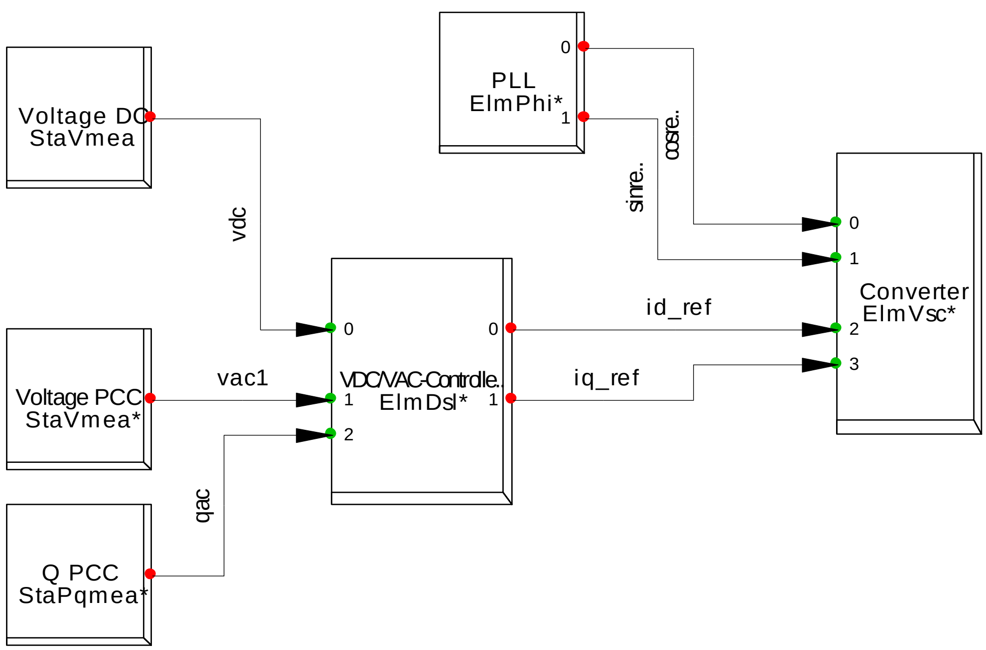

Figure 3.14 Block diagram of the STATCOM controller

Controller Block Diagram:

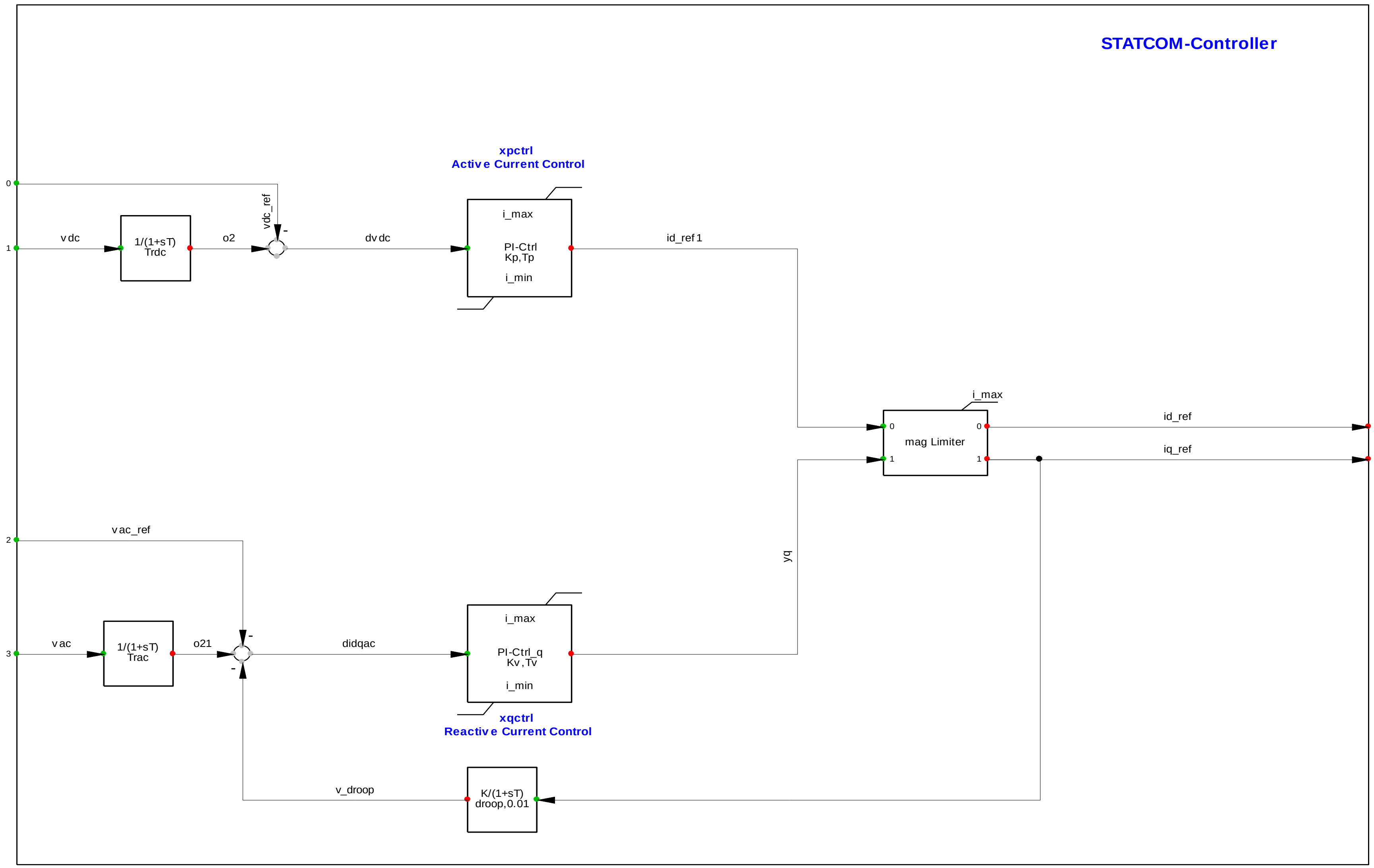

Figure 3.15 DSL implementation of the STATCOM controller

3.5 Location of STATCOM

There are a range of strategies utilized to optimize the designation of the device in power systems in literature. These strategies are categorized into the following classification [115]:

- Loss sensitivity analysis
- Cost analysis using Optimal Power Flow (OPF)
- Heuristic optimization techniques
- Continuation Power Flow (CPF) and
- Voltage stability analysis using modal analysis.

The voltage stability analysis was used to determine the area in the power system which needs reactive power compensation most. Simulation results demonstrate that there is a need for reactive power compensation at the section of the system with much load, since is it known that STATCOM gives effective voltage support at the bus to which it is connected. The device was connected to bus 14, which has the least voltage magnitude on the system. The location of the device helped to minimize the grid losses and increase maximum active power transfer.

CHAPTER FOUR: Result and Analysis

4.1 Load flow analysis

Load flow analysis remain a principal tool used in power system studies. The planning and operation of a power system requires such computations, to dissect the steady-state performance of the power system under different working conditions, and to consider the impacts of changes in equipment configuration. Load flow solutions produced for these reasons, were analyzed utilizing computer programs. The fundamental aim of load flow performance is to generate the load power utilization at all buses of a known electric power system, and power (active and reactive) at every bus.

The importance of load flow analysis in electrical power engineering includes numerical investigation of a power system. Unlike conventional circuit analysis, load flow typically uses streamlined notation; for example, a one-line diagram and per unit system, with focus on different types of AC power parameters. The important data obtained from the load flow study are the magnitude and phase angle of the voltage at each bus and the active and reactive power flowing in each line. In this work, DIgSILENT PowerFactory v15 was used to simulate the test system and a load flow study utilizing Newton-Raphson method carried out

4.1.1 Motivation for load flow analysis

By utilizing load flow study results, the compliance of system power and voltages to the allowable maximum and minimum limits at different points in the network under various operating conditions can be determined. The purpose of load flow analysis is to determine the following:

- Voltage magnitude at the buses.
- Line flow of active power, reactive power, current, and power factor in each section of the power system.
- Power losses in every line segment.
- The total power losses in the system.

The simulation and results analysis was based on a system rating of ±100 MVA with bus one set as the reference bus. With a specific objective to verify the model and outline the effect of STATCOM, six distinctive operating scenarios were considered as stated below. The system load data were increased in steps of 10%, up to 40% with and without STATCOM, to ascertain the loss mitigating effect of STATCOM on the grid in the event of sudden load increases in the system. The results of the power flow of each scenario were obtained and compared with the initial power flow result of standard load on the system. The different scenarios are detailed below:

Scenario 1: The power system with the normal load at all the load buses was considered as the standard operating condition, and the Newton-Raphson load flow was carried out with loading factor value equal to one without STATCOM as the base case.

Scenario 2: Scenario 1 with STATCOM.

Scenario 3: Scenario 1 with 10% increase in load with and without STATCOM.

Scenario 4: Scenario 1 with 20% increase in load with and without STATCOM.

Scenario 5: Scenario 1 with 30% increase in load with and without STATCOM.

Scenario 6: Scenario 1 with 40% increase in load with and without STATCOM.

4.2 Load flow study without STATCOM

For the load flow computation, the simulation converged without a mismatch in the iterative procedure on the third iteration. Making use of the Output Results tool of PowerFactory v15, the summary of the system for steady-state operation was obtained and it presented in table 4. The voltage profile for all the bus of the transmission network is shown in figure 4.1.

Table 4 Load flow summary for scenario one

System	Active Power (MW)	Reactive Power (Mvar)
Generation	272.38	75.42
Load	259.00	73.50
Grid Losses	13.38	23.15

Table 5 Load flow calculation bus voltage result without STATCOM

Bus number	Voltage (pu)
1	1.05
2	1.04
3	1.001
4	0.9641
5	0.9612
6	1.0006
7	1.00
8	1.05
***9**	**0.9481**
10	0.9607
11	0.9742
12	0.9858
13	0.9707
***14**	**0.8974**

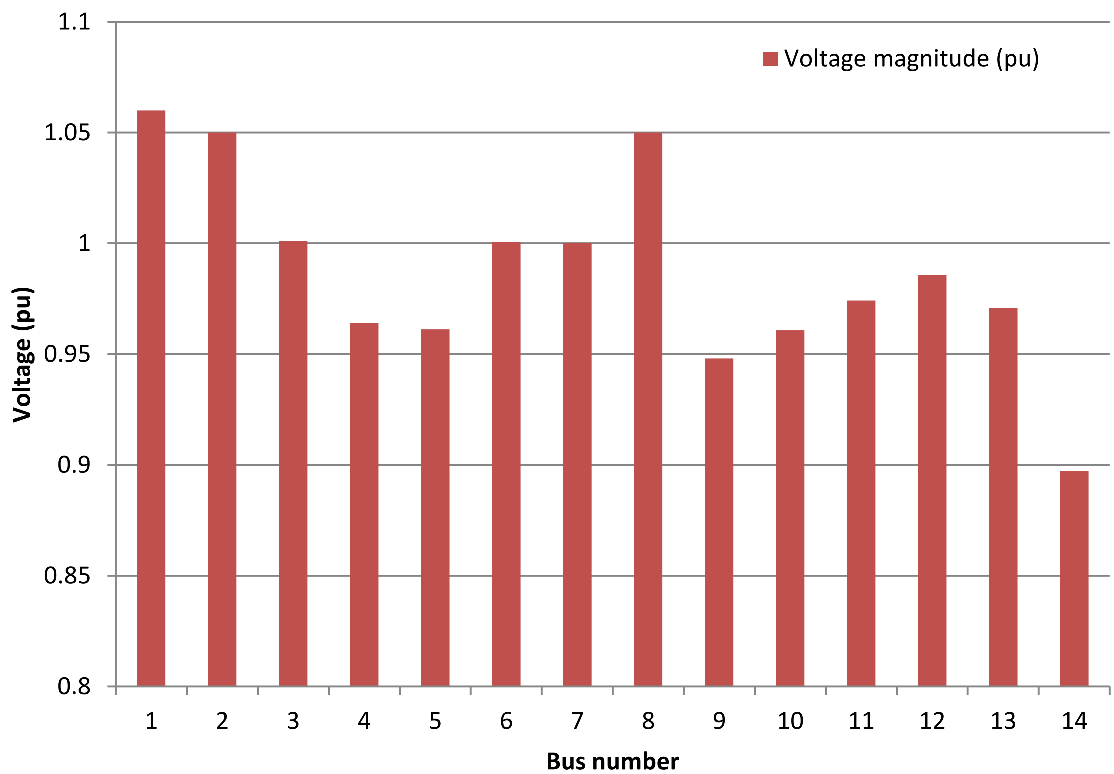

Figure 4.1 Magnitude and Voltage profile of the test system before STATCOM

From the power flow analysis, which is presented in figure 4.1, it is observed that buses 9 and 14 are the most critical buses. The system voltage profile and stability should be enhanced and maintained at the specified limits (0.95 and 1.05) by reducing the line losses in the system. Also, the steady state operational performance of the system in reference to the minimum and maximum voltage magnitude at the buses and power loss before the STATCOM device was connected for all the five scenarios are presented in table 6 below.

Table 6 Comparison of results before STATCOM placement

System	Before STATCOM placement		
	V_{Min}/V_{Max}	P_{Loss} (MW)	P_{Loss} (Mvar)
At normal load	0.8974/1.05	13.38	23.15
At 10% load increase	0.8965/1.05	14.72	27.79
At 20% load increase	0.8957/1.05	17.39	35.16
At 30% load increase	0.8947/1.05	19.73	39.73
At 40% load increase	0.8939/1.05	22.69	48.87

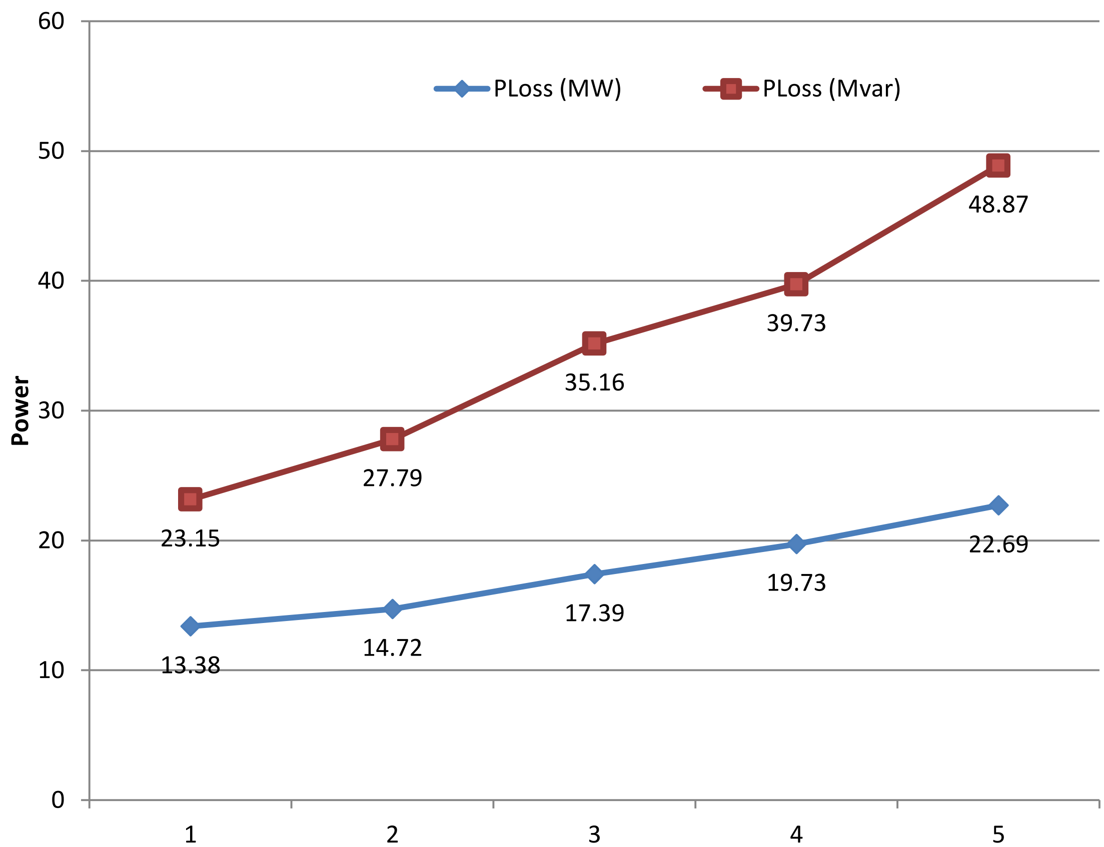

Figure 4.2 Total active and reactive power loss without STATCOM at varying load

It is observed from the table 7 that the system bus voltage without STATCOM has 2 buses with voltage below the allowable limit of 0.95 p.u. STATCOM was connected to bus 14 to mitigate the system power loss and improve the voltage at all the buses. Figure 4.2 presents the graph of the total active and reactive power losses in the system with normal load and at the increased load scenario from 10% to 40%.

Table 7 Calculation and comparison of critical bus before STATCOM placement

Bus number	At normal load	At 10% load increase	At 20% load increase	At 30% load increase	At 40% load increase
1	1.06	1.06	1.06	1.06	1.06
2	1.05	1.05	1.05	1.045	1.045
3	1.001	1.01	0.9998	0.9997	0.9996
4	0.9641	0.9636	0.9630	0.9627	0.9619
5	0.9612	0.9674	0.9669	0.9662	0.9657
6	1.0006	0.9996	0.9994	0.9993	0.9992
7	1.000	0.9587	0.9585	0.9585	0.9584
8	1.05	1.05	1.05	1.05	1.05
9	**0.9481**	**0.9473**	**0.9468**	**0.9462**	**0.9456**
10	0.9607	0.9597	0.9591	0.9584	0.9579
11	0.9742	0.9677	0.9675	0.9674	0.9673
12	0.9858	0.9848	0.9846	0.9845	0.9844
13	0.9707	0.9597	0.9595	0.9595	0.9594
14	**0.8974**	**0.8965**	**0.8957**	**0.8947**	**0.8939**

4.3 Load flow study with STATCOM

When STATCOM was connected to the test system at bus 14, the following results were obtained. It was observed that the voltage magnitude profile increased considerably from when the device was not connected. All through the variation of the loading factor of the system, STATCOM provided a noticeable difference in all cases.

Table 8 Load flow of bus voltage after STATCOM placement

	λ=1	
Bus number	Before STATCOM	After STATCOM
1	1.06	1.06
2	1.04	1.045
3	1.001	1.01
4	0.9684	0.9901
5	0.9681	0.9817
6	1.0006	1.031
7	1.000	1.01
8	1.05	1.05
9	**0.9481**	**1.0073**
10	0.9507	1.0019
11	0.9742	1.0065
12	0.9858	0.9973
13	0.9707	0.9865
14	**0.8974**	**1.0057**

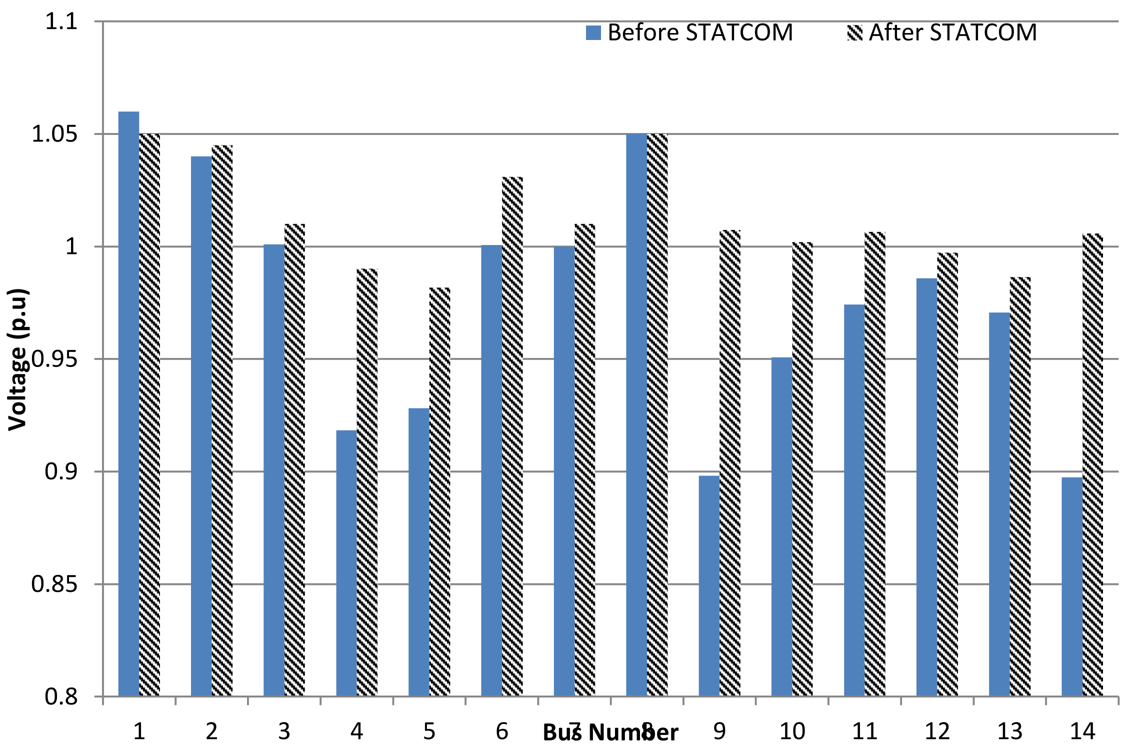

Figure 4.3 Comparison of bus voltage after STATCOM placement at normal load

When the device was connected to bus 14, which is the weakest bus, from figure 4.3 it was seen that the voltage magnitude of all the buses of the system had significantly improved.

Table 9 Comparison of bus voltage for varied load after STATCOM placement

	λ= 1.1		**λ=1.2**		**λ=1.3**		**λ=1.4**	
Bus Number	**Without STATCOM**	**With STATCOM**	**Without STATCOM**	**With STATCOM**	**Without STATCOM**	**With STATCOM**	**Without STATCOM**	**With STATCOM**
1	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
2	1.05	1.05	1.05	1.05	1.045	1.05	1.045	1.05
3	1.00	1.01	0.9998	1.0035	0.9997	1.0029	0.9996	1.0021
4	0.9827	0.9964	0.9811	0.9829	0.9609	0.9668	0.9506	0.9598
5	0.9274	0.9714	0.9269	0.9719	0.9267	0.9709	0.9264	0.9699
6	0.9996	1.01	0.9994	1.01	0.9993	1.01	0.9992	1.01
7	0.9587	0.9905	0.9585	0.9878	0.9585	0.9869	0.9584	0.9859
8	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
9	**0.8973**	**0.9841**	**0.8968**	**0.9832**	**0.8967**	**0.9813**	**0.8966**	**0.9799**
10	0.9497	0.9875	0.9496	0.9864	0.9495	0.9855	0.9494	0.9851
11	0.9677	0.9705	0.9675	0.9696	0.9674	0.9684	0.9673	0.9675
12	0.9848	0.9964	0.9846	0.9955	0.9845	0.9943	0.9844	0.9931
13	0.9597	0.9856	0.9595	0.9847	0.9595	0.9835	0.9594	0.9823
14	**0.8763**	**0.9947**	**0.8751**	**0.9938**	**0.8746**	**0.9926**	**0.8737**	**0.9917**

From table 9, it is evident that the voltage of all the buses improved when STATCOM was in operation, despite increasing the load up to 40% above the standard load margin, especially when comparing all the critical buses of the system to when the device was not connected. Figures 4.4 to 4.11 present the graphical comparison of before STATCOM and after STATCOM operation of the system.

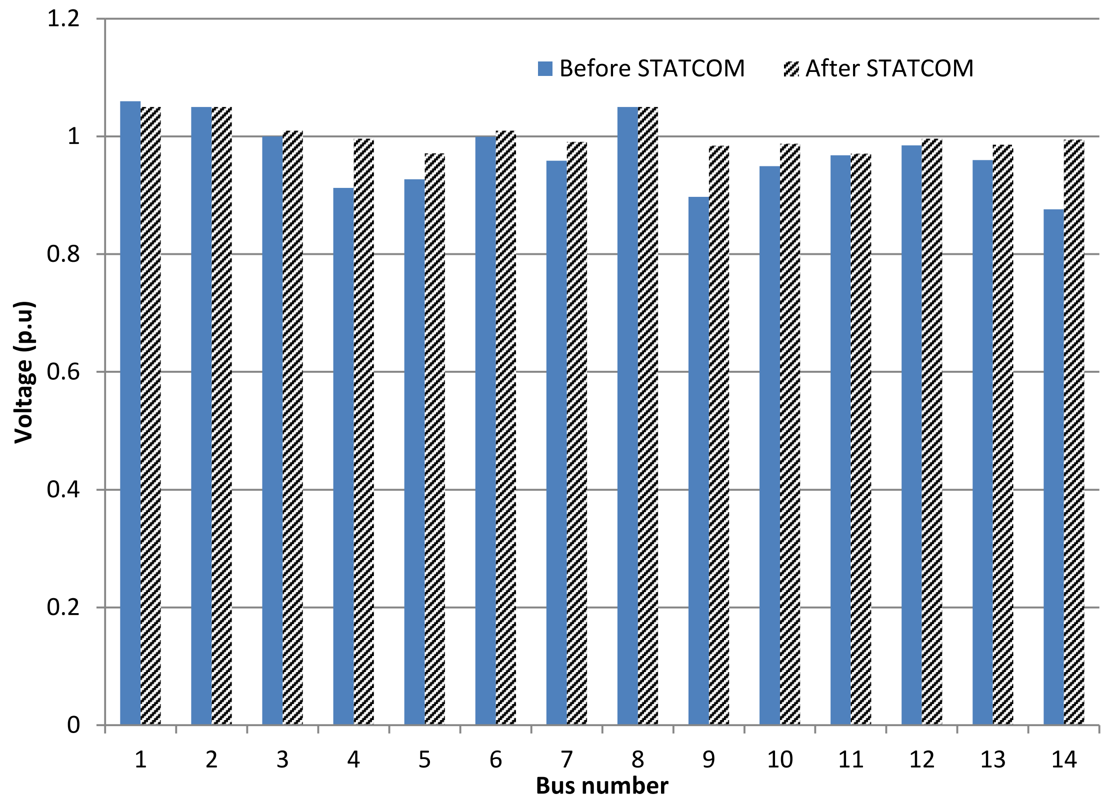

Figure 4.4 Comparison of bus voltage after STATCOM placement at 10% increased load

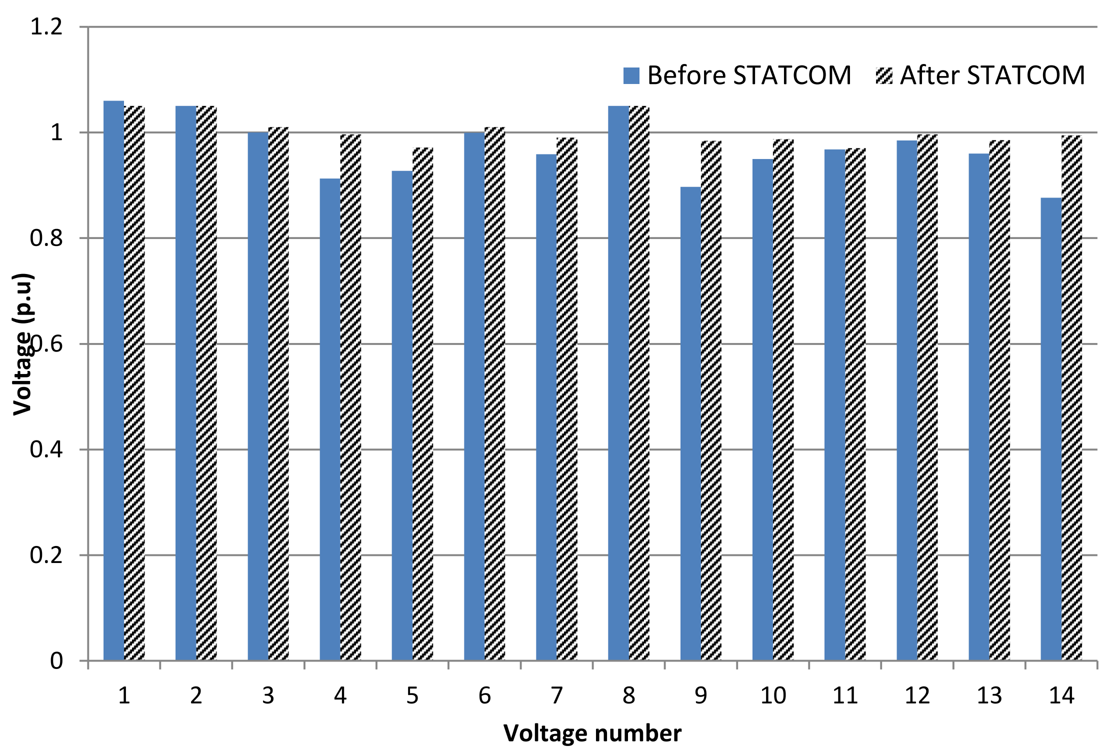

Figure 4.5 Comparison of bus voltage after STATCOM placement at 20% increased load

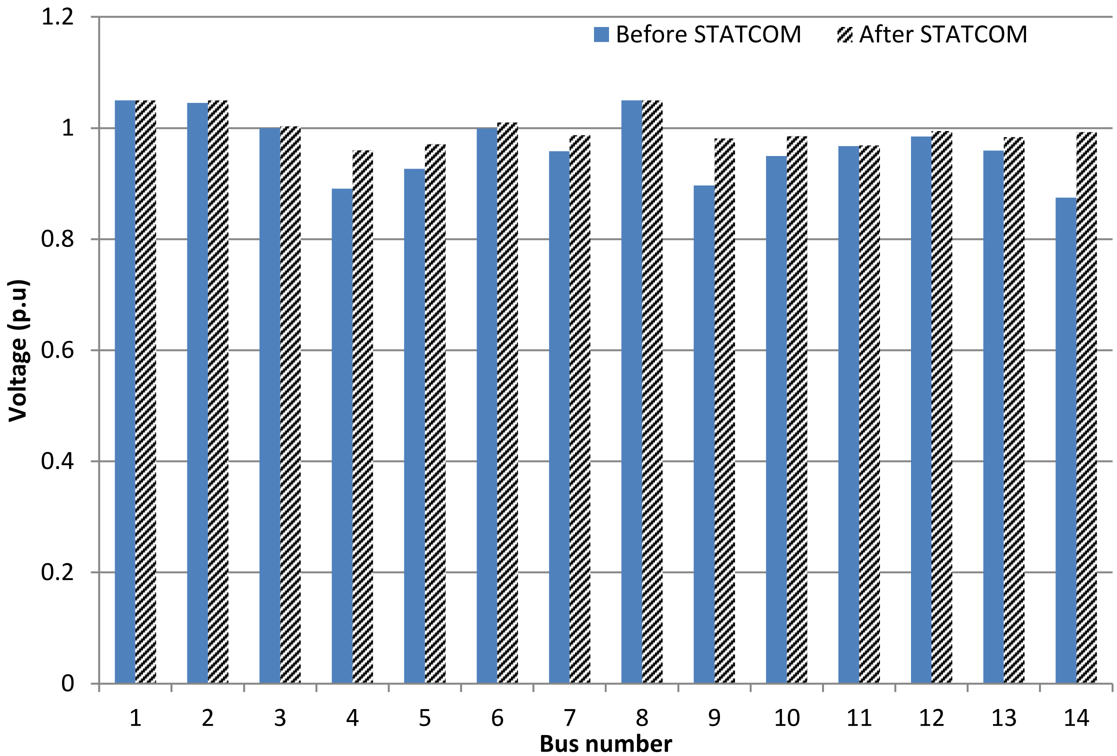

Figure 4.6 Comparison of bus voltage after STATCOM placement at 30% increased load

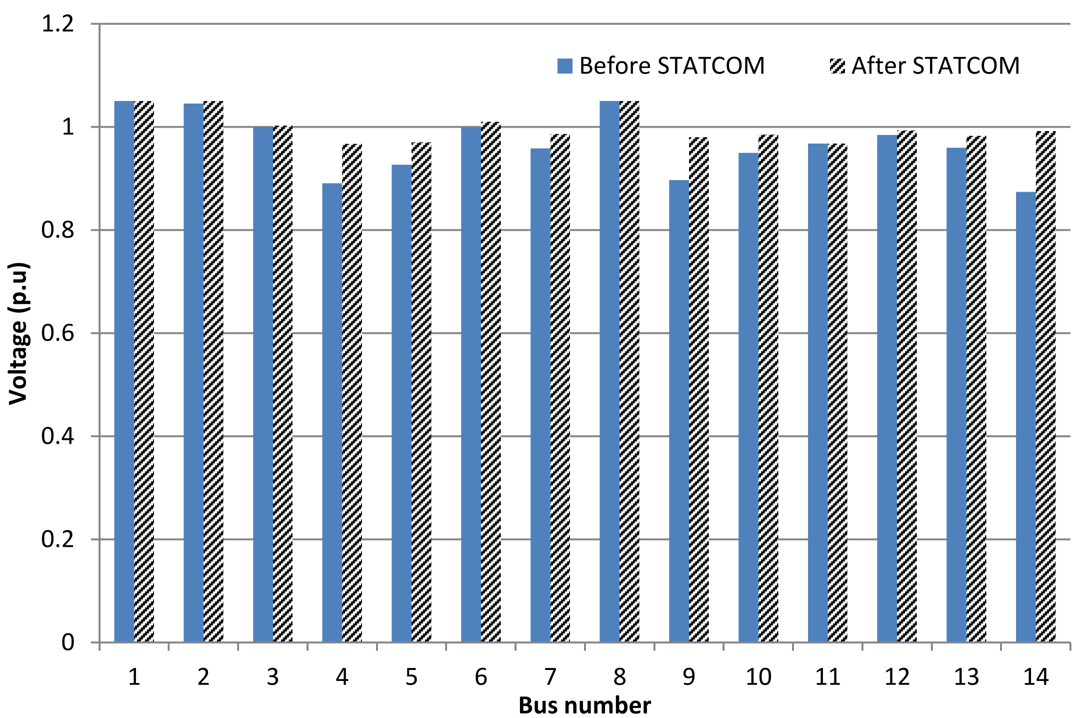

Figure 4.7 Comparison of bus voltage after STATCOM placement at 40% increased load

Figures 4.4, 4.5, 4.6 and 4.7 show the values of the bus voltage were improved with STATCOM; the power losses were mitigated and the power system remained stable by the minimization of the losses. A higher transmission voltage reasonably reduced the current flow through the transmission lines with resistance.

4.3.1 Active and reactive power losses with STATCOM

To investigate the impact of STATCOM in mitigating the power losses in the system, Newton-Raphson load flow program was run on the model without and with the device repeatedly for all the load conditions of the system. The results of pre and post insertion of the device are shown in Table 10. It is obvious from the table that the losses in the system are reduced after STATCOM was connected to the system.

Table 10 Power Losses after STATCOM placement

System	**After STATCOM placement**	
	P_{Loss} (MW)	**P_{Loss} (Mvar)**
At normal load	10.60	19.17
At 10% load increase	11.05	23.73
At 20% load increase	12.76	29.39
At 30% load increase	14.31	36.95
At 40% load increase	16.78	42.68

It can be seen from figure 4.8 below that the active power loss had reduced when the system without STATCOM is compared to that with STATCOM. The reactive power loss also decreased in the same order, as presented in figure 4.9. These are the results obtained in the case where the device was connected to bus 14.

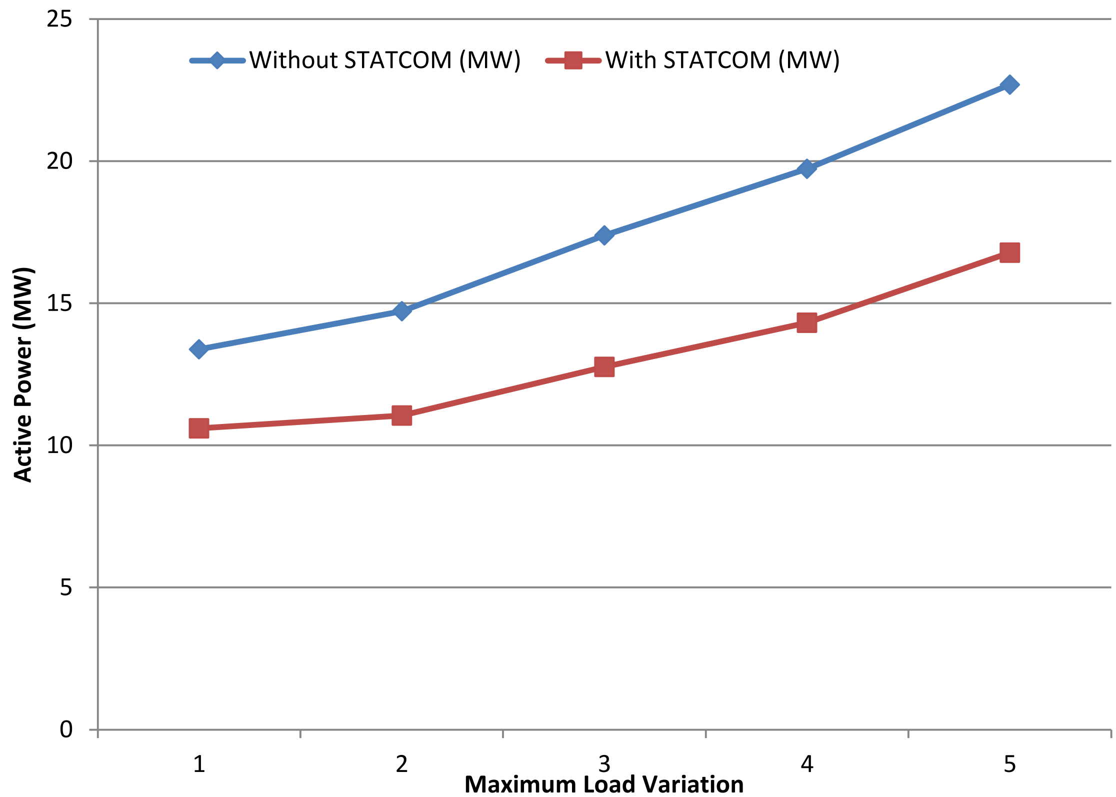

Figure 4.8 Comparison of active power loss without and with STATCOM

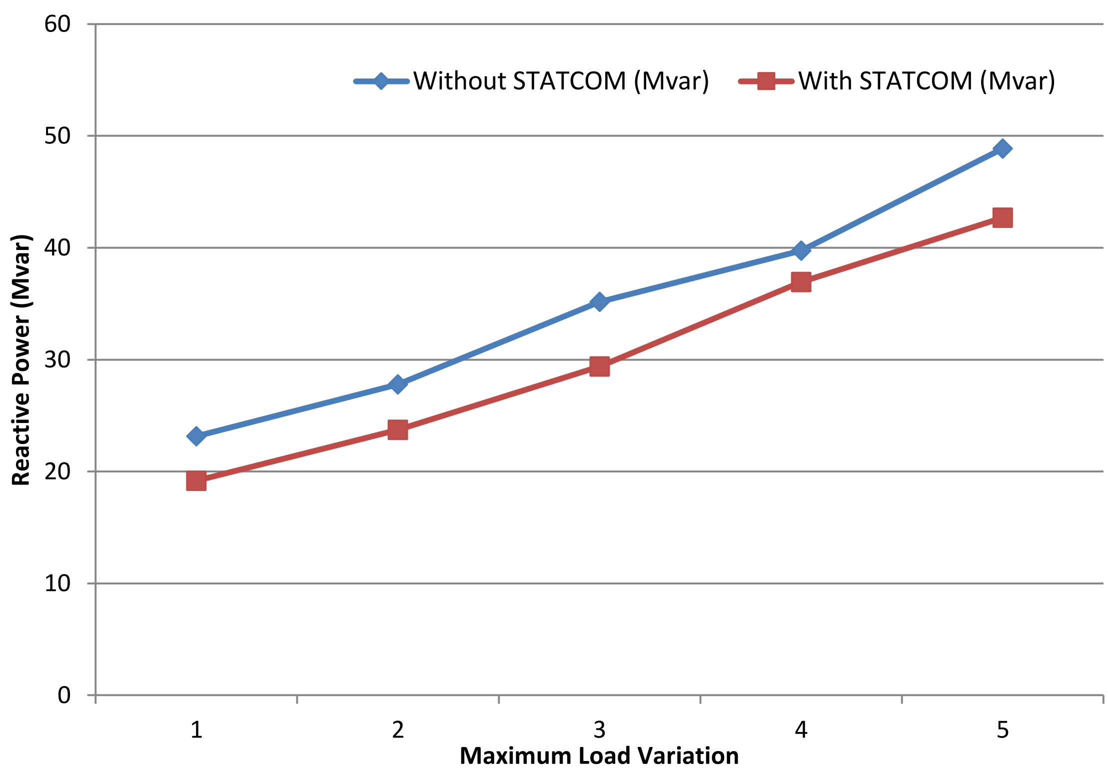

Figure 4.9 Comparison of reactive power loss without and with STATCOM

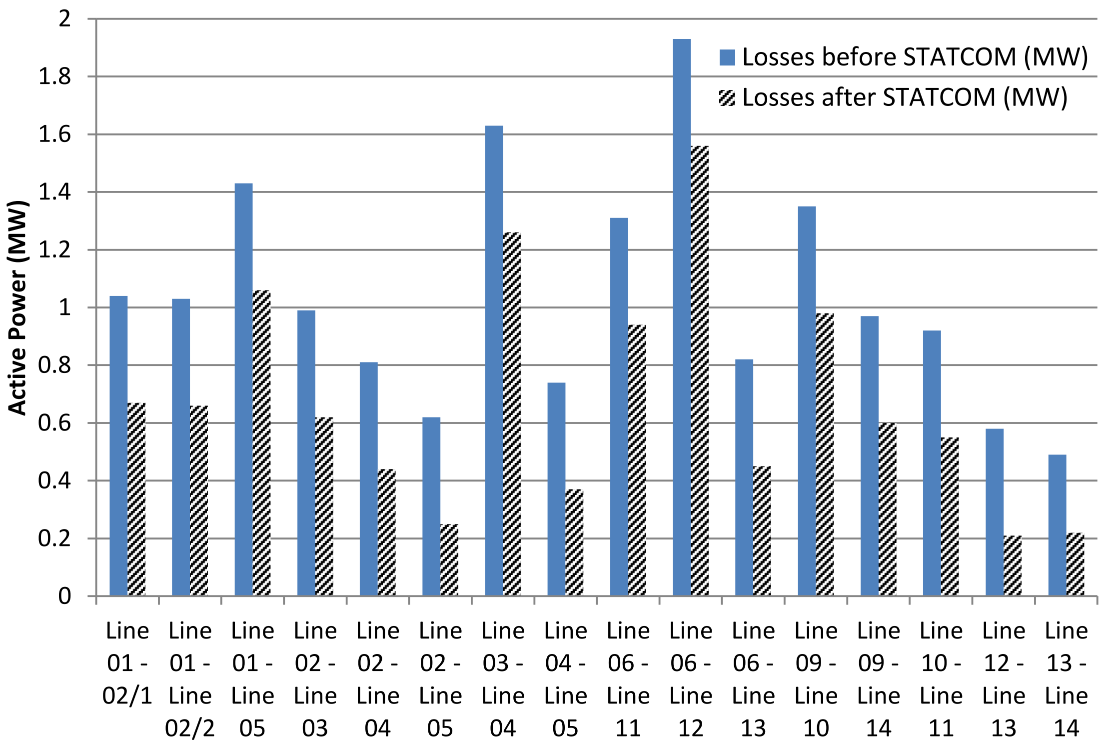

Figure 4.10 Comparison of active power loss on each line with STATCOM at bus 4

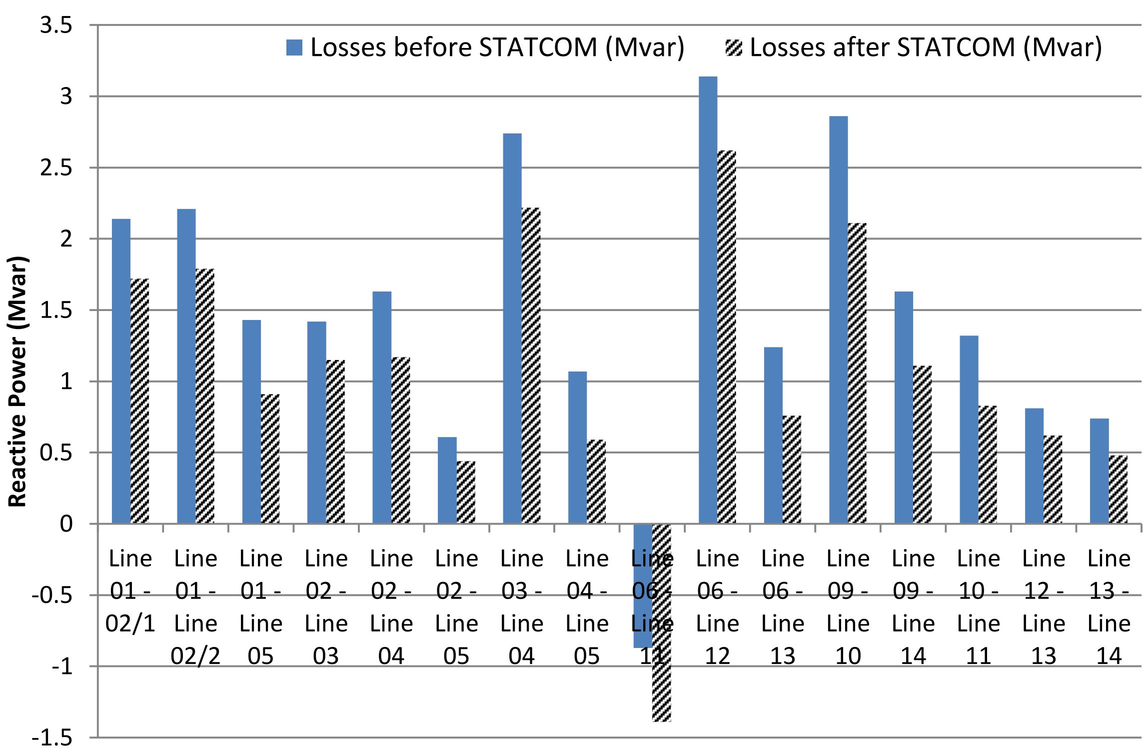

Figure 4.11 Comparison of reactive power loss on each line with STATCOM at bus 4

From figures 4.10 and 4.11, when STATCOM was connected to the system, both the active and reactive power losses in the transmission line decreased considerably. By reducing the line losses, the voltage profile and system stability were maintained. This is a better method by which power system losses can be mitigated.

CHAPTER FIVE: Conclusion and Recommendation

5.1 Conclusion

The performance of STATCOM for mitigating power losses and enhancing system voltage stability limits is validated using the IEEE 14 bus test system. The results obtained illustrate that the device controller concurrently minimizes the power losses and enhances the voltage profile of the system.

In the first place, the IEEE 14 bus transmission system was modeled in DIgSILENT PowerFactory v15 with standard load on the transmission system. At that point, the system was simulated by running a power flow study on it with the Newton-Raphson load flow program. Quantities of voltage magnitude profile and active and reactive power losses were observed to have an effect onthe voltage stability and power transfer of the system at the steady - state operating conditions before STATCOM was incorporated into the system. STATCOM built in PowerFactory v15 was incorporated into the system, and the power flow study was performed on the system again, to acquire voltage profile, active and reactive power losses in the system. The same process was repeated, increasing the maximum loading factor by increments of 10% up to 40%. The data collected were compared to deduce the effects of the device on the system quantities.

It was noted that there was a sufficient improvement in the voltage profile and power transfer on the transmission line with STATCOM; the active and reactive power losses was mitigated by 17.73% and 24.8% respectively when STATCOM was incorporated in the system at normal load. When the results obtained for all the scenarios for load increase in steps of 10% to 40% before STATCOM and after STATCOM placement were compared, it was observed that the active and reactive power losses were considerably reduced.

The suitability of STATCOM in enhancing voltage stability and mitigating active and reactive power losses at the load bus and the lines between the buses of the system is validated by the results obtained. In conclusion therefore, STATCOM gives effective voltage profile enhancement and power loss reduction when connected to the system. Also, active and reactive power losses on the line are mitigated when STATCOM is incorporated into the system.

5.2 Recommendations

This work has showcased STATCOM as an important and essential device that should be explored by utility and service providers to deliver reliable and quality power to the consumers.

Future work on STATCOM should consider the performance analysis of the device under different fault conditions. Also, different method of optimal placement of STATCOM device in a larger network should be investigated and analyzed by different analytical tools with higher level of accuracy such as: statistical inference, pattern recognition could be used to analyse results.

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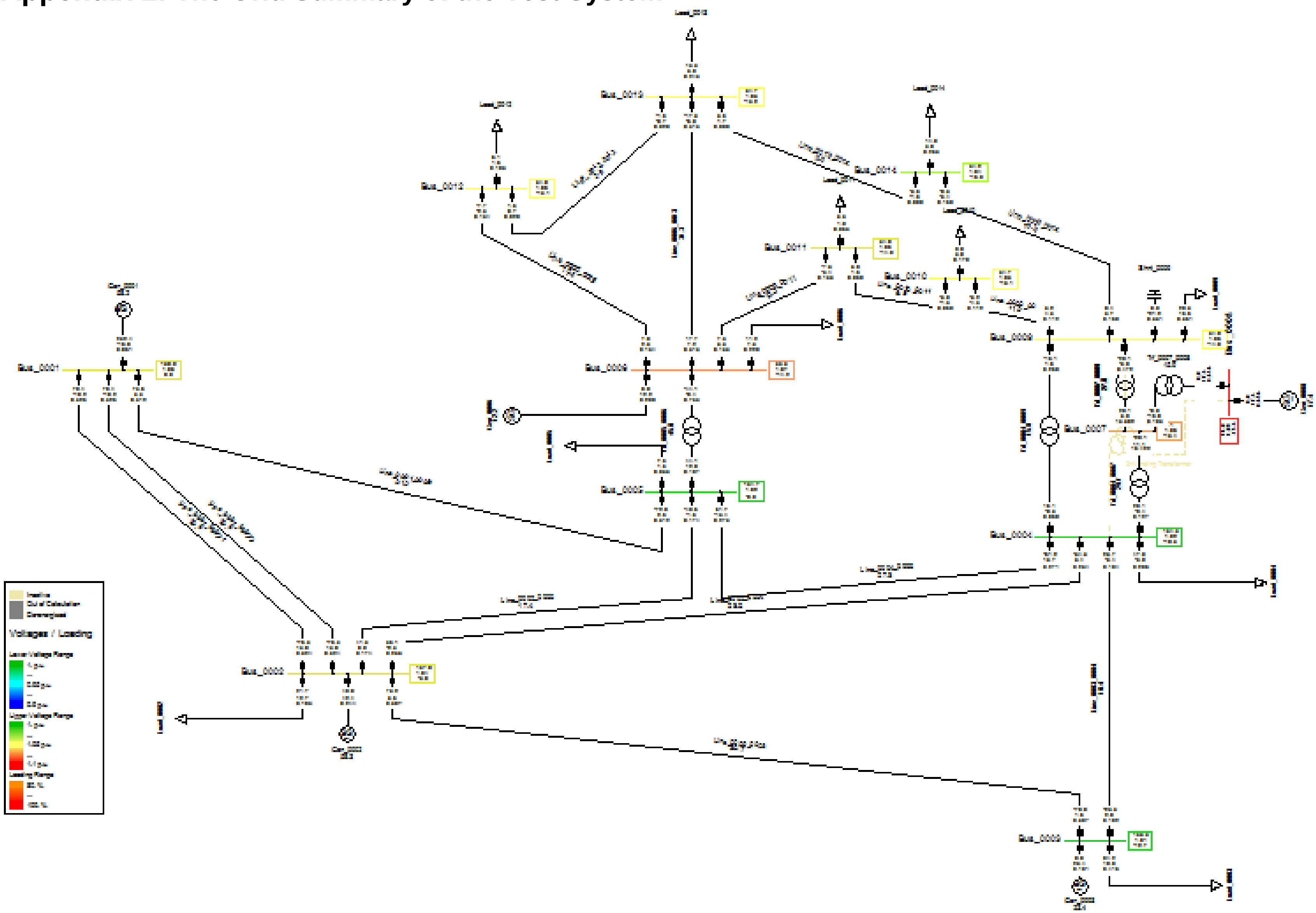
Appendix 1: The Grid Summary of the Test System



Appendix 2: Load Flow Calculation: Grid Summary

```
-----------------------------------------------------------------------------------------------------------------------------------
|                 |                                                                      |   DIgSILENT   | Project:
|                 |                                                                      | PowerFactory  |-----------------------------
|                 |                                                                      |    15.1.6     | Date:  5/16/2016
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                                Grid Summary
-----------------------------------------------------------------------------------------------------------------------------------
|      AC Load Flow, balanced, positive sequence                 |    Automatic Model Adaptation for Convergence             No
|      Automatic Tap Adjust of Transformers              No      |    Max. Acceptable Load Flow Error for
|      Consider Reactive Power Limits                    Yes     |       Nodes                                              1.00 kVA
|                                                                |       Model Equations                                    0.10 %
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                 System Stage: Grid            | Study Case: 01 - Load Flow Case Origin| Annex:                 / 1
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                 Summary
|
| No. of Substations      0         No. of Busbars        15        No. of Terminals      0          No. of Lines          16
| No. of 2-w Trfs.        5         No. of 3-w Trfs.      0         No. of syn. Machines  5          No. of asyn.Machines  0
| No. of Loads            11        No. of Shunts         2         No. of SVS            0
|
| Generation          =     272.38  MW           75.42   Mvar      282.63  MVA
| External Infeed     =       0.00  MW            0.00   Mvar        0.00  MVA
| Inter Grid Flow     =       0.00  MW            0.00   Mvar
| Load P(U)           =     259.00  MW           73.50   Mvar      269.23  MVA
| Load P(Un)          =     259.00  MW           73.50   Mvar      269.23  MVA
| Load P(Un-U)        =       0.00  MW            0.00   Mvar
| Motor Load          =       0.00  MW            0.00   Mvar        0.00  MVA
| Grid Losses         =      13.38  MW           23.15   Mvar
| Line Charging       =                         -28.32   Mvar
| Compensation ind.   =                           0.00   Mvar
| Compensation cap.   =                         -21.22   Mvar
|
| Installed Capacity  =     700.00  MW
| Spinning Reserve    =     130.62  MW
|
| Total Power Factor:
|   Generation        =          0.96  [-]
|   Load/Motor        =   0.96 / 0.00  [-]
|-----------------------------------------------------------------------------------------------------------------------------------
```

Appendix 3: STATCOM Controller Equation

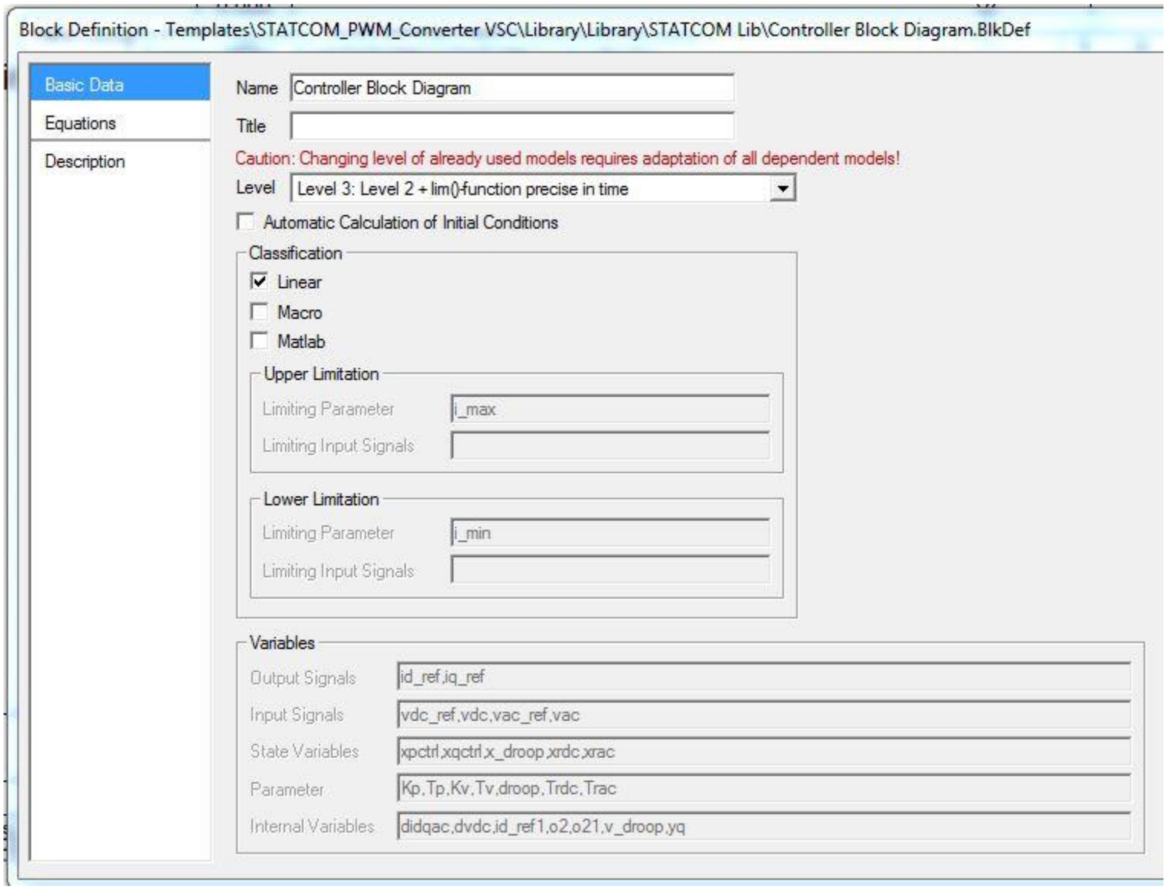
```
inc(xpctrl)=id_ref
inc(xqctrl)=iq_ref

inc(vdc_ref)=vdc
inc(vac_ref)=vac-v_droop
inc(x_droop)=droop*iq_ref
inc(xrdc)=vdc
inc(xrac)=vac

!inc0(id_ref)=0
!inc0(iq_ref)=0
!inc0(u)=1

!vardef(Ttr)='s';'Measuring time constant'
vardef(Kp)='p.u.';'Active Power Control Gain'
vardef(Tp)='s';'Active Power Control Time Constant'
vardef(Kv)='p.u.';'Voltage Control Gain'
vardef(Tv)='s';'Voltage Power Control Time Constant'
```

Appendix 4: Block definition of STATCOM Converter



Appendix 5: Load data

Bus number	Active Power (MW)	Reactive Power (MVar)
1	0	0
2	21.7	12.7
3	94.2	19.1
4	47.8	-3.9
5	7.6	1.6
6	11.2	7.5
7	0	0
8	0	0
9	29.5	16.6
10	9	5.8
11	3.5	1.8
12	6.1	1.6
13	13.8	5.8
14	14.9	5

Appendix 6: Generators data

Bus No.	Nominal kV	Bus Type	|V| (p.u.)	δ (deg.)	P_Load (MW)	Q_Load (MVAR)	P_Gen (MW)	Q_Gen (MVAR)	Generator Specifications		
									Vspec (p.u.)	Q_Max. (MVAR)	Q_Min. (MVAR)
1	HV	3	1.06	0	0	0	232.4	-16.9	1.06	0	0
2	HV	2	1.045	-4.98	21.7	12.7	40	42.4	1.045	50	-40
3	HV	2	1.01	-12.72	94.2	19.1	0	23.4	1.01	40	0
6	LV	2	1.07	-14.22	11.2	7.5	0	12.2	1.07	24	-6
8	TV	2	1.09	-13.36	0	0	0	17.4	1.09	24	-6

Bus Type	
1	Load Bus
2	Generator Bus
3	Slack/Swing Bus