Chapter One

General Back Ground

1.1Introduction

In the last two decades, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. Flexible AC transmission systems or FACTS are devices which allow the flexible and dynamic control of power systems. Enhancement of system stability using FACTS controllers has been investigated. The FACTS controllers offer a great opportunity to regulate the transmission of alternating current (AC), increasing or diminishing the power flow in specific lines and responding almost instantaneously to the stability problems. The potential of this technology is based on the possibility of controlling the route of the power flow and the ability of connecting networks that are not adequately interconnected, giving the possibility of trading energy between distant agents. Flexible Alternating Current Transmission System (FACTS) is a static equipment used for the AC transmission of electrical energy. It is meant to enhance controllability and increase power transfer capability. It is generally a power electronics based device [1].

The FACTS devices can be divided in three groups, dependent on their switching technology mechanically switched (such as phase shifting, transformers), thyristor switched or fast switched, using IGBTs. While some types of FACTS, such as the phase shifting transformer (PST) and the static VAR compensator (SVC) are already well known and used in power systems, new developments in power electronics and control have extended the application range of FACTS. Furthermore, intermittent renewable energy sources and increasing international power flows provide new applications for FACTS. The additional flexibility and controllability of FACTS allow to mitigate the problems associated with the unreliable of supply issues of renewable. SVCs and STATCOM devices are well suited to provide ancillary services (such as voltage control) to the grid and fault rid through capabilities which standard wind farms cannot provide Furthermore, FACTS reduce oscillations in the grid, which is especially interesting when dealing with the stochastic behavior of renewable [1].

1.2 STATIC SYNCHRONOUS COMPENSATOR(STATCOM)

STATCOM is a static synchronous generator operated as a shunt-connected static VAR compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage. The STATCOM, like its conventional counterpart, the SVC, controls transmission voltage by the reactive shunt compensation. It can be based on a voltage source and current source converter. Fig 1.1 show a one-line diagram of STATCOM based on voltage source converter [2].

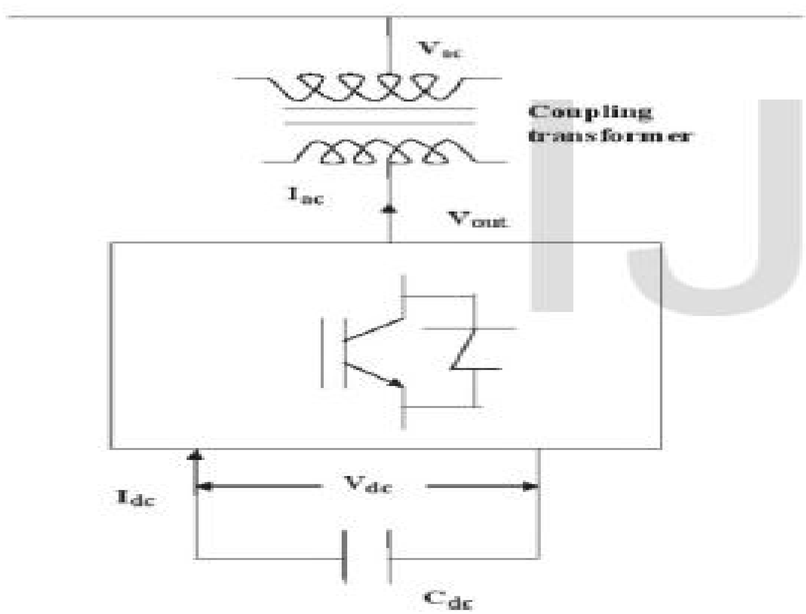


Fig 1.1 circuit of Statcom

A STATCOM can supply the required reactive power under various operating conditions, to control the network voltage actively and thus, improve the steady state stability of the network. The STATCOM can be operated over its full output current range even at very low voltage levels and the maximum Var generation or absorption changes linearly with the utility or ac system voltage. The STATCOM (or SSC) is a shunt-connected reactive-power compensation device that is capable of generating and/ or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. It is in general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. Specifically, the STATCOM considered is a voltage-source converter that, from a given input of dc voltage, produces a set of 3-phase ac-output voltages, each in phase with and coupled to the corresponding ac system voltage through a relatively small reactance (which is provided by either an interface reactor or the leakage inductance of a coupling transformer) [2].

The dc voltage is provided by an energy-storage capacitor and a STATCOM can improve power-system performance in such areas as the following:

1. The dynamic voltage control in transmission and distribution systems
2. The power-oscillation damping in power-transmission systems;
3. The transient stability
4. The voltage flicker control
5. The control of not only reactive power but also (if needed) active power in the connected line, requiring a dc energy source.

1.2.1Advantages of STATCOM

1. It occupies a small footprint, for it replaces passive banks of circuit elements by compact electronic converters;

2. It offers modular, factory-built equipment, thereby reducing site work and commissioning time

3. It uses encapsulated electronic converters, thereby minimizing its environmental impact [2].

1.3 Statement of Problem

Voltage Levels in some Sudanese busbars been weak because heavily loaded of some transmission lines in recent years, many voltage instability incidents have occurred in the Sudanese power system. The main cause of the voltage instability is the reactive power limit of the system. Flexible Alternative Current transmission systems devices can play very important role in preventing voltage instability. The aim of this research is to Improvement of Sudanese national grid by using STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

1.4Motivation’s

Today, due to the delay of the transmission lines and generation construction projects, Sudanese power system is operating close to their operational limits and system conditions have become increasingly complex. Under this situation, one of the major problems that may occur often is the voltage instability. Using of FACTS devises like STATCOM devises can solve the Sudanese power system voltage problems. And that what encourage us to study the use of this devices in Sudanese national grid.

1.5Thesis Objectives

- Find suitable location and number of STATCOM devices to use in Sudanese national grid
- Enhance the grid voltage and power during peak load.
- Decrease Sudanese national grid Losses.

1.6 Thesis Methodology

The Sudan national grid under peak load was taken as case study, simulation was developed in load flow program by Neplan software which solves power flow equation using Newton-Raphson method. Firstly, start load flow for Sudan national grid under peak load then the voltage is measured and recorded for all buses. Then the voltage is checked if all voltage within the limit. otherwise the STATCOM devices is installed at weakest buses and then make load flow again and see the enhancement.

1.7 Lay out

This thesis is organized into five chapters these chapters can be summarized as follows: -

Chapter two literature review. Chapter three mathematical models of STATCOM. Chapter four presents the result and discussion of the simulation of National Grid of Sudan which is used as the case study in this thesis. Chapter five focuses on the general conclusions of the thesis and the possible solutions in order to improve the voltage profile of the Sudan National Grid and the recommendations for future work are represented.

Chapter Two

Literature Review

2.1 Introduction

Capacitors generate and reactors (inductors) absorb reactive power when connected to an ac power source. They have been used with mechanical switches for (coarsely) controlled Var generation and absorption since the early days of ac power transmission. Continuously variable var generation or absorption for dynamic system compensation was originally provided by. over- or under excited rotating synchronous machines and later by saturating reactors in conjunction with fixed capacitors. Since the early1970 high power, line commutated thyristors in conjunction with capacitors and reactors have been employed in various circuit configurations to produce variable reactive output. These in effect provide a variable shunt impedance by synchronously switching shunt capacitors and/or reactors "in" and "out" of the network [3]. Using appropriate switch control, the var output can be controlled continuously from maximum capacitive to maximum inductive output at a given bus voltage.

More recently gate turn-offthyristors and other power semiconductors with internal turnoff capability has been used in switching converter circuits to generate and absorb reactive power without the use of ac capacitors or reactors. These perform as ideal synchronous compensators (condensers), in which the magnitude of the internally generated ac voltage is varied to control the var output. All of the different semiconductor power circuits, with their internal control enabling them to produce var output proportional to an input reference, are collectively termed by the joint IEEE and CIGRE definition, static var generators (SVG). Thus, a static var compensator (SVC) is by the IEEE CIGRE co-definition, a static var generator whose output is varied so as to maintain or control specific parameters (e.g., voltage, frequency) of the electric power system. It is important that the reader appreciate the difference between these two terms, static var generator and static var compensator, the static var generator is a self-sufficiently functioning device that draws controllable reactive current from an alternating power source. The control input to the var generator can be an arbitrary (within the operating range) reactive current, impedance, or power reference signal that the SVG is to establish at its output. Thus, the static var generator can be viewed as a power amplifier that faithfully reproduces the reference signal at the desired power level. The functional use of the var generator is clearly defined by the reference signal provided. Consequently, according to the IEEE-CIGRE definition, a static var generator becomes a static var compensator when it is equipped with special external (or system) controls which derive the necessary reference for its input, from the operating requirements and prevailing variables of the power system, to execute the desired compensation of the transmission line. This means that different types of var generator can be operated with the same external control to provide substantially the same compensation functions. Evidently, the type and structure of the var generator will ultimately determine the basic operating characteristics (e.g., voltage vs.var output, response time, harmonic generation), whereas the external characteristics control the functional capabilities (e.g., voltage regulation, power factor control, power oscillation damping), of the static Var compensator [3].

The FACTS controllers offer a great opportunity to regulate the transmission of alternating current (AC), increasing or diminishing the power flow in specific lines and responding almost instantaneously to the stability problems. The potential of this technology is based on the possibility of controlling the route of the power flow and the ability of connecting networks that are not adequately interconnected, giving the possibility of trading energy between distant agents. Flexible Alternating Current Transmission System (FACTS) is a static equipment used for the AC transmission of electrical energy. It is meant to enhance controllability and increase power transfer capability. It is generally a power electronics based device. The FACTS devices can be divided in three groups, dependent on their switching technology: mechanically switched (such as phase shifting transformers), thyristor switched or fast switched, using IGBTs. While some types of FACTS, such as the phase shifting transformer (PST) and the static VAR compensator (SVC) are already well known and used in power systems, new developments in power electronics and control have extended the application range of FACTS. Furthermore, intermittent renewable energy sources and increasing international power flows provide new applications for FACTS. The additional flexibility and controllability of FACTS allow to mitigate the problems associated with the unreliable of supply issues of renewable. SVCs and STATCOM devices are well suited to provide ancillary services (such as voltage control) to the grid and fault rid through capabilities which standard wind farms cannot provide Furthermore, FACTS reduce oscillations in the grid, which is especially interesting when dealing with the stochastic behavior of renewable [1].

2.2 History of FACTS Controllers

Hingorani (1993) and introduced different FACTS controllers such as phase angle regulator, static VAR compensator, sub synchronous resonance damper and static condenser to improve all round performance of power system. It has also been stated that the improvement of power semiconductors is held up as a major factor to the increased importance in future power system. Using power electronic circuits, the line parameters such as the phase angle, the line end voltages and the impedance can be controlled at a faster rate [4].

Arindam Ghosh used power electronic devices to enhance both system stability and power transfer limits using a linearized discrete model [5].

Matsuno (2002) had proposed various types of FACTS controllers such as SVC, STATCOM and variable speed pumped storage (VSPS). They studied their necessity, technical problems in developing the FACTS controllers, and their solutions [6].

Schauder and Mehta (1993) discussed the Advanced Static VAR Compensator (ASVC) using self-commutating inverter. They have also introduced two types of inverters for STATCOM and analyzed. Singh et al (2009) proposed a fast acting static STATCOM, which was used as the state of-the-art dynamic shunt compensator for reactive power control in transmission and distribution system [7].

Mohagheghi (2003) introduced a nonlinear identification of STATCOM connected to a power system using Continually Online Trained (COT) Artificial Neural Networks (ANNs) [8].

Jianye Chen et al (2006) focused on a new kind of STATCOM, where thyristors instead of self-commutated devices are used as switching devices. Hinton et al (2001) had given some guidelines on the principles of design for replaceable control components to improve the performance for a FACTS controller [9].

El Moursi et al (2006), (2010) and (2011) proposed a reactive power controller for STATCOM and SSSC and introduced a Coordinated Voltage Control Scheme for SEIG-based Wind Park Utilizing Substation [10].

2.3 Example of FACTS Controllers for Enhancing Power System Control

1. Static Synchronous Compensator (STATCOM)
2. Static VAR Compensator (SVC) -Controls voltage
3. Unified Power Flow Controller (UPFC)
4. Convertible Series Compensator (CSC)
5. Inter-phase Power Flow Controller (IPFC)
6. Static Synchronous Series Controller (SSSC)

Each of the above mentioned controllers have impact on voltage, impedance, and/or angle (and power) Thyristor Controlled Series Compensator (TCSC)-Controls impedance Thyristor Controlled Phase Shifting Transformer (TCPST)-

Controls angle Super Conducting Magnetic Energy Storage (SMES)-Controls voltage and power.

2.4 Classification

There are different classifications for the FACTS devices: Depending on the type of connection to the network FACTS devices can differentiate four categories

- serial controllers
- derivation controllers
- serial to serial controllers
- serial-derivation controllers

Depending on technological features, the FACTS devices can be divided into two generations first generation: used thyristors with ignition controlled by gate(SCR). second generation: semiconductors with ignition and extinction controlled by gate (GTO´s, MCTS, IGBTS, IGCTS, etc.).

These two classifications are independent, existing for example, devices of a group of the first classification that can belong to various groups of the second classification. The main difference between first and second generation devices is the capacity to generate reactive power and to interchange active power. The first generation FACTS devices work like passive elements using impedance or tap changer transformers controlled by thyristors. The second generation FACTS devices work like angle and module controlled voltage sources and without inertia, based in converters, employing electronic tension sources (three-phase inverters, auto-switched voltage sources, synchronous voltage sources, voltage source control) fast proportioned and controllable and static synchronous voltage and current sources [1].

2.5 FIRST GENERATION OF FACTS

There are two generations of realization of power electronics based FACTS controllers, the first generations have resulted in the static var compensators (SVC) and the thyristor- Controlled series capacitors (TCSC) [1].

2.5.1 Static VAR Compensator (SVC)

A static VAR compensator (or SVC) is an electrical device for providing fast-acting reactive power on high-voltage electricity transmission networks. SVCs are part of the Flexible AC transmission system device family, regulating voltage and stabilizing the system. The term "static" refers to the fact that the SVC has no moving parts (other than circuit breakers and disconnects, which do not move under normal SVC operation). Prior to the invention of the SVC, power factor compensation was the preserve of large rotating machines such as synchronous condensers. The SVC is an automated impedance matching device, designed to bring the system closer to unity power factor. If the power system's reactive load is capacitive (leading), the SVC will use reactors (usually in the form of Thyristor-Controlled Reactors) to consume VARs from the system, lowering the system voltage. Under inductive (lagging) conditions, the capacitor banks are automatically switched in, thus providing a higher system voltage. They also may be placed near high and rapidly varying loads, such as arc furnaces, where they can smooth flicker voltage. It is known that the SVCs with an auxiliary injection of a suitable signal can considerably improve the dynamic stability performance of a power system. It is observed that SVC controls can significantly influence nonlinear system behavior especially under high-stress operating conditions and increased SVC gains [1].

2.5.2 Thyristor-Controlled Series Capacitor (TCSC)

TCSC controllers use thyristor-controlled reactor (TCR) in parallel with capacitor segments of series capacitor bank. The combination of TCR and capacitor allow the capacitive reactance to be smoothly controlled over a wide range and switched upon command to a condition where the bi-directional thyristor pairs conduct continuously and insert an inductive reactance into the line. TCSC is an effective and economical means of solving problems of transient stability, dynamic stability, steady state stability and voltage stability in long transmission lines. TCSC, the first generation of FACTS, can control the line impedance through the introduction of a thyristor controlled capacitor in series with the transmission line. A TCSC is a series controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. The functioning of TCSC can be comprehended by analyzing the behavior of a variable inductor connected in series with a fixed capacitor [1].

2.5.3 Thyristor-Controlled Phase Shifter (TCPS)

In a TCPS control technique the phase shift angle is determined as a nonlinear function of rotor angle and speed. However, in real-life power system with a large number of generators, the rotor angle of a single generator measured with respect to the system reference will not be very meaningful [1].

2.6 SECOND GENERATION OF FACTS

The second generation of FACTS devices has produced the static Synchronous Compensators (STATCOM), The static Synchronous Series compensators (SSSC) and the unified Power Flow Controller (UPFC) [1].

2.6.1 Static Compensator (STATCOM)

The emergence of FACTS devices and in particular GTO thyristor-based STATCOM has enabled such technology to be proposed as serious competitive alternatives to conventional SVC. A static synchronous compensator (STATCOM) is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power, it can also provide active AC power. It is a member of the FACTS family of devices. Usually a STATCOM is installed to support electricity networks that have a poor power factor and often poor voltage regulation. There are however, other uses, the most common use is for voltage stability. From the power system dynamic stability viewpoint, the STATCOM provides better damping characteristics than the SVC as it is able to transiently exchange active power with the system [1].

2.6.2 Static Synchronous Series Compensator (SSSC)

This device works the same way as the STATCOM. It has a voltage source converter serially connected to a transmission line through a transformer. It is necessary an energy source to provide a continuous voltage through a condenser and to compensate the losses of the VSC. A SSSC is able to exchange active and reactive power with the transmission system. But if our only aim is to balance the reactive power, the energy source could be quite small. The injected voltage can be controlled in phase and magnitude if we have an energy source that is big enough for the purpose. With reactive power compensation only the voltage is controllable, because the voltage vector forms 90º degrees with the line intensity. In this case the serial injected voltage can delay or advanced the line current. This means that the SSSC can be uniformly controlled in any value, in the VSC working slot [1].

2.6.3 Unified Power Flow Controller (UPFC)

A unified power flow controller (UPFC) is the most promising device in the FACTS concept. It has the ability to adjust the three control parameters, i.e. the bus voltage, transmission line reactance, and phase angle between two buses, either simultaneously or independently. A UPFC performs this through the control of the in-phase voltage, quadrature voltage, and shunt compensation. The UPFC is the most versatile and complex power electronic equipment that has emerged for the control and optimization of power flow in electrical power transmission systems. It offers major potential advantages for the static and dynamic operation of transmission lines. The UPFC was devised for the real-time control and dynamic compensation of ac transmission systems, providing multifunctional flexibility required to solve many of the problems facing the power industry. Within the framework of traditional power transmission concepts, the UPFC is able to control, simultaneously or selectively, all the parameters affecting power flow in the transmission line. Alternatively, it can independently control both the real and reactive power flow in the line unlike all other controllers [1].

Table2.1 Number of facts devices used over the world and their total MVA

Type	**Number**	**Total Installed Power in MVA**
SVC	600	90
STATCOM	15	1.2
Series Compensation	700	350
TCSC	10	2
HVDC B2B	41	14
HVDC VSC B2B	1+7(with cable)	900
UPFC	2-3	250

2.7 Benefits of Control of Power Systems

Once power system constraints are identified and through system studies viable solutions options are identified, the benefits of the added power system control must be determined. The following offers a list of such benefits [4].

Increased Loading and More Effective Use of Transmission Corridors

- Added Power Flow Control
- Improved Power System Stability
- Increased System Security

- Increased System Reliability
- Added Flexibility in Starting New Generation
- Elimination or Deferral of the Need for New Transmission Lines

2.8 Benefits of utilizing FACTS devices

The benefits of utilizing FACTS devices in electrical transmission systems can be summarized as follows [4]

- ✓ Better utilization of existing transmission system assets.
- ✓ Increased transmission system reliability and availability.
- ✓ Increased dynamic and transient grid stability and reduction of loop flows.
- ✓ Increased quality of supply for sensitive industries.
- ✓ Environmental benefits Better utilization of existing transmission system assets.

2.9 The STATCOM

The STATCOM is a VSC system whose prime function is to exchange reactive power with the host AC system. In an electric power transmission system, the STATCOM can be used to increase the line power transmission capacity, to enhance the voltage/angle stability or to damp the system oscillatory modes. In a distribution system, the STATCOM is mainly used for voltage regulation; however, it can also supply real power to the loads in the case of a blackout if it is augmented with an energy storage device, for example, a battery storage system. Moreover, the STATCOM may also be employed to balance a distribution network by compensating for load imbalances [5].

Flexible ac transmission systems (FACTS) devices such as static synchronous compensator (STATCOM) and static VAR compensator (SVC) are frequently used to address voltage stability and power quality issues in transmission and distribution systems. Static synchronous compensators based on PWM voltage source converters normally have better dynamic performance during ac network disturbances, smaller footprint and produce fewer harmonics than those using multiple thyristor-based converters with complex transformers, and static VAR compensators. But they suffer from high conversion losses and are also expensive [5].

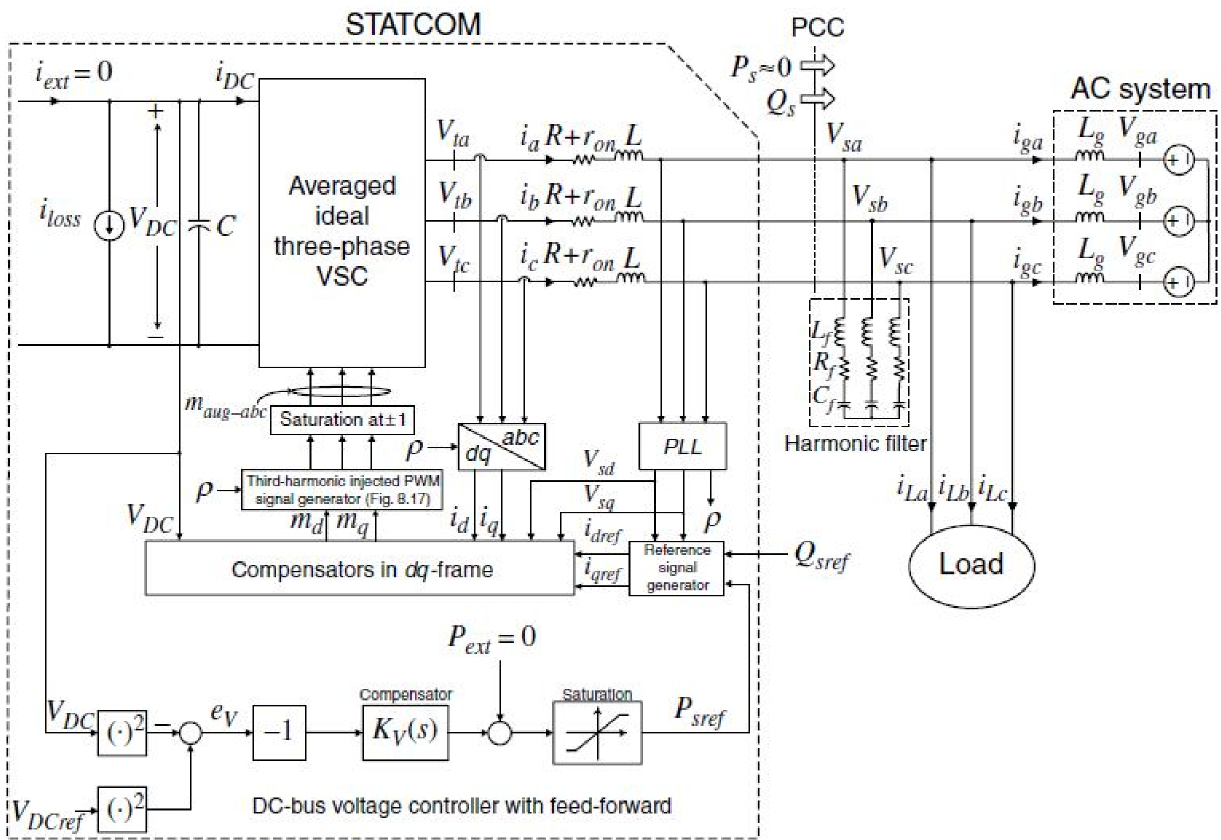


Fig (2.1) Schematic diagram of the STATCOM

2.9.1 STATCOM or Static Synchronous Compensator

Is a shunt device, which uses force-commutated power electronics (i.e. GTO, IGBT) to control power flow and improve transient stability on electrical power networks. It is also a member of the so-called Flexible AC Transmission System (FACTS) devices. The STATCOM basically performs the same function as the static var compensators but with some advantages.

The term Static Synchronous Compensator is derived from its capabilities and operating principle, which are similar to those of rotating synchronous compensators (i.e. generators), but with relatively faster operation [5].

Fig 2.2 Statcom in field

2.9.2Applications

STATCOMs are typically applied in long distance transmission systems, power substations and heavy industries where voltage stability is the primary concern.

In addition, static synchronous compensators are installed in select points in the power system to perform the following:

1. Voltage support and control
2. Voltage fluctuation and flicker mitigation
3. Unsymmetrical load balancing
4. Power factor correction
5. Active harmonics cancellation
6. Improve transient stability of the power system

2.9.3 Design

STATCOM is composed of the following components:

1- Voltage-Source Converter (VSC)

The voltage-source converter transforms the DC input voltage to an AC output voltage. Two of the most common VSC types are described below.

A. Square-wave Inverters using Gate Turn-Off Thyristors Generally, four three-level inverters are utilized to make a 48-step voltage waveform. Subsequently, it controls reactive power flow by changing the DC capacitor input voltage, simply because the fundamental component of the converter output voltage is proportional to the DC voltage.

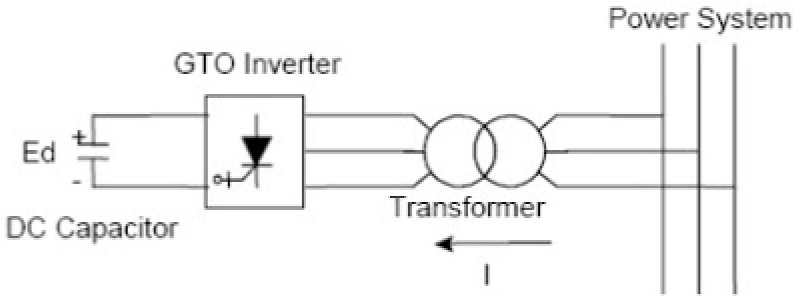


Fig 2.3 GTO-based STATCOM Simple Diagram

In addition, special interconnection transformers are employed to neutralize harmonics contained in the square waves produced by individual inverters.

B. PWM Inverters using Insulated Gate Bipolar Transistors (IGBT)

It uses Pulse-Width Modulation (PWM) technique to create a sinusoidal waveform from a DC voltage source with a typical chopping frequency of a few kHz. In contrast to the GTO-based type, the IGBT-based VSC utilizes a fixed DC voltage and varies its output AC voltage by changing the modulation index of the PWM modulator. Moreover, harmonic voltages are mitigated by installing shunt filters at the AC side of the VSC.

2- DC Capacitor

This component provides the DC voltage for the inverter.

3-Inductive Reactance (X)

It connects the inverter output to the power system. This is usually the leakage inductance of a coupling transformer.

4-Harmonic Filters Mitigate harmonics and other high frequency components due to the inverters.

2.10 PRINCIPLE OF OPERATION

A STATCOM is a controlled reactive-power source. It provides the desired reactive-power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC). A single-line STATCOM power circuit is shown in Fig.(a), where a VSC is connected to a utility bus through magnetic coupling [9].

STATCOM is seen as an adjustable voltage source behind a reactance meaning that capacitor banks and shunt reactors are not needed for reactive-power generation and absorption, thereby giving a STATCOM a compact design, or small footprint, as well as low noise and low magnetic impact. The exchange of reactive power between the converter and the ac system can be controlled by varying the amplitude of the 3-phase output voltage, Es, of the converter, as illustrated in Fig. (c). If the amplitude of the output voltage is increased above that of the utility bus voltage, Et, then a current flow through the reactance from the converter to the ac system and the converter generates capacitive-reactive power for the ac system. If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the ac system to the converter and the converter absorbs inductive-reactive power from the ac system [9]

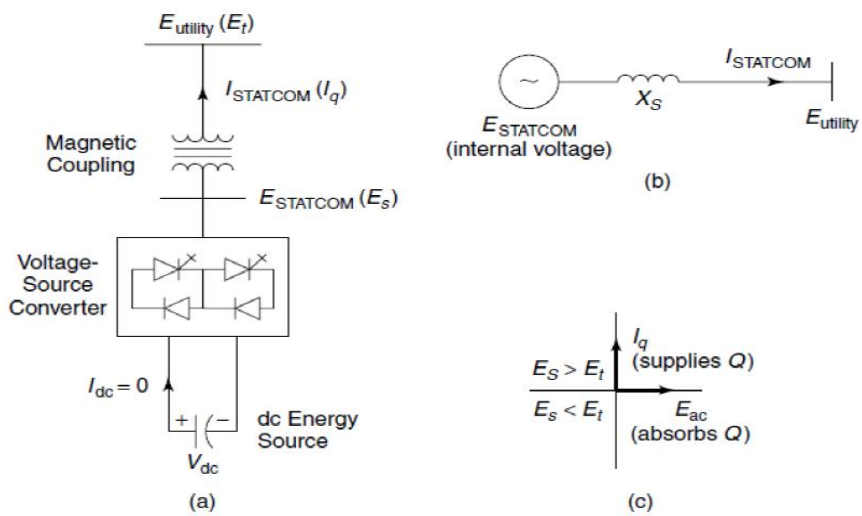


Fig 2.4 The STATCOM operating principle diagram (a) power circuit (b) equivalent circuit and (c) power exchange

If the output voltage equals the ac system voltage, the reactive-power exchange becomes zero, in which case the STATCOM is said to be in a floating state. Adjusting the phase shift between the converter-output voltage and the ac system voltage can similarly control real-power exchange between the converter and the ac system. In other words, the converter can supply real power to the ac system from its dc energy storage if the converter-output voltage is made to lead the ac-system voltage [9].

On the other hand, it can absorb real power from the ac system for the dc system if its voltage lags behind the ac-system voltage. A STATCOM provides the desired reactive power by exchanging the instantaneous reactive power among the phases of the ac system. The mechanism by which the converter internally generates and/ or absorbs the reactive power can be understood by considering the relationship between the output and input powers of the converter. The converter switches connect the dc-input circuit directly to the ac-output circuit. Thus the net instantaneous power at the ac output terminals must always be equal to the net instantaneous power at the dc-input terminals (neglecting losses). Assume that the converter is operated to supply reactive-output power. In this case, the real power provided by the dc source as input to the converter must be zero. Furthermore, because the reactive power at zero frequency (dc) is by definition zero, the dc source supplies no reactive Power as input to the converter and thus clearly plays no part in the generation of reactive-output power by the converter [9].

In other words, the converter simply interconnects the three output terminals so that the reactive-output currents can flow freely among them. If the terminals of the ac system are regarded in this context, the converter establishes a circulating reactive-power exchange among the phases. However, the real power that the converter exchanges at its ac terminals with the ac system must, of course, be supplied to or absorbed from its dc terminals by the dc capacitor. Although reactive power is generated internally by the action of converter switches, a dc capacitor must still be connected across the input terminals of the converter. The primary need for the capacitor is to provide a circulating-current path as well as a voltage source. The magnitude of the capacitor is chosen so that the dc voltage across its terminals remains fairly constant to prevent it from contributing to the ripples in the dc current. The VSC-output voltage is in the form of a staircase wave into which smooth sinusoidal current from the ac system is drawn, resulting in slight fluctuations in the output power of the converter [9].

However, to not violate the instantaneous power-equality constraint at its input and output terminals, the converter must draw a fluctuating current from its dc source. Depending on the converter configuration employed, it is possible to calculate the minimum capacitance required to meet the system requirements, such as ripple limits on the dc voltage and the rated-reactive power support needed by the ac system. The VSC has the same rated-current capability when it operates with the capacitive- or inductive-reactive current. Therefore, a VSC having a certain MVA rating gives the STATCOM twice the dynamic range in MVAR (this also contributes to a compact design). A dc capacitor bank is used to support (stabilize) the controlled dc voltage needed for the operation of the VSC. The reactive power of a STATCOM is produced by means of power-electronic equipment of the voltage-source-converter type. The VSC may be a 2- level or 3-level type, depending on the required output power and voltage. A number of VSCs are combined in a multi-pulse connection to form the STATCOM. In the steady state, the VSCs operate with fundamental-frequency switching to minimize converter losses. However, during transient conditions caused by line faults, a pulse width–modulated (PWM) mode is used to prevent the fault current from entering the VSCs. In this way, the STATCOM is able to withstand transients on the ac side without blocking [9].

2.10.1 STATCOM versus SVC

The STATCOM has the ability to provide more capacitive reactive power during faults, or when the system voltage drops abnormally, compared to ordinary static var compensator. This is because the maximum capacitive reactive power generated by a STATCOM decreases linearly with system voltage, while that of the SVC is proportional to the square of the voltage. Also, the STATCOM has a faster response as it has no time delay associated with thyristor firing. Nevertheless, these advantages come at a higher price (about 20% more) [4].

Chapter Three

Mathematical Model

3.1 Introduction

Power flow analysis is fundamental to the study of power systems, in fact power flow forms the core of power system analysis, and power flow study plays a key role in the planning of addition or expansion of transmission and generation facilities. A power flow solution is often the starting point for many other types of power system analyses such as stability analysis and contingency analysis, In addition, power flow analysis is at the heart of contingency analysis and the implementation of real-time monitoring systems [12].

3.2 Power Flow Solution

A power flow study (load-flow study) is a steady-state analysis whose target is to determine the voltages, currents, and real and reactive power flows in a system under a given load conditions.

To solve the power flow problem, the buses in the system classified into three type depend on the physical aspect of the system and the specified quantities in the bus, transmission line is presented using pi model and the system is model using admittance matrix [12].

3.2.1 Types of buses

Slack Bus: The slack bus for the system is a single bus for which the voltage magnitude and angle are specified, the real and reactive power are unknowns.

The bus selected as the slack bus must have a source of both real and reactive power, since the injected power at this bus must “swing” to take up the “slack” in the solution.

The best choice for the slack bus (since, in most power systems, many buses have real and reactive power sources) requires experience with the particular system under study but generally is chosen as largest generation in the system. The behavior of the solution is often influenced by the bus chosen.

Load Bus (P-Q Bus): A load bus is defined as any bus of the system for which the real and reactive power are specified. Load buses may contain generators with specified real and reactive power outputs; however, it is often convenient to designate any bus with specified injected complex power as a load bus.

Voltage Controlled Bus (P-V Bus): Any bus for which the voltage magnitude and the injected real power are specified is classified as a voltage controlled (or P-V) bus [12]. The injected reactive power is a variable (with specified upper and lower bounds) in the power flow analysis. A P-V bus must have a variable source of reactive power such as a generator [12]

3.3Numerical Solution of Power Flow

There are four quantities of interest associated with each bus: real power, reactive power, voltage magnitude, and voltage angle at every bus of the system, two of these four quantities will be specified and the remaining two will be unknowns. So there are only two equations and four variables in power flow solution so that can't be solve analytically but the solution can be done by using numerical iterative method for nonlinear equation, the most iterative method of numerical solution used for power flow solution are [12]:

1. Gauss Method
2. Gauss-Seidel Method.
3. Newton-Raphson (NR) Method.
4. Decoupled Newton Methods.
5. Fast Decoupled Load Flow (FDLF).

3.3.1Gauss method

This is an iterative method used in the calculation of power flow analysis. This method was named after the German mathematician Carl Friedrich Gauss and

Philipp Ludwig von Seidel. It is also known as Liesmann method or the method of successive displacement. In this method an initial value of voltage is guessed and a new value for the voltage is calculated for each bus. In this method the new voltage value obtained at the other bus cannot be used for the calculation of voltage at another bus until the iteration is completed. This disadvantage is one of the disadvantages of Gauss method [12].

3.3.2 Gauss-Seidel method

This method is based on the Gauss method. In this method an initial value of voltage is guessed and the newly calculated value replaces the initial value and the iteration is stopped when the solution converges. But later this method was limited for only small problems because of the complexity in the calculations.

Computations for this method using the admittance matrix deduce:

$Ip=\frac{Pp-jQp}{Vp^{n}}$ ………………………………………..3.1

; p= 1, 2, 3, …, n and p slack bus

For a system with n total of buses, the calculated voltage at any bus p and Pp and jQp

the real and reactive powers at any bus p are given:

$\boldsymbol{Vp^{k}}=\frac{1}{Ypp}\left(\frac{Pp-jQp}{Vp^{n}}-\sum_{q=1}^{p-1}\boldsymbol{Ypq\,Vq^{k}}-\sum_{q=p=1}^{n}\boldsymbol{YpqVq^{k-1}}\right)$: $q\neq p$…………3.2

Where: k is the iteration count.

The Gauss-Seidel method of solution of power flow problems has an excessive number of iterations before the voltage corrections are within and acceptable precision index. The number of iterations required is reduced considerably if the correction in voltage at each bus is multiplied by some constant that increases the amount of correction to bring the voltage closer to the value it is approaching. The multipliers that accomplish this improved convergence are acceleration factors. The difference between the newly calculated voltage and the best previous voltage at the bus is multiplied by the appropriate acceleration factor to obtain a better correction to be added to the previous value. The acceleration factor for the real component of correction may differ from that for the imaginary component. For any system, optimum values for acceleration factors exist, and poor choice of factors may result in less rapid convergence or make convergence impossible. In most cases, an acceleration factor of 1.6 is used in power flow analysis. However, studies may be made to determine the best choice for a particular system. At a bus where the voltage magnitude rather than reactive power is specified, the real and reactive components of the voltage for each iteration are found by computing a value for the reactive power. Thus from equation:

Pp-jQp=(Ypp Vp+$\sum_{q=1}^{p-1} \boldsymbol{Ypq\ Vq^{k}}$+$\sum_{q=p+1}^{n} \boldsymbol{YpqVq^{k-1}}$) $\boldsymbol{Vp^{n}}$:q≠p……..3.3

For q= p, then:

Pp-jQp=$\boldsymbol{Vp^{n}} \sum_{q-1}^{n} \boldsymbol{YpqVq^{k}}$ ………………………………………………3.4

The reactive power is then evaluated for the best previous voltage values at the buses.

Qp=-Im($\boldsymbol{Vp^{n}} \sum_{q=1}^{n} \boldsymbol{YpqVq^{k}}$)

The new value of reactive power is substituted in equation to find a new value Of Vp

The line flows in line Pq is thus:

Spq=Ppq-jQpq=VpIp……………………………………………….3.5

Spq=Vp($\boldsymbol{Vp^{n}}$)$\boldsymbol{Ypq^{n}}$+VpVq*Ysh………………..………………...3.6

3.3.3Advantages of Gauss-Seidel Method

• The Gauss-Seidel method uses rectangular coordinates when programming.

• It requires the fewest number of arithmetic operations to complete an iteration because of the sparsity of the network matrix and simplicity of the solution technique

•It takes less time per iteration.

• It is easy to program and has the most efficient utilization of core memory.

3.3.4Disadvantages of Gauss-Seidel Method

• Gauss-Seidel is characteristically long in solving due to its slow convergence and often difficulty is experienced with unusual network conditions such as negative reactive branches.

• In Gauss-Seidel method, each bus is treated independently. Each correction to one bus requires subsequent correction to all buses to which it is connected [12].

3.4 Newton-Raphson Method

The Newton–Raphson (N-R) method has powerful convergence characteristics, though computational and storage requirements are heavy. The sparsity techniques and ordered elimination led to its earlier acceptability and it continues to be a powerful load-flow algorithm even in today's environment for large systems and optimization. A lesser number of iterations are required for convergence, as compared to the Gauss–Seidel method, provided that the initial estimate is not far removed from the final results, and these do not increase with the size of the system. This method uses the Gauss–Seidel method to obtain good initial voltages as the starting values and the results input into the N-R method as a starting estimate. These voltages are used to calculate real power P at every bus except the swing bus and also reactive power Q wherever reactive power is specified. To apply the Newton-Raphson method to the solution of load flow equations, bus voltages and line admittances may be expressed in polar form or rectangular form. For polar form representation, then the voltages, line admittances and real and reactive powers are expressed as:

$Vp=Vp\angle \delta p$ ……………………………………………………….3.7

$Vq=Vq\angle \delta a$ ……………………………………………………...3.8

$Ypq=Ypq\angle \theta pq$……………………………………………………3.9

Where δ is the angle of the bus voltage and θ is the bus admittance angle. The static power flow is given by:

$$P_p - jQ_p = \sum_{q=1}^{n} V_p V_q Y_{pq} < (\theta_{pq} + \partial_q - \partial_p) \quad \text{.........................3.10}$$

Hence

$$P_p = \sum_{q=1}^{n} V_p V_q Y_{pq} \cos(\theta_{pq} + \delta_q - \delta_p) \quad \text{..3.11}$$

$$Q_p = -\sum_{q=1}^{n} V_p V_q Y_{pq} \sin(\theta_{pq} + \partial_q - \partial_p) \quad \text{.............................3.12}$$

For rectangular representation, then:

$$P_p j Q_p = V_p^* \sum_{\substack{q=1 \\ q \neq p}}^{n} Y_{pq} V_q \quad \text{..3.13}$$

$$V_p = e_p + j f_p \quad \text{..3.14}$$

$$Y_{pq} = G_{pq} - jB_{pq} \quad \text{...3.15}$$

Using the values of Vp and Ypq the expression for the power at bus p is:

$$P_p = \sum_{q=1}^{n} (e_p (e_a \; G_{pq} + f_p \; B_{pq}) + f_p (f_q \; G_{pq} - e_q \; B_{pq})) \quad \text{......................3.16}$$

$$Q_p = \sum_{q=1}^{n} (f_p (e_a \; G_{pq} + f_q \; B_{pq}) + e_p (f_p \; G_{pq} - e_a \; B_{pq})) \quad \text{.....3.17}$$

The changes are bus power are the differences between the scheduled powers and the calculated powers, that is:

$$\Delta P_p = P_{p.sched} - P_p \quad \text{..3.18}$$

$$\Delta Q_p = Q_{p.sched} - Q_p \quad \text{...3.19}$$

The Newton-Raphson requires a set of equations expressing the relationship between the changes in real and reactive powers and components of the voltages.

$$(11) \quad \begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \vdots \\ \Delta Q_n \end{bmatrix} = \left[\begin{array}{ccc|ccc} \frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_n} & \frac{\partial P_2}{\partial |V_2|} & \cdots & \frac{\partial P_2}{\partial |V_n|} \\ \vdots & & \vdots & \vdots & & \vdots \\ \frac{\partial P_n}{\partial \delta_2} & \cdots & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial |V_2|} & \cdots & \frac{\partial P_n}{\partial |V_n|} \\ \hline \frac{\partial Q_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_n} & \frac{\partial Q_2}{\partial |V_2|} & \cdots & \frac{\partial Q_2}{\partial |V_n|} \\ \vdots & & \vdots & \vdots & & \vdots \\ \frac{\partial Q_n}{\partial \delta_2} & \cdots & \frac{\partial Q_n}{\partial \delta_n} & \frac{\partial Q_2}{\partial |V_2|} & \cdots & \frac{\partial Q_n}{\partial |V_n|} \end{array} \right] \begin{bmatrix} \Delta \delta_2 \\ \vdots \\ \Delta \delta_n \\ \Delta V_2 \\ \vdots \\ \Delta V_n \end{bmatrix}$$

Where the square matrix of partial derivatives is a Jacobian matrix.

The matrix representation is reduced as thus:

$$\begin{vmatrix} \Delta P \\ \Delta Q \end{vmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{vmatrix} \Delta \delta \\ \Delta V \end{vmatrix}$$

From equations the new bus voltages can be calculated by multiplying the changes of real and reactive power by the inverse of the Jacobian matrix.

3.4.1Advantages of the Newton-Raphson

(i). The Newton-Raphson method has quadrature convergence characteristics and therefore, has fewer iterations. For large systems, it is faster, more accurate and more reliable than the Gauss-Seidel method.

(ii). It is used with advantage for large systems.

(iii). N-R method is based on calculating the voltage corrections while taking account of all the interactions as compared to the Gauss-Seidel which treats each bus independently and each correction to one bus requires subsequent correction to all the buses connected to it[12].

2.3.2Disadvantages of the Newton-Raphson

(i). The Newton-Raphson method takes longer time as elements of the Jacobian are to be computed for each iteration.

3.5Fast Decoupled Method

The Fast Decoupled Power Flow Method (FDPFM) is an approximation (simplification) of Newton-Raphson algorithm (N-R) by using knowledge of physical characteristics of electrical systems. The decoupling principle recognizes that in the steady state, active powers are strongly related to voltage angles, and reactive powers to voltage magnitudes. This implies that the load flow problem can be solved separately by two synthetic networks that is P-δ and Q-V networks, taking advantage of real power-reactive power (P–Q) decoupling. Therefore, the full derivative equation can be decoupled into two equations as:

$\Delta P = (\frac{\partial p}{\partial \delta})\ \Delta \boldsymbol{\delta}$ …………………………………………………………………….3.20

$\Delta Q= \quad -(\frac{\partial p}{\partial \delta}) \quad) \quad \Delta \boldsymbol{\delta}$ ……………………………………………………….3.21

The sub matrix involved in equation and is only half the size of the Jacobian matrix. This method due to its calculations simplifications, fast convergence and reliable results became the most widely used method in load flow analysis. However, FDPFM for some cases, where there is high R/X ratios or heavy loading (Low Voltage) at some buses are present, does not converge well and is ineffective. For these cases, many efforts and developments have been made to overcome these convergence obstacles. Some of them targeted the convergence of systems with high R/X ratios, others those with low voltage buses. However, the methods used in most utility companies are the Gauss-Seidel (G-S) and Newton-Raphson (N-R) method, with the N-R method has becoming the de-facto industry standard. The main reason for this is that the convergence properties of the N-R scheme are very desirable when the initial, guessed solution is quite good that is, when it is chosen close to the correct solution. In this project, the N-R method is used to solve the power flow problem [12].

3.6 Importance of load flow study

Power flow analysis is very important in planning stages of new networks or addition to existing ones like adding new generator sites, meeting increase load demand and locating new transmission sites.

The load flow solution gives the nodal voltages and phase angles and hence the power injection at all the buses and power flows through interconnecting power channels. It is helpful in determining the best location as well as optimal capacity of proposed generating station, substation and new lines. It determines the voltage of the buses. The voltage level at the certain It determines the voltage of the buses. The voltage level at the certain buses must be kept within the closed tolerances. System transmission loss minimizes.

Economic system operation with respect to fuel cost to generate all the power needed The line flows can be known. The line should not be overloaded, it means, we should not operate the close to their stability or thermal limits. Load flow study is the first point to many other studies in a power system such as contingency analysis, stability analysis and state estimation of power system.

3.7Modeling of power system with STATCOM

Based on the operating principle of the STATCOM, the equivalent circuit can be derived, which is given in fig. 2. In the derivation, it is assumed that,1. Harmonic generated by the STATCOM is neglected 2. The system as well as the STATCOM is assumed three phase balanced. The STATCOM can be equivalently represented by a controllable fundamental frequency positive sequence voltage source Vsh. In principle, the STATCOM output voltage can be regulated such that the reactive power of the STATCOM can be changed. [13]

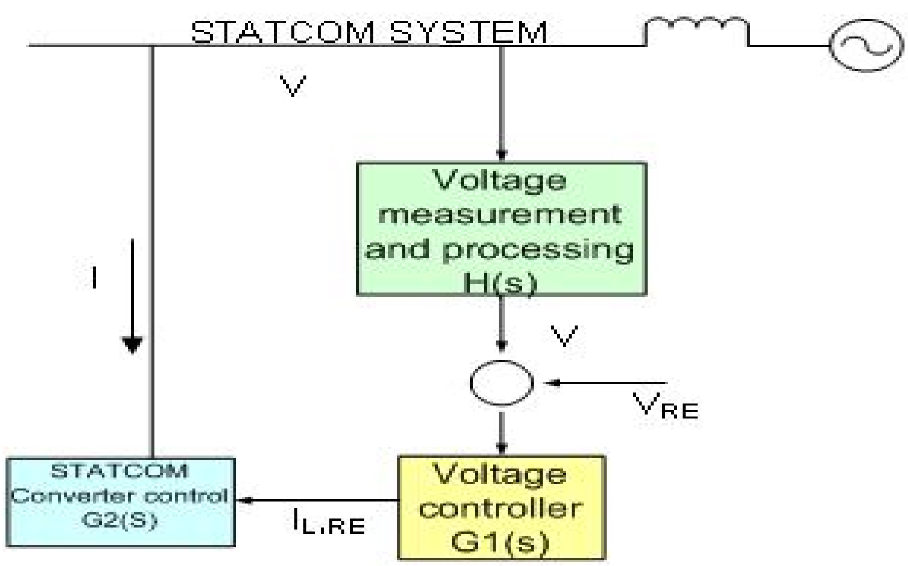


Fig 3.1 STATCOM voltage regulators and control loop

Based on the equivalent circuit, it can be established, Vi is the voltage at bus i, Ish is the current through the STATCOM shunt converter. Psh and Qshare the shunt converter branch active and reactive power flows respectively. The power flow direction of Psh and Qsh is leaving bus i. Zsh is the equivalent STATCOM shunt coupling transformer impedance. Flow constrains of STATCOM is

Psh=Vi^2 Gsh –ViVsh(Gsh cos($\theta i - \theta sh$) + $bsh \sin(\theta i - \theta sh)$)….3.22

Qsh=-Vi^2 bsh - ViVsh(Gsh cos($\theta i - \theta sh$) + $bsh \sin(\theta i - \theta sh)$….3.23

Where gsh+jbsh=$\frac{1}{Zsh}$ ……………………..……………………………3.24

The operating constraint of the STATCOM is the active power exchange via the DC link as described by:

PE=Re (Vsh Ish) ……………………………………………………….3.25

Re (Vsh Ish)= Vi^2 Gsh(Gsh cos($\theta i - \theta sh$) + $bsh \sin(\theta i - \theta sh)$)3.26

The principle of operation of VSC based STATCOM depends on the control strategy for regulating the interchange of power between the converter/inverter circuit and the grid and it depends also on the output AC voltage of the converter/inverter circuit. If the magnitude of the voltage of the converter is equal to the voltage of the grid Vsh$< Vi$, the interchange of reactive power between the STATCOM and the grid is equal to zero. In contrast, if the voltage of the converter is less than the grid voltage at point of common connection (PCC) Vsh$< Vi$, the STATCOM absorbs reactive power (draws lagging current). However, if the STATCOM controlled happens to be in such a way that the output voltage of the converter is higher than the grid voltage at PCC Vsh$< Vi$, reactive power is injected into the grid. Also, note that the capacity for injecting reactive power into the grid is limited by the maximum voltage and the maximum current allowed by the semiconductors. In practice, it is also necessary to control the active power exchange of the STATCOM by regulating the phase angle Ɵsh= Ɵi - Ɵsh between the voltage at the VSC (Vsh=Vsh$< \theta sh$) and the voltage at the PCC is Vi=Vi$< \theta i$ so that the VSC absorbs active power from the grid to maintain a constant voltage for the DC link .

The STATCOM is a FACTS controller based on voltage sourced converter (VSC). A VSC generate a synchronous voltage of fundamental frequency, controllable magnitude and phase angle. If a VSC is shunt-connected to a system via a coupling transformer as shown in Fig. 1, the resulting STATCOM can inject or absorb reactive power to or from the bus to which it is connected and thus regulate the bus voltage magnitude. This STATCOM model is known as Power Injection Model (PIM) or Voltage Source Model (VSM). Steady state modelling of STATCOM within the Newton-Raphson method in rectangular co-ordinates is carried out as follows [9]:

The Thevenin equivalent circuit representing the fundamental frequency operation of the switched-mode voltage sourced converter and its transformer is shown in Figure 3.2.

Vstc =Vk +Zsc Istc…………………………………………………………3.27

is expressed in Norton equivalent form

Istc =In – YscVk……………………………………………………………3.28

In =Ysc Vstc ………………..……………………………………...3.29

In these expressions Vk, represents bus k voltage and Vstc represents the voltage source inverter. In is the Norton's current while Istc is the inverter's current. Also Zstc, and Ysc are the transformer's impedance and short-circuit admittance respectively. The STATCOM voltage injection Vstc bound constraints is as follows:

Vstc min$\leq \boldsymbol{Vstc} \leq \boldsymbol{Vstc\ max}$

Where Vstc min and Vstc max are the STATCOM's minimum and maximum voltages. The current expression in is transformed into a power expression by the VSC and power injected into bus K as shown in equations and respectively.

Sstc =Vstc $\boldsymbol{Istc^*} = \boldsymbol{Vstc^2}\,\boldsymbol{Ysc^*}$ – Vstc $\boldsymbol{Ysc^*}\ \boldsymbol{Vk^*}$ …………………..3.30

Sk = Vk $\boldsymbol{Istc^*} = \boldsymbol{Vstc^2}\,\boldsymbol{Ysc^*} -$ Vstc $\boldsymbol{Ysc^*}\ \boldsymbol{Vk^*}$ ……………………3.31

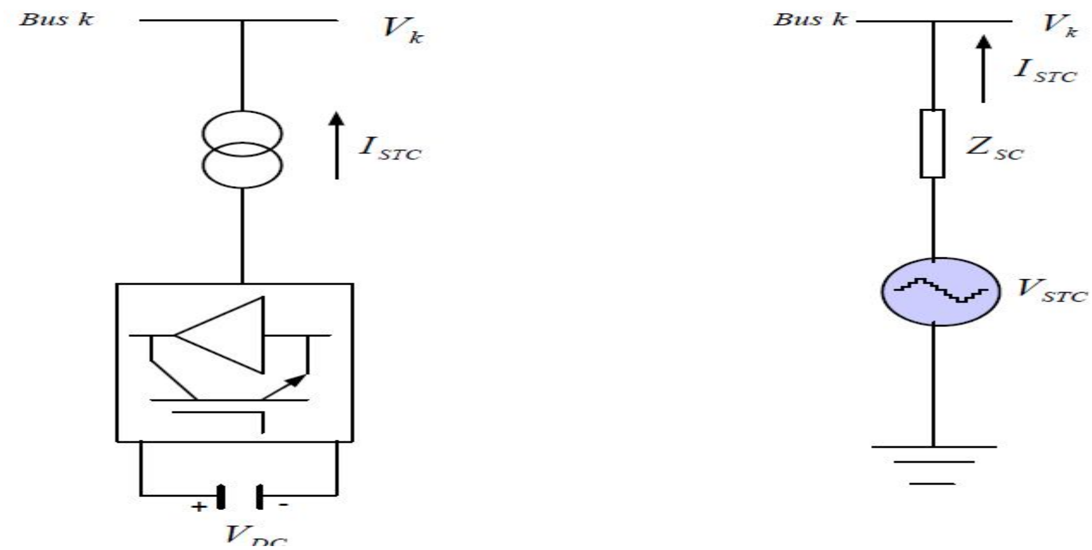


Fig3.2 A) Statcom schematic diagram B) Statcom equivalent

Using the rectangular coordinate representation,

Vk = ek+ j fk ……………………………………………………………3.32

V stc= estc + j fstc…………………………………………………………3.33

Vstc= $(etc^2 + ftc^2)^{1/2}$ ………………………………………………….3.34

$\delta\ stc = \tan^{-1}\frac{fstc}{estc}$…………………………………………………………3.35

Where Vstc and δ stc are the STATCOM voltage magnitude and angle respectively ek and fk are the real and imaginary parts of the bus voltage respectively.

estc and fstc are the real and imaginary parts of the STATCOM voltage respectively

The active and reactive powers for the STATCOM and node k respectively are

Qstc = Gsc(estc ek – fstc ek) + Bsc(- $estc^2$ - $fstc^2$ + estc ek + fstc fk)…3.36

And

Pk= Gsc(ek^2+fk^2- (estc ek – fstc fk)+ Bsc(ek fstc –fk estc)……………..3.37

Qk=Gsc(ek fstc-fk estc) + Bsc(ek fstc + fk estc) – (ek^2+fk^2)…………..3.38

Pstc= Gsc ($estc^2$ + $fstc^2$) – (estc ek +fstc fk)+ Bsc(ek fstc –fk estc)…….3.39

3.8V-I CHARACTERISTICS OF STATCOM

A typical V-I characteristic of a STATCOM is depicted in Fig.

The STATCOM can supply both the capacitive and the inductive compensation and is able to independently control its output current over the rated maximum capacitive or inductive range irrespective of the amount of ac-system voltage.

The STATCOM can provide full capacitive-reactive power at any system voltage—even as low as 0.15 pu.

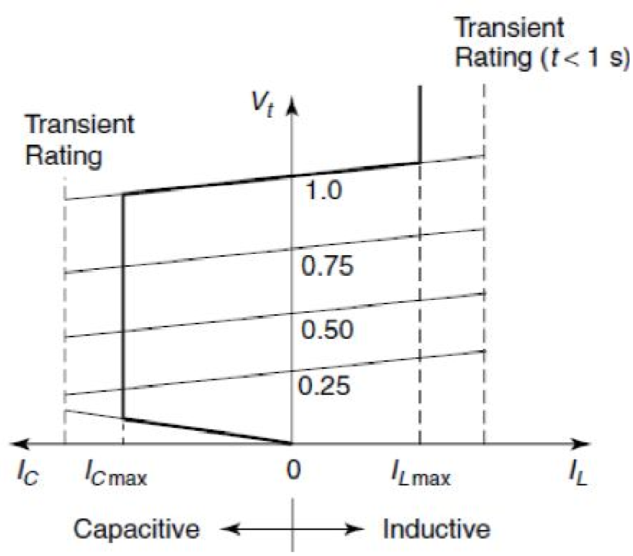


Fig 3.3V-I CHARACTERISTICS OF STATCOM

The characteristic of a STATCOM reveals another strength of this technology: that it is capable of yielding the full output of capacitive generation almost independently of the system voltage (constant-current output at lower voltages). This capability is particularly useful for situations in which the STATCOM is needed to support the system voltage during and after faults where voltage collapse would otherwise be a limiting factor [13].

Figure illustrates that the STATCOM has an increased transient rating in both the capacitive- and the inductive-operating regions. The maximum attainable transient overcurrent in the capacitive region is determined by the maximum current turn-off capability of the converter switches. In the inductive region, the converter switches are naturally commutated; therefore, the transient-current rating of the STATCOM is limited by the maximum allowable junction temperature of the converter switches. In practice, the semiconductor switches of the converter are not lossless, so the energy stored in the dc capacitor is eventually used to meet the internal losses of the converter, and the dc capacitor voltage diminishes.

However, when the STATCOM is used for reactive-power generation, the converter itself can keep the capacitor charged to the required voltage level. This task is accomplished by making the output voltages of the converter lag behind the ac-system voltages by a small angle (usually in the 0.18–0.28 range).

In this way, the converter absorbs a small amount of real power from the ac system to meet its internal losses and keep the capacitor voltage at the desired level. The same mechanism can be used to increase or decrease the capacitor voltage and thus, the amplitude of the converter-output voltage to control the var generation or absorption. The reactive- and real-power exchange between the STATCOM and the ac system can be controlled independently of each other.

Any combination of real power generation or absorption with var generation or absorption is achievable if the STATCOM is equipped with an energy-storage device of suitable capacity, as depicted in Fig3.3.With this capability, extremely effective control strategies for the modulation of reactive- and real-output power can be devised to improve the transient- and dynamic-system-stability limits.

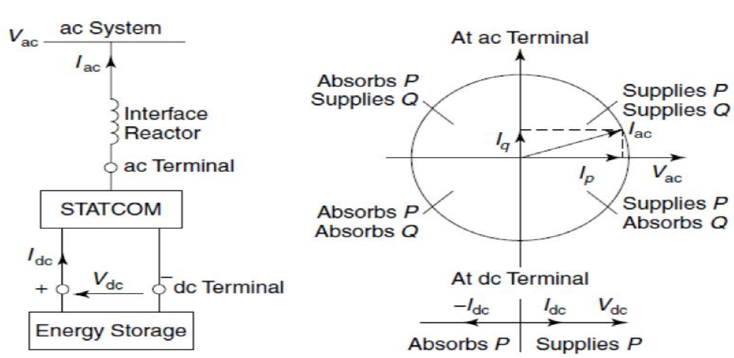


Fig3.4 Statcom operation

3.9Modes of Operation

The STATCOM can be operated in two different modes:

A. Voltage Regulation

The static synchronous compensator regulates voltage at its connection point by controlling the amount of reactive power that is absorbed from or injected into the power system through a voltage-source converter.

In steady-state operation, the voltage V2 generated by the VSC through the DC capacitor is in phase with the system voltage V1 ($\delta=0$), so that only reactive power (Q) is flowing (P=0).

1. When system voltage is high, the STATCOM will absorb reactive power (inductive behavior)

2. When system voltage is low, the STATCOM will generate and inject reactive power into the system (capacitive).

Subsequently, the amount of reactive power flow is given by the equation:

Q = [V1(V1-V2)] / X ……………………………………………………3.40

B. Var Control

In this mode, the STATCOM reactive power output is kept constant independent of other system parameter

3.9.1 Linearized Power Equations

A single-phase power network with n-buses is described by2*(n-1) non-linear equations. The inclusion of one STATCOM model augments the number of equations by two. The solution of the combined system of non-linear equations is carried out by iteration using the full Newton-Raphson method. The Jacobian used in conventional power flow is suitably extended to take account of the new elements contributed by the STATCOM. The set of linearized power flow equations for the complete system is

$$\begin{bmatrix} \Delta P_k \\ \Delta |V_k|^2 \\ \Delta P_{STC} \\ \Delta Q_{STC} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial e_k} & \frac{\partial P_k}{\partial f_k} & \frac{\partial P_k}{\partial e_{STC}} & \frac{\partial P_k}{\partial f_{STC}} \\ \frac{\partial |V_k|^2}{\partial e_k} & \frac{\partial |V_k|^2}{\partial f_k} & 0 & 0 \\ \frac{\partial P_{STC}}{\partial e_k} & \frac{\partial P_{STC}}{\partial f_k} & \frac{\partial P_{STC}}{\partial e_{STC}} & \frac{\partial P_{STC}}{\partial f_{STC}} \\ \frac{\partial Q_{STC}}{\partial e_k} & \frac{\partial Q_{STC}}{\partial f_k} & \frac{\partial Q_{STC}}{\partial e_{STC}} & \frac{\partial Q_{STC}}{\partial f_{STC}} \end{bmatrix} \begin{bmatrix} \Delta e_k \\ \Delta f_k \\ \Delta e_{STC} \\ \Delta f_{STC} \end{bmatrix}$$

3.10 Restriction of Operation

1. In a STATCOM, the maximum reactive power that can be supplied to the grid depends on the maximum voltage and current permitted by the power semi-conductor, so it’s necessary to include the following restriction.

The VSC output voltage must fall within the allowed limits of operation:

1. $\boldsymbol{Vsh^{min}} \le \boldsymbol{Vsh} \le \boldsymbol{Vsh^{max}}$, $-\boldsymbol{\pi} \le \boldsymbol{\theta sh} \le \boldsymbol{\pi}$

Where$\boldsymbol{Vsh^{max}}$ is the voltage rating of the STATCOM, While $\boldsymbol{Vsh^{min}}$ is the minimal voltage limit of the STATCOM.

2. The current flowing through a STATCOM Ish

must be less than the current rating Ish$\le \boldsymbol{Ish^{max}}$Where $\boldsymbol{Ish^{max}}$ is the current rating of the STATCOM converter while Ish the magnitude of current through the STATCOM and given by Ish=$\frac{\boldsymbol{Vi-Vsh}}{\boldsymbol{Zsh}}$ In contrast, it is necessary to include external restriction of the grid voltage at the PCC. According to the specific regulation of the grid operator, the grid voltage at the PCC must be within certain allowed limits. $\boldsymbol{Vi^{min}} < \boldsymbol{Vi} < \boldsymbol{Vi^{max}}$.[13]

Chapter Four

Simulation Results and Discussion

4.1 Introduction

The load-flow problem models the nonlinear relationships among bus power injections, power demands, and bus voltages and angles, given the network constants and the circuit parameters. It is the heart of most system-planning studies and also the starting point for transient and dynamic stability studies. This chapter provides a formulation of the load flow problem and its associated solution strategies.

4.2 Case study Load flow model of national grid

The National grid of Sudan is modelled using 500, 220 and 110 KV buses (66 bus-bars). The lines ohmic per unit length data and transformer data are obtained and then converted and expressed in per unit representation. Bus data which represent power generation(PGi) and load (PLi,) (QLi) of the transmission network are obtained.

4.2.1 The National grid of Sudan

Up to the year 2002, the combined grid-connected generating capacity in Sudan was 728 MW. This was far lower than the required rate and the government sought to increase it to avoid blackouts. The design capacity of generation in the national network amounted to 1234.6 MW up to the end of 2008:

342.8 MW which were from water generation

180 MW from steam generation

45.2 MW from diesel generation

65 MW from gas generation

450 MW from mixed generation

In addition to thermal plants outside the national electricity network in most of Sudanese cities with a 151.6 MW capacity.

in 2006, Construction of Marwi Dam project was intended to roughly double Sudan's power generation in addition to increasing the national network security. Marwi Dam with its peak output of 1260 MW will almost double this capacity if it runs successfully. NEPLAN is used for analysis of this network as shown in figure (4.3. The NEPLAN obtain the Voltage magnitude, voltage angle, active and reactive power at any bus, and also active and reactive power and losses in transmission lines

4.3Data Survey

Data of the network of the national grid are obtained from the National grid control center and it covered all of the following items:

1\Transmission lines types and parameters as series resistances, series reactance's and charging capacitances per unit length and lines total length in kilometers.

2\ Number of circuits of transmission lines and its current capacity limited by circuit breakers and relays settings.

3\ Number of transformers and its data.

4\ Generation unit's maximum output powers and its VAR limits.

Last modifications on the system configuration.

5\ Load on the network at heavy load condition.

6\ Relays setting for maximum permissible current.

The parameters are expressed in per unit values; power base is chosen as100 MVA and each of the voltage levels500, 220 and110 are taken as voltage.

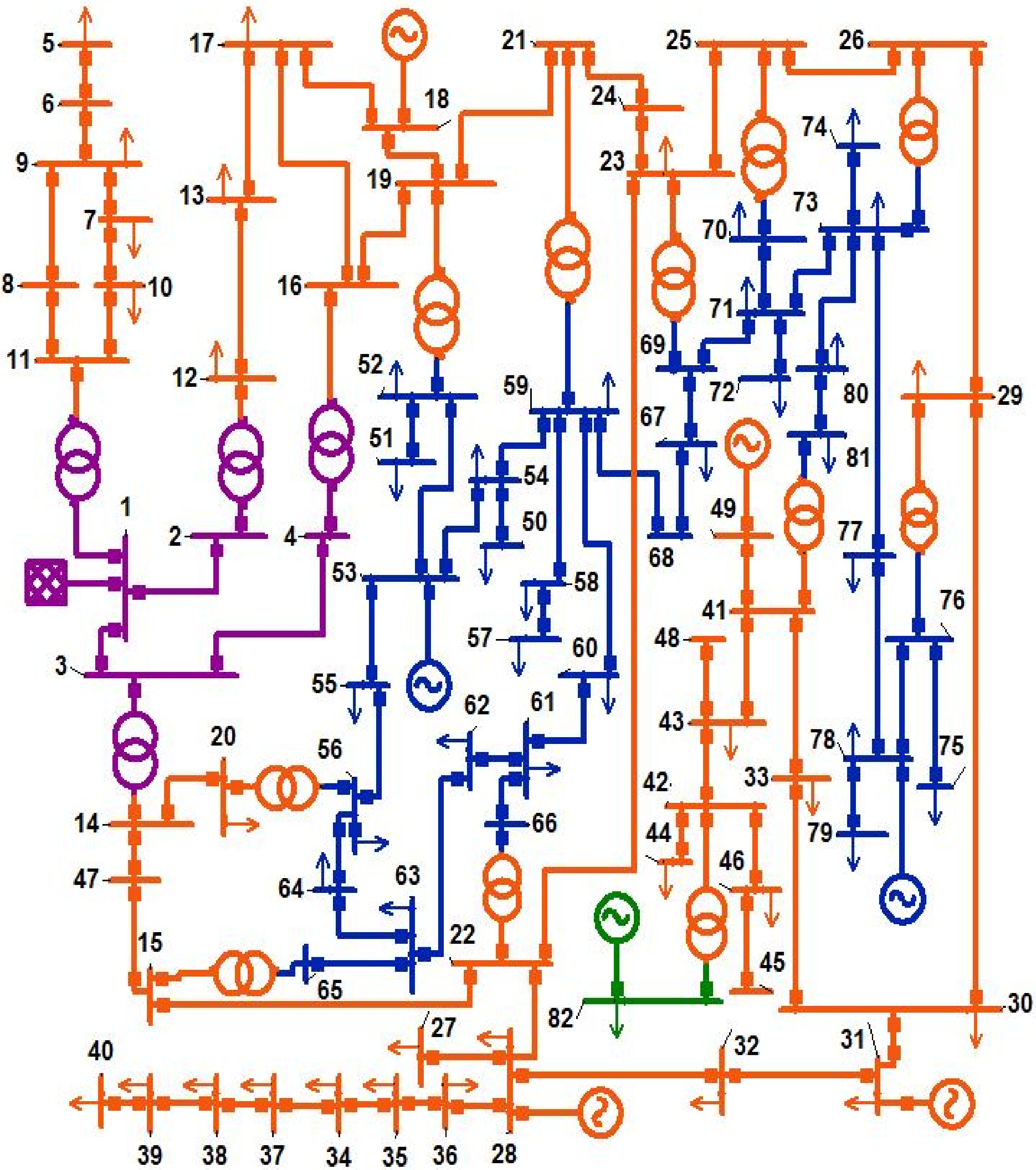


Fig 4.1 National grid of Sudan

Table 4.1NG bus codes and numbers

Bus-bar Number	Bus-bar Name	Bus-bar Code
1	MARWI POWER PLANT13.8KV	MWP13.8
2	GARI 11KV	GAR11
3	ROSSERIES 11KV	ROS11
4	KHARTOUM NORTH 11KV	KHN11
5	SENNAR POWER PLANT11KV	SNP11
6	MARWI POWER PLANT500KV	MWP500
7	MRKHIAT500KV	MRK500
8	KABASHI 500KV	KAB500
9	ATBARA 500KV	ATB500
10	GARI 220KV	GAR220
11	ROSSERIES 220KV	ROS220
12	MARWI POWER PLANT220KV	MWP220
13	KABASHI 220KV	KAB220
14	SENNAR JUNCTION 220KV	SNJ220
15	MARINJAN 220KV	MAR220
16	GIAD 220KV	GAD220
17	KILO X 220KV	KLX220
18	JABEL AWLIASTATION220KV	JAS220
19	IED BABIKER 220KV	IBA220
20	FREE ZONE 220KV	FRZ220
21	SHANDI 220KV	SHN220
22	ATBARA 220KV	ATB220
23	MASHKOUR 220KV	MSH220
24	MAHDIA 220KV	MHD220
25	RABAK 220KV	RBK220
26	MRKHIAT220KV	MRK220
27	PORTSUDAN 220KV	PORT220

28	MARWI TOWN 220KV	MWT220
29	DEBA 220KV	DEB220
30	DONGOLA 220KV	DON220
31	KHARTOUM NORTH 110KV	KHN110
32	SENNAR POWER PLANT110KV	SNP110
33	KUKU 110KV	KUK110
34	KILO X 110KV	KLX110
35	FAROUG 110KV	FAR110
36	LOCAL MARKET 110KV	LOM110
37	IED BABIKER 110KV	IBA110
38	IZERGAB 110KV	IZG110
39	MAHDIA 110KV	MHD110
40	OMDURMAN 110KV	OMD110
41	MUGRAN 110KV	MUG110
42	SHAGRA 110KV	SHG110
43	JABEL AWLIASTATION110KV	JAS110
44	GIAD 110KV	GAD110
45	BAGAIR 110KV	BAG110
46	HASSAHIESA 110KV	HAS110
47	HAG ABDALLAH 110KV	HAG110
48	MARINJAN 110KV	MAR110
49	SENNAR JUNCTION 110KV	SNJ110
50	MNAGIL 110KV	MNG110
51	RANK 220KV	RNK220
52	TANDALTI 220KV	TND220
53	OMRAWABA 220KV	OMR220
54	OBAID 220KV	OBD220
55	KHARTOUM EAST 110KV	KHE110
56	RABAK 110KV	RBK110
57	MINA SHRIEF 110KV	MIS110

58	ALFAO 110KV	FAO110
59	GDARIF 110 KV	GDA110
60	BANAT 110KV	BNT110
61	GAMOIEA 220KV	GAM220
62	GAMOIEA 110KV	GAM110
63	GENIED 110 KV	GEN110
64	GDARIF 220 KV	GDA220
65	HAWATA 220 KV	HAW220
66	SINGA 220 KV	SNG220

Table 4.2 NG line data (Per Unit Data)

No.	From Bus	To Bus	R(P.U)	X(P.U)	1/2B	> 1 or < 1 tr. tap at bus nl ,= 1 for lines
1	1	6	0	0.012094	0	1.05
2	2	10	0	0.02325	0	1.09
3	3	11	0	0.03439	0	1.03
4	4	31	0	0.0205	0	1.09
5	5	32	0	0.056	0	0.95
6	6	12	0	0.1696	0	0.95
7	6	7	0.0019208	0.0189336	0.05244499	1
8	6	9	0.002352	0.023184	0.07891312	1
9	7	26	0	0.0848	0	1.05
10	7	8	0.0004256	0.0041952	0.39	1
11	8	13	0	0.0848	0	1
12	9	22	0	0.0848	0	1.09
13	10	19	0.00415283	0.01871900	0.11908839	1
14	10	20	0.00034607	0.00155991	0.00992403	1
15	12	28	0.00533884	0.02830991	0.023304	1
16	13	20	0.00179958	0.00811157	0.05160497	1
17	14	49	0	0.06975	0	1.09

18	14	15	0.00659504	0.03497107	0.11520758	1
19	14	66	0.00392562	0.02081611	0.06854117	1
20	15	48	0	0.03389	0	1.15
21	15	16	0.01107024	0.05870144	0.19338415	1
22	16	44	0	0.1395	0	1.09
23	16	17	0.00337603	0.01790186	0.05897530	1
24	16	18	0.00249173	0.01123140	0.07148927	1
25	17	34	0	0.01866	0	1.1
26	17	19	0.00096900	0.00436776	0.02780138	1
27	18	43	0	0.066	0	0.95
28	18	23	0.01024380	0.04617355	0.29375137	1
29	18	26	0.00526033	0.04617355	0.150845	1
30	19	37	0	0.05784	0	1.09
31	19	13	0.00207644	0.00935950	0.05957439	1
32	20	21	0.00795971	0.03587809	0.22825275	1
33	22	27	0.07066115	0.37469008	0.30843529	1
34	23	25	0.00747520	0.03369421	0.21435910	1
35	24	39	0	0.063	0	1.09
36	24	26	0.00138429	0.00623966	0.03969613	1
37	25	51	0.02260557	0.10189380	0.16205945	1
38	25	52	0.01536570	0.06926033	0.11015676	1
39	25	56	0	0.06975	0	1.09
40	26	61	0.00263016	0.01185537	0.07542264	1
41	28	29	0.02198347	0.11657024	0.09595764	1
42	29	30	0.02198347	0.11657024	0.09595764	1
43	31	33	0.00161776	0.00704752	0.00162424	1
44	31	37	0.00332231	0.01333884	0.00595442	1
45	32	47	0.17256198	0.20876033	0.00980245	1
46	32	49	0.02876033	0.03479338	0.00163374	1
47	32	57	0.19844628	0.24007438	0.01127282	1
48	33	34	0.00524876	0.02286528	0.00526976	1
49	33	55	0.00177190	0.00711405	0.00079392	1
50	34	35	0.00387603	0.01556198	0.00694682	1

51	36	42	0.00083057	0.00333471	0.00148860	1
52	37	38	0.00885950	0.03557024	0.01587845	1
53	38	39	0.00221487	0.00889256	0.00396961	1
54	39	40	0.00257479	0.01033760	0.00461467	1
55	40	41	0.00268553	0.01078223	0.00481315	1
56	41	42	0.00304545	0.01222727	0.00545821	1
57	42	43	0.00996694	0.04001652	0.01786325	1
58	44	45	0.00862809	0.01043801	0.00049012	1
59	44	46	0.22145454	0.26790909	0.01257981	1
60	46	48	0.15818181	0.19136363	0.00898558	1
61	46	63	0.00415289	0.01667355	0.00744302	1
62	47	48	0.10066115	0.12177686	0.00571809	1
63	48	50	0.05666528	0.15596446	0.01197086	1
64	48	58	0.20419834	0.24703305	0.01159956	1
65	49	56	0.27609917	0.33401652	0.01568392	1
66	51	11	0.02392066	0.10782148	0.17148728	1
67	52	53	0.01083905	0.04885661	0.07770517	1
68	53	54	0.01744214	0.07861983	0.12504281	1
69	59	58	0.44003305	0.53233884	0.02499625	1
70	60	62	0.0045681	0.0183409	0.0081873	1
71	61	62	0	0.06975	0	1.09
72	64	59	0	0.06975	0	1.09
73	64	65	0.0076136	0.0343181	0.2183287	1
74	66	11	0.0139752	0.0741053	0.2440065	1
75	66	65	0.0062933	0.0280785	0.1786325	1

4.4 Results and Discussions

4.4.1Analysis of Load flow result

The load flow analysis of National Grid of Sudan are carry-out based on Newton-Raphson method on peak load. The load flow is done without any compensation at any bus. The result shows that 43 buses found to be under normal voltage level (Vbus< 0.95 P.U)

Table 4.3 Load flow analysis before enhancement

NAME	U KV	U %	U ang	P LOAD	Q LOAD	P GEN	Q GEN	Q SHUNT
ATB5	502.15	100.43	-8.7	0	0	0	0	0
B-1230801506	11.55	105	3.1	0	0	125	35.74	0
B-1230801512	11.55	105	3.1	0	0	125	35.74	0
B-1230801515	11.55	105	3.1	0	0	125	35.74	0
B-1230801518	11.55	105	3.1	0	0	125	35.74	0
BAG1	96.482	87.71	-21.5	14.6	12.7	0	0	-3.847
BNT1	99.299	90.27	-18	50	10	0	0	0
DEB2S1	219.48	99.76	-11.7	0	0	0	0	0
DEB2S2	219.48	99.76	-11.7	4.5	1.8	0	0	19.906
DON2S1	221.112	100.51	-12.2	0	0	0	0	0
DON2S2	221.112	100.51	-12.2	8.8	3.4	0	0	0
FAO1	98.554	89.59	-34.7	40	1.6	0	0	0
FAR1	95.652	86.96	-20.8	84	51.4	0	0	0
FRZ2	206.285	93.77	-12.4	7	3.5	0	0	0
GAD1	96.692	87.9	-21.6	0	0	0	0	0
GAD2	191.438	87.02	-17	0	0	0	0	0
GAM1	99.791	90.72	-17.4	0	0	0	0	0
GAM2	192.209	87.37	-15.8	0	0	0	0	0
GAR_G1	11.132	101.2	-7	0	0	33	27	0
GAR_G10	11.137	101.24	-7	0	0	33	27	0
GAR_G11	11.137	101.24	-7	0	0	33	27	0

GAR_G12	11.134	101.22	-6.7	0	0	35	27	0
GAR_G13	10.956	99.6	-5	0	0	55	27	0
GAR_G14	10.956	99.6	-5	0	0	55	27	0
GAR_G2	11.132	101.2	-7	0	0	33	27	0
GAR_G3	11.129	101.17	-6.6	0	0	35	27	0
GAR_G4	11.132	101.2	-7	0	0	33	27	0
GAR_G5	11.132	101.2	-7	0	0	33	27	0
GAR_G6	11.129	101.17	-6.6	0	0	35	27	0
GAR_G7	11.127	101.16	-7	0	0	33	27	0
GAR_G8	11.137	101.24	-7	0	0	33	27	0
GAR_G9	11.134	101.22	-6.7	0	0	35	27	0
GAR2S1	206.733	93.97	-12.3	100	20	0	0	0
GAR2S2	206.939	94.06	-12.2	0	0	0	0	0
GBA_6	5.844	97.4	-41.6	3.4	1.6	5.4	2.9	0
GBA66	64.003	96.97	-41.9	0	0	0	0	0
GDF1	109.275	99.34	-26.5	0	0	0	0	0
GDF2	215.669	98.03	-24.7	0	0	0	0	0
GDF66	68.487	103.77	-29.4	12.2	5.9	0	0	0
GEN1	95.55	86.86	-28.3	0	0	0	0	0
HAG1	99.083	90.08	-32.9	13.7	1.4	0	0	0
HAS1	95.538	86.85	-28.3	13.4	18.7	0	0	-3.772
HWT2	207.45	94.3	-27.4	210	5	0	0	0
IBA1	98.943	89.95	-17.8	45	26.5	0	0	0
IBA2	195.473	88.85	-14.8	0	0	0	0	0
IZG1	96.191	87.45	-22.1	154	28.8	0	0	-3.823
JAP33	31.355	95.01	-18.1	0	0	0	0	0
JAP69_1	0.63	91.33	-16.5	0	1.178	1.9	0	0
JAP69_2	0.63	91.33	-16.5	0	1.178	1.9	0	0
JAP69_3	0.63	91.33	-16.5	0	1.178	1.9	0	0
JAP69_4	0.63	91.33	-16.5	0	1.178	1.9	0	0
JAP69_5	0.63	91.33	-16.5	0	1.178	1.9	0	0
JAP69_6	0.63	91.33	-16.5	0	1.178	1.9	0	0
JAP69_7	0.63	91.33	-16.5	0	1.178	1.9	0	0

JAP69_8	0.63	91.33	-16.5	0	1.178	1.9	0	0
JAS1	101.235	92.03	-18.9	0	0	0	0	0
JAS2	192.317	87.42	-15.7	0	0	0	0	0
KAB2	202.477	92.03	-13.1	0	0	0	0	0
KAB5	490.943	98.19	-10.6	0	0	0	0	0
KHE1	96.49	87.72	-17.7	88.2	46.2	0	0	0
KHN1	97.441	88.58	-16.4	0	0	0	0	0
KHN11_GT_4	9.961	90.56	-14.7	0	0	15	10.6	0
KHN11_GT1	10.363	94.21	-23	0	0	13	10.6	0
KHN11_ST1	11.735	99.45	-10.5	0	0	33	17	0
KHN11_ST2	11.735	99.45	-10.5	0	0	33	17	0
KHN11_ST3	11	100	-10.8	0	0	60	18.765	0
KHN11_ST4	11	100	-10.8	0	0	60	18.765	0
KHN11_ST5	11	100	-8.1	0	42.416	110	0	0
KHN11_ST6	11	100	-8.1	0	42.416	110	0	0
KHN3	29.306	88.81	-27.1	64	7.437	0	0	-3.943
KL366	63.885	96.8	-42	2	1	0	0	0
KLX1	97.076	88.25	-19.9	0	16.8	0	0	0
KLX2	192.144	87.34	-16	0	0	0	0	22.884
KSL66	66.073	100.11	-46.9	0	0	0	0	0
KUK1	96.794	87.99	-17.5	0	0	0	0	0
LOM1	96.495	87.72	-20.7	164	42.5	0	0	0
MAN1	100.157	91.05	-33.4	10	2.2	0	0	0
Mar-01	101.085	91.9	-32.4	110	31.1	0	0	0
Mar-02	188.216	85.55	-25	0	0	0	0	0
MHD1	96.065	87.33	-22.6	163	60	0	0	-3.813
MHD2	189.083	85.95	-16.3	0	0	0	0	0
MNA1	92.946	84.5	-33.9	15.7	5.7	0	0	0
MRK2	192.413	87.46	-15.4	0	0	0	0	0
MRK5	492.725	98.54	-10.3	0	0	0	0	0
MRW5_S1	511.048	102.21	-6	0	0	0	0	0
MRW5_S2	511.072	102.21	-6	0	0	0	0	0
MSH2	210.777	95.81	-7.4	0	0	0	0	27.537

MUG1	94.631	86.03	-23.2	54.5	16.275	0	0	0
MUG1_1	94.625	86.02	-23.2	89.025	48.825	0	0	0
MWAIS2	218.934	99.52	-9.1	0	0	0	0	0
MWAIS3_1	32.868	99.6	-9.3	0	0	0	0	0
MWAIS3_2	32.868	99.6	-9.3	0	0	0	0	0
MWP14_1	13.524	98	0	0	0	117.256	14.151	0
MWP14_10	13.524	98	0.4	0	0	125	13.407	0
MWP14_2	13.524	98	0	0	0	117.42	12.594	0
MWP14_3	13.524	98	-12.5	125	0	0	14.04	0
MWP14_4	13.524	98	-12.5	125	0	0	15.713	0
MWP14_5	13.524	98	0.4	0	0	125	15.071	0
MWP14_6	13.524	98	0.4	0	0	125	13.412	0
MWP14_7	13.524	98	0.3	0	0	125	15.063	0
MWP14_8	13.524	98	0.3	0	0	125	13.422	0
MWP14_9	13.524	98	0.4	0	0	125	15.082	0
MWT2S1	216.957	98.62	-10.8	0	0	0	0	0
MWT2S2	216.957	98.62	-10.8	129	40	0	0	0
NHLF66	62.386	94.52	-42.9	4.1	2	0	0	0
OBE2	224.685	102.13	-2.6	6.1	3.7	0	0	31.291
OMD1	94.895	86.27	-23.5	153	32.7	0	0	-1.861
POR2	187.651	85.3	-30.4	94	9.9	0	0	21.826
RBK1	109.307	99.37	-3.4	30	5	0	0	0
RBK11	92.778	84.34	-33.4	11.2	5.4	0	0	0
RBK2	225.094	102.32	-2.2	0	0	0	0	31.405
RNK2	221.897	100.86	-6.8	0.5	0.5	0	0	30.52
ROS11_1	11	100	-11.7	0	0	30	7.145	0
ROS11_2	11	100	-12.8	0	0	15	6.375	0
ROS11_3	11	100	-6.9	0	0	40	8.087	0
ROS11_4	11	100	-11.4	0	0	40	9.444	0
ROS11_5	10.388	94.44	-17.3	0	0	0	0	13.378
ROS11_5	11	100	-7.3	0	0	40	8.149	0
ROS11_6	11	100	-6.9	0	0	40	7.479	0
ROS11_7	11	100	-6.9	0	0	40	7.48	0

ROS2	214.954	97.71	-16.9	200	3.3	0	0	0
RWS66	66.34	100.51	-33	2	0.9	0	0	0
SENJ1	98.733	89.76	-31.5	78.6	5.3	0	0	0
SENJ2	195.547	88.88	-26.3	0	0	0	0	23.702
SENP1	98.599	89.64	-31.8	3	1	0	0	0
SHEH	229.9	104.5	-18.6	0	0	200	36.62	0
SHG1	95.925	87.2	-21.8	112	41.5	0	0	0
SHK66	65.155	98.72	-35.9	2	0.969	0	0	0
SHN2	211.186	95.99	-12.3	11.5	5.8	0	0	0
SIN2	202.07	91.85	-25.7	50	15	0	0	25.309
TAN2	225.593	102.54	-2.4	1.2	0.2	0	0	31.545
UMR2	225.553	102.52	-2.6	2.6	1	0	0	31.533

4.5 Identification of Weakest Bus and Transmission Line:

There are servals effective methods for identification of weak bus-bars or transmission lines in our research we will use FAST VOLTAGE STABILITY METHOD.

4.5.1 Fast voltage stability index (FVSI)

Identification of weakest bus is for objective to identify the best location for reactive power compensation for the improvement of static voltage stability margin of the system. In this study a line based voltage stability index called Fast Voltage Stability Index (FVSI) is utilized as the indicator voltage stability indices are calculated for each weak line in order to evaluate the stability limit by using (Fast Voltage Stability Index (FVSI)) method by using the next equation, Taking the symbols ‘i’ as the sending bus and ‘j’ as the receiving bus

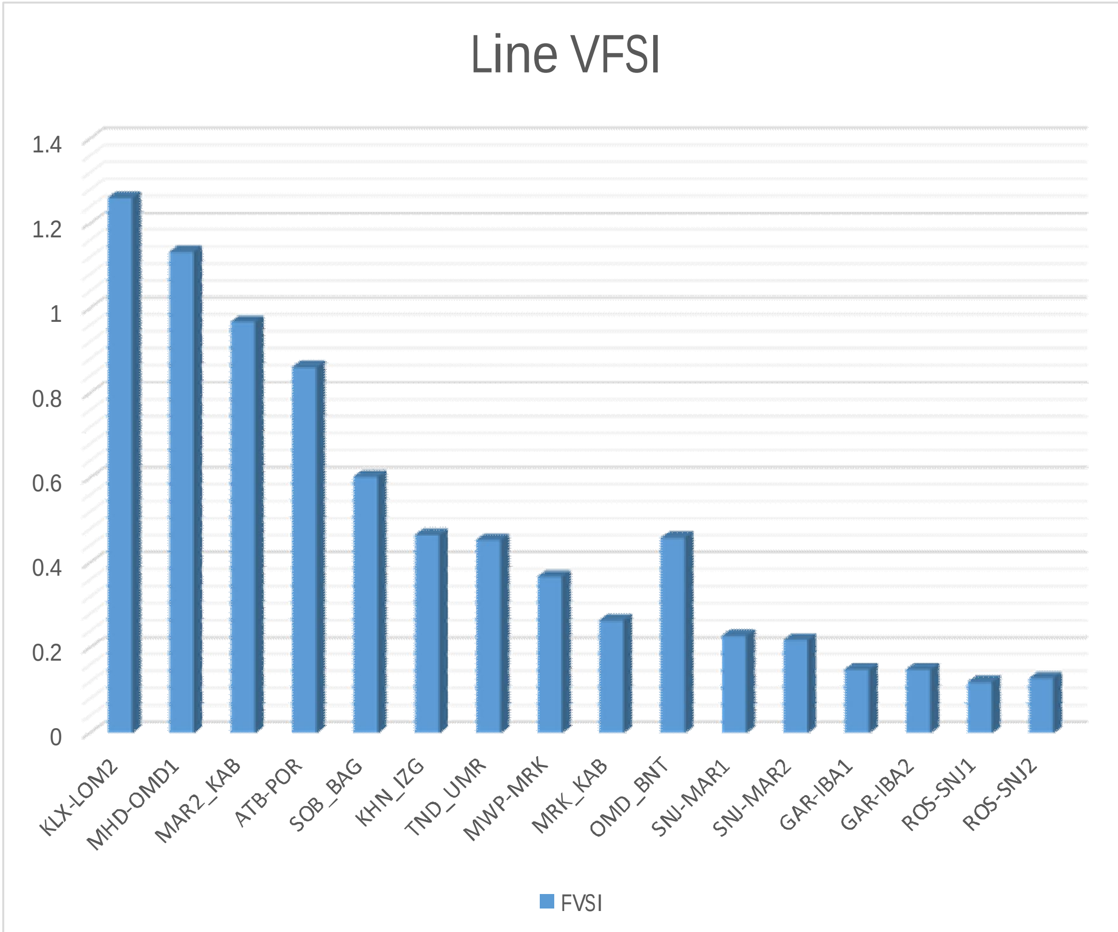
$$\text{FVSI}_{ij} = \frac{4Z^2 Qj}{Vi^2 \; Xij} \qquad \ldots\ldots 4.1$$

where, Z = line impedance, Xij = line reactance, Qj = reactive power at the receiving end and Vi = sending end voltage

The value of FVSI that is evaluated close to 1 indicates that the particular line is close to its instability point which may lead to voltage collapse in the entire system. To maintain a secure condition, the value of FVSI should be maintained well less than 1. The lines are rearranged according to (FVSI) values from highest to lowest and shown in table 4.4. This arrangement represents the most severe lines in the system which is the candidate locations for **STATCOM** installation

Table 4.4 Ranking of weak lines depend on FVSI values

Rank	**Line name**	**FVSI**
1	KLX-LOM2	**1.262**
2	MHD-OMD1	**1.134**
3	MAR2_KAB	**0.97**
3	ATB-POR	***0.862***
4	SOB_BAG	**0.6043**
5	KHN_IZG	**0.467**
6	TND_UMR	**0.455**
7	MWP-MRK	**0.369**
8	MRK_KAB	***0.266***
9	OMD_BNT	***0.46***
10	SNJ-MAR1	***0.23***
11	SNJ-MAR2	***0.22***
12	GAR-IBA1	***0.15***
13	GAR-IBA2	***0.15***
14	ROS-SNJ1	***0.12***
15	ROS-SNJ2	***0.13***



4.6Load flow results after enhancement by using STATCOMS

We start our enhancement by installing STATCOM device at bus bar LOM1 we find that from a previous researches that LOM1 is more substation loaded and unstable and have an under voltage problems. The enhancement of the voltage at this bus bar and by the way the grid is done by using Statcom device added to this bus bar and setting the current (Ic & IL), then the Statcoms started to generate MVAR and the voltage in this bus bar increased and also at the other buses, in the next schedule we see the bus bars voltage after the enhancement

Table 4.5 load flow analysis after enhancement by (LOM1) STATCOM

NAME	U KV	U %	U ang	P LOAD	Q LOAD	P GEN	Q GEN	Q SHUNT
ATB2	216.378	98.35	-8.6	55	15	0	0	0
ATB5	507.573	101.51	-5.9	0	0	0	0	0
BAG1	99.78	90.71	-16.3	14.6	12.7	0	0	-4.114
BNT1	101.879	92.62	-13.6	50	10	0	0	0
DEB2S1	216.408	98.37	-9.4	0	0	0	0	0
DEB2S2	216.408	98.37	-9.4	4.5	1.8	0	0	19.352
DON2S1	217.988	99.09	-10	0	0	0	0	0
DON2S2	217.988	99.09	-10	8.8	3.4	0	0	0
FAO1	100.637	91.49	-29.3	40	1.6	0	0	0
FAR1	99.475	90.43	-15.4	84	51.4	0	0	0
FRZ2	211.056	95.93	-8.4	7	3.5	0	0	0
GAD1	99.927	90.84	-16.4	0	0	0	0	0
GAD2	196.65	89.39	-12.4	0	0	0	0	0
GAM1	102.358	93.05	-13	0	0	0	0	0
GAM2	197.072	89.58	-11.5	0	0	0	0	0
GAR_G1	11.358	103.25	-3.2	0	0	33	27	0
GAR_G10	11.363	103.3	-3.2	0	0	33	27	0
GAR_G11	11.363	103.3	-3.2	0	0	33	27	0
GAR_G12	11.36	103.27	-2.9	0	0	35	27	0
GAR_G13	11.186	101.69	-1.3	0	0	55	27	0
GAR_G14	11.186	101.69	-1.3	0	0	55	27	0
GAR_G2	11.358	103.25	-3.2	0	0	33	27	0
GAR_G3	11.355	103.23	-2.9	0	0	35	27	0
GAR_G4	11.358	103.25	-3.2	0	0	33	27	0
GAR_G5	11.358	103.25	-3.2	0	0	33	27	0
GAR_G6	11.355	103.23	-2.9	0	0	35	27	0
GAR_G7	11.353	103.21	-3.2	0	0	33	27	0
GAR_G8	11.363	103.3	-3.2	0	0	33	27	0
GAR_G9	11.36	103.27	-2.9	0	0	35	27	0
GAR2S1	211.529	96.15	-8.3	100	20	0	0	0

GAR2S2	211.731	96.24	-8.2	0	0	0	0	0
GBA66	64.064	97.07	-36	0	0	0	0	0
GDF1	110.033	100.03	-21.2	0	0	0	0	0
GDF2	217.024	98.65	-19.5	0	0	0	0	0
GDF66	68.913	104.41	-24	12.2	5.9	0	0	0
GEN1	98.509	89.55	-23	0	0	0	0	0
HAG1	101.381	92.16	-27.5	13.7	1.4	0	0	0
HAS1	98.497	89.54	-23	13.4	18.7	0	0	-4.009
HWT2	209.478	95.22	-22.2	210	5	0	0	0
IBA1	101.469	92.24	-13	45	26.5	0	0	0
IBA2	200.759	91.25	-10.5	0	0	0	0	0
IZG1	99.233	90.21	-17.1	154	28.8	0	0	-4.069
JAP69_1	0.652	94.52	-11.7	0	1.178	1.9	0	0
JAP69_2	0.652	94.52	-11.7	0	1.178	1.9	0	0
JAP69_3	0.652	94.52	-11.7	0	1.178	1.9	0	0
JAP69_4	0.652	94.52	-11.7	0	1.178	1.9	0	0
JAP69_5	0.652	94.52	-11.7	0	1.178	1.9	0	0
JAP69_6	0.652	94.52	-11.7	0	1.178	1.9	0	0
JAP69_7	0.652	94.52	-11.7	0	1.178	1.9	0	0
JAP69_8	0.652	94.52	-11.7	0	1.178	1.9	0	0
JAS1	104.551	95.05	-14	0	0	0	0	0
JAS2	197.293	89.68	-11.2	0	0	0	0	0
KAB2	207.281	94.22	-9.1	0	0	0	0	0
KAB5	499.927	99.99	-7.3	0	0	0	0	0
KHE1	98.978	89.98	-12.7	88.2	46.2	0	0	0
KHN1	99.585	90.53	-11.4	0	0	0	0	0
KHN11_GT_4	10.171	92.47	-9.8	0	0	15	10.6	0
KHN11_GT1	10.661	96.92	-17.7	0	0	13	10.6	0
KHN11_ST1	11.8	100	-5.7	0	0	33	11.885	0
KHN11_ST2	11.8	100	-5.7	0	0	33	11.885	0
KHN11_ST3	11	100	-5.9	0	0	60	5.306	0
KHN11_ST4	11	100	-5.9	0	0	60	5.306	0
KHN11_ST5	11	100	-3.3	0	59.656	110	0	0

KHN11_ST6	11	100	-3.3	0	59.656	110	0	0
KL366	63.946	96.89	-36.1	2	1	0	0	0
KLX1	100.842	91.67	-14.7	0	16.8	0	0	0
KLX2	197.791	89.9	-11.5	0	0	0	0	24.249
KSL11	10.388	94.43	-42.2	10.9	5.6	5.8	5.7	-6.421
KSL66	65.774	99.66	-40.8	0	0	0	0	0
KUK1	99.275	90.25	-12.5	0	0	0	0	0
LOM1	100.588	91.44	-15.3	79.9	42.5	0	0	-78.401
MAN1	102.679	93.34	-28	10	2.2	0	0	0
Mar-01	103.574	94.16	-27.1	110	31.1	0	0	0
Mar-02	192.371	87.44	-20	0	0	0	0	0
MHD1	99.247	90.22	-17.6	163	60	0	0	-4.07
MHD2	194.068	88.21	-12.1	0	0	0	0	0
MNA1	94.967	86.33	-28.5	15.7	5.7	0	0	0
MRK2	197.135	89.61	-11.3	0	0	0	0	0
MRK5	501.282	100.26	-7	0	0	0	0	0
MRW5_S1	514.508	102.9	-3.6	0	0	0	0	0
MRW5_S2	514.52	102.9	-3.6	0	0	0	0	0
MSH2	213.452	97.02	-3	0	0	0	0	28.241
MUG1	98.295	89.36	-17.9	54.5	16.275	0	0	0
MUG1_1	98.288	89.35	-17.9	89.025	48.825	0	0	0
MWAIS2	216.025	98.19	-6.7	0	0	0	0	0
MWP14_1	13.524	98	0	0	0	70.982	2.498	0
MWP14_10	13.524	98	2.8	0	0	125	5.834	0
MWP14_2	13.524	98	0	0	0	71.001	1.557	0
MWP14_3	13.524	98	-10	125	0	0	6.436	0
MWP14_4	13.524	98	-10	125	0	0	8.078	0
MWP14_5	13.524	98	2.8	0	0	125	7.506	0
MWP14_6	13.524	98	2.8	0	0	125	5.821	0
MWP14_7	13.524	98	2.7	0	0	125	7.367	0
MWP14_8	13.524	98	2.7	0	0	125	5.723	0
MWP14_9	13.524	98	2.8	0	0	125	7.499	0
MWT2S1	213.966	97.26	-8.5	0	0	0	0	0

MWT2S2	213.966	97.26	-8.5	129	40	0	0	0
NHLF66	62.448	94.62	-37	4.1	2	0	0	0
OBE2	225.726	102.6	1.8	6.1	3.7	0	0	31.582
OMD1	98.331	89.39	-18.3	153	32.7	0	0	-1.998
POR2	192.009	87.28	-26.5	94	9.9	0	0	22.852
RBK1	108.477	98.62	1	30	5	0	0	0
RBK11	94.727	86.12	-28	11.2	5.4	0	0	0
RBK2	226.125	102.78	2.3	0	0	0	0	31.694
RNK2	223.06	101.39	-2.2	0.5	0.5	0	0	30.84
ROS11_1	11	100	-6.8	0	0	30	5.655	0
ROS11_2	11	100	-7.9	0	0	15	4.884	0
ROS11_3	11	100	-2.1	0	0	40	6.831	0
ROS11_4	11	100	-6.5	0	0	40	7.173	0
ROS11_5	10.449	94.99	-12.4	0	0	0	0	13.536
ROS11_5	11	100	-2.4	0	0	40	6.844	0
ROS11_6	11	100	-2.1	0	0	40	6.228	0
ROS11_7	11	100	-2	0	0	40	6.234	0
ROS2	216.115	98.23	-12	200	3.3	0	0	0
RWS66	66.696	101.05	-27.5	2	0.9	0	0	0
SENJ1	100.539	91.4	-26.1	78.6	5.3	0	0	0
SENJ2	198.754	90.34	-21.2	0	0	0	0	24.485
SENP1	100.487	91.35	-26.5	3	1	0	0	0
SHEH	229.9	104.5	-13.3	0	0	200	26.065	0
SHG1	99.79	90.72	-16.4	112	41.5	0	0	0
SHK66	65.435	99.14	-30.3	2	0.969	0	0	0
SHN2	215.169	97.8	-8.8	11.5	5.8	0	0	0
SIN2	204.589	93	-20.5	50	15	0	0	25.944
TAN2	226.631	103.01	2	1.2	0.2	0	0	31.836
UMR2	226.594	103	1.9	2.6	1	0	0	31.825

As we can see from the above table voltage increased in all busses, but still less than 0.95 P.U in 38 burbars so we will add another STATCOM device at bus bar (MAR2) The enhancement of the voltage at this busbar and by the way the grid is done by using Statcom device added to this bus bar and setting the current (Ic & IL) ,then the Statcoms started to generate MVAR and the voltage in this bus bar increased and also at the other buses , in the next schedule we see the busbars voltage after the enhancement.

Table 4.6load flow analysis after enhancement by (MAR2) STATCOM

NAME	U KV	U %	U ang	P LOAD	Q LOAD	P GEN	Q GEN	Q SHUNT
ATB2	218.952	99.52	-8.4	55	15	0	0	0
ATB5	511.858	102.37	-5.8	0	0	0	0	0
B-1230801518	11.55	105	7.6	0	0	125	20.963	0
BAG1	103.664	94.24	-15.9	14.6	12.7	0	0	-4.441
BNT1	104.532	95.03	-13.2	50	10	0	0	0
DEB2S1	217.675	98.94	-9.2	0	0	0	0	0
DEB2S2	217.675	98.94	-9.2	4.5	1.8	0	0	19.58
DON2S1	219.276	99.67	-9.8	0	0	0	0	0
DON2S2	219.276	99.67	-9.8	8.8	3.4	0	0	0
FAO1	109.584	99.62	-27.5	40	1.6	0	0	0
FAR1	101.933	92.67	-14.9	84	51.4	0	0	0
FRZ2	215.105	97.78	-8.2	7	3.5	0	0	0
GAD1	103.954	94.5	-16	0	0	0	0	0
GAD2	203.579	92.54	-12.2	0	0	0	0	0
GAM1	104.998	95.45	-12.7	0	0	0	0	0
GAM2	202.077	91.85	-11.2	0	0	0	0	0
GAR_G1	11.55	105	-3.2	0	0	33	27	0
GAR_G10	11.554	105.04	-3.2	0	0	33	27	0
GAR_G11	11.554	105.04	-3.2	0	0	33	27	0
GAR_G12	11.552	105.02	-2.9	0	0	35	27	0
GAR_G13	11.382	103.47	-1.4	0	0	55	27	0
GAR_G14	11.382	103.47	-1.4	0	0	55	27	0
GAR_G2	11.55	105	-3.2	0	0	33	27	0
GAR_G3	11.547	104.97	-2.9	0	0	35	27	0

GAR_G4	11.55	105	-3.2	0	0	33	27	0
GAR_G5	11.55	105	-3.2	0	0	33	27	0
GAR_G6	11.547	104.97	-2.9	0	0	35	27	0
GAR_G7	11.545	104.95	-3.2	0	0	33	27	0
GAR_G8	11.554	105.04	-3.2	0	0	33	27	0
GAR_G9	11.552	105.02	-2.9	0	0	35	27	0
GAR2S1	215.598	98	-8.1	100	20	0	0	0
GAR2S2	215.797	98.09	-8.1	0	0	0	0	0
GBA66	67.709	102.59	-33.9	0	0	0	0	0
GDF1	113.758	103.42	-19.7	0	0	0	0	0
GDF11_1	11.942	108.57	-19.6	0	0	0	0	0
GDF11_2	11.944	108.59	-19.5	0	0	0	0	0
GDF2	223.371	101.53	-18.2	0	0	0	0	0
GDF3_2	33.586	101.78	-19.7	0	0	0	0	15.537
GDF3_4	33.586	101.78	-19.7	0	0	0	0	15.537
GDF66	71.443	108.25	-22.3	12.2	5.9	0	0	0
GEN1	106.802	97.09	-22.3	0	0	0	0	0
HAG1	111.361	101.24	-26.1	13.7	1.4	0	0	0
HAS1	106.789	97.08	-22.3	13.4	18.7	0	0	-4.712
HWT2	218.794	99.45	-20.9	210	5	0	0	0
IBA1	103.373	93.98	-12.6	45	26.5	0	0	0
IBA2	205.243	93.29	-10.2	0	0	0	0	0
IZG1	101.501	92.27	-16.5	154	28.8	0	0	-4.257
JAP69_1	0.671	97.18	-11.5	0	1.178	1.9	0	0
JAP69_2	0.671	97.18	-11.5	0	1.178	1.9	0	0
JAP69_3	0.671	97.18	-11.5	0	1.178	1.9	0	0
JAP69_4	0.671	97.18	-11.5	0	1.178	1.9	0	0
JAP69_5	0.671	97.18	-11.5	0	1.178	1.9	0	0
JAP69_6	0.671	97.18	-11.5	0	1.178	1.9	0	0
JAP69_7	0.671	97.18	-11.5	0	1.178	1.9	0	0
JAP69_8	0.671	97.18	-11.5	0	1.178	1.9	0	0
JAS1	107.373	97.61	-13.6	0	0	0	0	0
JAS2	202.904	92.23	-11	0	0	0	0	0

KAB2	211.368	96.08	-8.9	0	0	0	0	0
KAB5	507.092	101.42	-7.1	0	0	0	0	0
KHE1	100.672	91.52	-12.2	88.2	46.2	0	0	0
KHN1	101.076	91.89	-11	0	0	0	0	0
KHN11_ST1	11.8	100	-5.3	0	0	33	6.986	0
KHN11_ST2	11.8	100	-5.3	0	0	33	6.986	0
KHN11_ST3	11	100	-5.5	0	4.059	60	0	0
KHN11_ST4	11	100	-5.5	0	4.059	60	0	0
KHN11_ST5	11	100	-3	0	71.65	110	0	0
KHN11_ST6	11	100	-3	0	71.65	110	0	0
KLX1	103.266	93.88	-14.2	0	16.8	0	0	0
KLX2	202.698	92.14	-11.2	0	0	0	0	25.467
KUK1	100.963	91.78	-12	0	0	0	0	0
LOM1	103.046	93.68	-14.8	79.9	42.5	0	0	-80.316
MAN1	113.41	103.1	-26.7	10	2.2	0	0	0
Mar-01	114.18	103.8	-25.9	110	31.1	0	0	0
Mar-02	212.287	96.49	-19.7	0	0	0	0	165.461
MHD1	101.615	92.38	-17	163	60	0	0	-4.267
MHD2	198.459	90.21	-11.8	0	0	0	0	0
MNA1	104.1	94.64	-26.6	15.7	5.7	0	0	0
MRK2	201.512	91.6	-11	0	0	0	0	0
MRK5	508.102	101.62	-6.9	0	0	0	0	0
MRW5_S1	517.213	103.44	-3.5	0	0	0	0	0
MRW5_S2	517.224	103.44	-3.5	0	0	0	0	0
MSH2	216.651	98.48	-2.9	0	0	0	0	29.094
MUG1	100.798	91.63	-17.3	54.5	16.275	0	0	0
MUG1_1	100.792	91.63	-17.3	89.025	48.825	0	0	0
MWAIS2	217.225	98.74	-6.6	0	0	0	0	0
MWAIS3_1	32.611	98.82	-6.9	0	0	0	0	0
MWAIS3_2	32.611	98.82	-6.9	0	0	0	0	0
MWP14_1	13.524	98	0	0	3.518	69.394	0	0
MWP14_10	13.524	98	2.8	0	0.084	125	0	0
MWP14_2	13.524	98	0	0	4.437	69.334	0	0

MWP14_3	13.524	98	-9.9	125	0	0	0.493	0
MWP14_4	13.524	98	-9.9	125	0	0	2.11	0
MWP14_5	13.524	98	2.9	0	0	125	1.594	0
MWP14_6	13.524	98	2.8	0	0.112	125	0	0
MWP14_7	13.524	98	2.8	0	0	125	1.352	0
MWP14_8	13.524	98	2.7	0	0.293	125	0	0
MWP14_9	13.524	98	2.8	0	0	125	1.573	0
MWT2S1	215.199	97.82	-8.4	0	0	0	0	0
MWT2S2	215.199	97.82	-8.4	129	40	0	0	0
OBE2	227.183	103.26	2	6.1	3.7	0	0	31.991
OMD1	100.777	91.62	-17.7	153	32.7	0	0	-2.098
POR2	195.633	88.92	-25.8	94	9.9	0	0	23.722
RBK1	109.176	99.25	1.2	30	5	0	0	0
RBK11	103.631	94.21	-26.2	11.2	5.4	0	0	0
RBK2	227.568	103.44	2.4	0	0	0	0	32.099
RNK2	225.512	102.51	-1.9	0.5	0.5	0	0	31.522
ROS11_1	11	100	-6.3	0	0	30	0.013	0
ROS11_2	11	100	-7.4	0	0.761	15	0	0
ROS11_3	11	100	-1.7	0	0	40	2.078	0
ROS11_4	11	100	-6.1	0	1.42	40	0	0
ROS11_5	10.681	97.1	-11.8	0	0	0	0	14.142
ROS11_5	11	100	-2	0	0	40	1.907	0
ROS11_6	11	100	-1.7	0	0	40	1.493	0
ROS11_7	11	100	-1.6	0	0	40	1.517	0
ROS2	220.51	100.23	-11.4	200	3.3	0	0	0
SENJ1	108.848	98.95	-24.5	78.6	5.3	0	0	0
SENJ2	213.681	97.13	-20.4	0	0	0	0	28.301
SENP1	109.08	99.16	-24.9	3	1	0	0	0
SHEH	229.9	104.5	-11.8	0	23.361	200	0	0
SHG1	102.317	93.02	-15.9	112	41.5	0	0	0
SHK66	68.577	103.9	-28.4	2	0.969	0	0	0
SHN2	218.547	99.34	-8.5	11.5	5.8	0	0	0
SIN2	216.074	98.22	-19.6	50	15	0	0	28.939

TAN2	228.084	103.67	2.2	1.2	0.2	0	0	32.245
UMR2	228.051	103.66	2.1	2.6	1	0	0	32.236

As we can see from the above table voltage increased in all busses, but still less than 0.95 P.U in 23 busbars so we will add another STATCOM device at busbar (MHD1) The enhancement of the voltage at this busbar and by the way the grid is done by using Statcom device added to this busbar and setting the current (Ic & IL) ,then the Statcoms started to generate MVAR and the voltage in this busbar increased and also at the other buses , in the next schedule we see the busbars voltage after the enhancement.

Table 4.7 load flow analysis after enhancement by (MHD1) STATCOM

NAME	U KV	U %	U ang	P LOAD	Q LOAD	P GEN	Q GEN	Q SHUNT
ATB2	219.828	99.92	-8.3	55	15	0	0	0
ATB5	513.447	102.69	-5.7	0	0	0	0	0
BAG1	104.899	95.36	-15.6	14.6	12.7	0	0	-4.547
BNT1	105.719	96.11	-13	50	10	0	0	0
DEB2S1	218.216	99.19	-9.2	0	0	0	0	0
DEB2S2	218.216	99.19	-9.2	4.5	1.8	0	0	19.677
DON2S1	219.826	99.92	-9.7	0	0	0	0	0
DON2S2	219.826	99.92	-9.7	8.8	3.4	0	0	0
FAO1	110.354	100.32	-27.1	40	1.6	0	0	0
FAR1	103.29	93.9	-14.7	84	51.4	0	0	0
FRZ2	216.353	98.34	-8.1	7	3.5	0	0	0
GAD1	105.173	95.61	-15.7	0	0	0	0	0
GAD2	205.585	93.45	-12	0	0	0	0	0
GAM1	106.179	96.53	-12.5	0	0	0	0	0
GAM2	204.317	92.87	-11.1	0	0	0	0	0
GAR_G1	11.55	105	-3.1	0	0	33	24.895	0
GAR_G10	11.55	105	-3.1	0	0	33	24.718	0

GAR_G11	11.55	105	-3.1	0	0	33	24.718	0
GAR_G12	11.55	105	-2.8	0	0	35	24.818	0
GAR_G13	11.44	104	-1.4	0	0	55	27	0
GAR_G14	11.44	104	-1.4	0	0	55	27	0
GAR_G2	11.55	105	-3.1	0	0	33	24.895	0
GAR_G3	11.55	105	-2.8	0	0	35	24.997	0
GAR_G4	11.55	105	-3.1	0	0	33	24.895	0
GAR_G5	11.55	105	-3.1	0	0	33	24.895	0
GAR_G6	11.55	105	-2.8	0	0	35	24.997	0
GAR_G7	11.55	105	-3.1	0	0	33	25.057	0
GAR_G8	11.55	105	-3.1	0	0	33	24.718	0
GAR_G9	11.55	105	-2.8	0	0	35	24.818	0
GAR2S1	216.809	98.55	-7.9	100	20	0	0	0
GAR2S2	217.002	98.64	-7.9	0	0	0	0	0
GDF1	114.063	103.69	-19.3	0	0	0	0	0
GDF11_1	11.974	108.86	-19.2	0	0	0	0	0
GDF11_2	11.976	108.88	-19.1	0	0	0	0	0
GDF2	223.889	101.77	-17.8	0	0	0	0	0
GDF3_2	33.677	102.05	-19.3	0	0	0	0	15.622
GDF3_4	33.677	102.05	-19.3	0	0	0	0	15.622
GDF66	71.649	108.56	-21.9	12.2	5.9	0	0	0
GEN1	107.905	98.1	-21.9	0	0	0	0	0
HAG1	112.209	102.01	-25.7	13.7	1.4	0	0	0
HAS1	107.891	98.08	-21.9	13.4	18.7	0	0	-4.81
HWT2	219.552	99.8	-20.5	210	5	0	0	0
IBA1	104.718	95.2	-12.4	45	26.5	0	0	0
IBA2	207.027	94.1	-10.1	0	0	0	0	0
IZG1	103.696	94.27	-16.3	154	28.8	0	0	-4.443
JAP69_1	0.68	98.53	-11.3	0	1.178	1.9	0	0
JAP69_2	0.68	98.53	-11.3	0	1.178	1.9	0	0
JAP69_3	0.68	98.53	-11.3	0	1.178	1.9	0	0
JAP69_4	0.68	98.53	-11.3	0	1.178	1.9	0	0
JAP69_5	0.68	98.53	-11.3	0	1.178	1.9	0	0

JAP69_6	0.68	98.53	-11.3	0	1.178	1.9	0	0
JAP69_7	0.68	98.53	-11.3	0	1.178	1.9	0	0
JAP69_8	0.68	98.53	-11.3	0	1.178	1.9	0	0
JAS1	108.774	98.89	-13.4	0	0	0	0	0
JAS2	204.988	93.18	-10.8	0	0	0	0	0
JAS33	33.794	102.41	-13.4	12.4	7.5	0	0	0
KAB2	212.84	96.75	-8.8	0	0	0	0	0
KAB3_1	31.886	96.62	-8.9	0	0	0	0	0
KAB3_2	31.886	96.62	-8.9	0	0	0	0	0
KAB5	510.234	102.05	-7	0	0	0	0	0
KHE1	101.808	92.55	-12	88.2	46.2	0	0	0
KHN1	102.148	92.86	-10.8	0	0	0	0	0
KHN11_ST1	11.8	100	-5.1	0	0	33	3.466	0
KHN11_ST2	11.8	100	-5.1	0	0	33	3.466	0
KHN11_ST3	11	100	-5.4	0	10.786	60	0	0
KHN11_ST4	11	100	-5.4	0	10.786	60	0	0
KHN11_ST5	11.09	100.82	-2.9	0	75	110	0	0
KHN11_ST6	11.09	100.82	-2.9	0	75	110	0	0
KLX1	104.605	95.1	-14	0	16.8	0	0	0
KLX2	204.645	93.02	-11	0	0	0	0	25.959
KSL11	11.073	100.67	-39.2	10.9	5.6	5.8	5.7	-7.296
KSL66	70.102	106.21	-38	0	0	0	0	0
KUK1	102.096	92.81	-11.8	0	0	0	0	0
LOM1	104.465	94.97	-14.6	79.9	42.5	0	0	-81.423
MAN1	114.343	103.95	-26.3	10	2.2	0	0	0
Mar-01	115.103	104.64	-25.5	110	31.1	0	0	0
MAR11_1	11.452	104.1	-25.8	0	0	0	0	0
MAR11_2	11.386	103.51	-26.4	0	0	0	0	0
Mar-02	213.839	97.2	-19.4	0	0	0	0	166.671
MHD1	104.076	94.61	-16.8	163	60	0	0	-67.569
MHD2	201.168	91.44	-11.6	0	0	0	0	0
MNA1	104.834	95.3	-26.2	15.7	5.7	0	0	0
MRK2	203.893	92.68	-10.9	0	0	0	0	0

MRK5	511.19	102.24	-6.8	0	0	0	0	0
MRW5_S1	518.368	103.67	-3.5	0	0	0	0	0
MRW5_S2	518.379	103.68	-3.5	0	0	0	0	0
MSH2	217.771	98.99	-2.8	0	0	0	0	29.395
MUG1	102.753	93.41	-17	54.5	16.275	0	0	0
MUG1_1	102.747	93.41	-17	89.025	48.825	0	0	0
MWAIS2	217.737	98.97	-6.5	0	0	0	0	0
MWAIS3_1	32.688	99.05	-6.8	0	0	0	0	0
MWAIS3_2	32.688	99.05	-6.8	0	0	0	0	0
MWP14_1	13.524	98	0	0	6.103	68.434	0	0
MWP14_10	13.524	98	2.9	0	2.611	125	0	0
MWP14_2	13.524	98	0	0	7.009	68.34	0	0
MWP14_3	13.524	98	-9.8	125	2.044	0	0	0
MWP14_4	13.524	98	-9.8	125	0.437	0	0	0
MWP14_5	13.524	98	2.9	0	0.931	125	0	0
MWP14_6	13.524	98	2.9	0	2.646	125	0	0
MWP14_7	13.524	98	2.8	0	1.217	125	0	0
MWP14_8	13.524	98	2.8	0	2.863	125	0	0
MWP14_9	13.524	98	2.9	0	0.958	125	0	0
MWT2S1	215.726	98.06	-8.3	0	0	0	0	0
MWT2S2	215.726	98.06	-8.3	129	40	0	0	0
NHLF66	66.5	100.76	-34.4	4.1	2	0	0	0
OBE2	227.613	103.46	2.1	6.1	3.7	0	0	32.112
OMD1	103.001	93.64	-17.4	153	32.7	0	0	-2.192
POR2	196.85	89.48	-25.5	94	9.9	0	0	24.019
RBK1	109.382	99.44	1.3	30	5	0	0	0
RBK11	104.34	94.85	-25.7	11.2	5.4	0	0	0
RBK2	227.994	103.63	2.5	0	0	0	0	32.22
RNK2	225.968	102.71	-1.7	0.5	0.5	0	0	31.65
ROS11_1	11	100	-6	0	0.539	30	0	0
ROS11_2	11	100	-7.1	0	1.314	15	0	0
ROS11_3	11	100	-1.4	0	0	40	1.613	0
ROS11_4	11	100	-5.8	0	2.262	40	0	0

ROS11_5	10.703	97.3	-11.5	0	0	0	0	14.202
ROS11_5	11	100	-1.8	0	0	40	1.424	0
ROS11_6	11	100	-1.4	0	0	40	1.03	0
ROS11_7	11	100	-1.3	0	0	40	1.055	0
ROS2	220.94	100.43	-11.1	200	3.3	0	0	0
SENJ1	109.514	99.56	-24.1	78.6	5.3	0	0	0
SENJ2	214.871	97.67	-20	0	0	0	0	28.618
SENP1	109.775	99.8	-24.5	3	1	0	0	0
SHEH	229.9	104.5	-11.4	0	27.393	200	0	0
SHG1	103.938	94.49	-15.6	112	41.5	0	0	0
SHN2	219.628	99.83	-8.4	11.5	5.8	0	0	0
SIN2	217.009	98.64	-19.3	50	15	0	0	29.19
TAN2	228.513	103.87	2.3	1.2	0.2	0	0	32.367
UMR2	228.481	103.86	2.2	2.6	1	0	0	32.358

As we can see from the above table voltage increased in all busses, but still less than 0.95 P.U in 23 busbars so we will add another STATCOM device at busbar (POR2) The enhancement of the voltage at this busbar and by the way the grid is done by using Statcom device added to this busbar and setting the current (Ic & IL) ,then the Statcoms started to generate MVAR and the voltage in this busbar increased and also at the other buses , in the next schedule we see the busbars voltage after the enhancement

Table 4.8 load flow analysis after enhancement by (MAR2) STATCOM

NAME	U KV	U %	U ang	P LOAD	Q LOAD	P GEN	Q GEN	Q SHUNT
ATB2	222.627	101.19	-8.3	55	15	0	0	0
ATB5	517.047	103.41	-5.7	0	0	0	0	0
B-1230801506	11.55	105	7.9	0	0	125	17.948	0
B-1230801512	11.55	105	7.9	0	0	125	17.948	0
B-1230801515	11.55	105	7.9	0	0	125	17.948	0

B-1230801518	11.55	105	7.9	0	0	125	17.948	0
BAG1	105.119	95.56	-15.5	14.6	12.7	0	0	-4.566
BNT1	105.932	96.3	-12.9	50	10	0	0	0
DEB2S1	218.689	99.4	-9.1	0	0	0	0	0
DEB2S2	218.689	99.4	-9.1	4.5	1.8	0	0	19.762
DON2S1	220.308	100.14	-9.7	0	0	0	0	0
DON2S2	220.308	100.14	-9.7	8.8	3.4	0	0	0
FAO1	110.504	100.46	-26.9	40	1.6	0	0	0
FAR1	103.515	94.1	-14.6	84	51.4	0	0	0
FRZ2	216.901	98.59	-8	7	3.5	0	0	0
GAD1	105.392	95.81	-15.6	0	0	0	0	0
GAD2	205.985	93.63	-11.9	0	0	0	0	0
GAM1	106.391	96.72	-12.4	0	0	0	0	0
GAM2	204.718	93.05	-11	0	0	0	0	0
GAR_G1	11.55	105	-3	0	0	33	24.006	0
GAR_G10	11.55	105	-3	0	0	33	23.827	0
GAR_G11	11.55	105	-3	0	0	33	23.827	0
GAR_G12	11.55	105	-2.7	0	0	35	23.927	0
GAR_G13	11.465	104.22	-1.3	0	0	55	27	0
GAR_G14	11.465	104.22	-1.3	0	0	55	27	0
GAR_G2	11.55	105	-3	0	0	33	24.006	0
GAR_G3	11.55	105	-2.7	0	0	35	24.108	0
GAR_G4	11.55	105	-3	0	0	33	24.006	0
GAR_G5	11.55	105	-3	0	0	33	24.006	0
GAR_G6	11.55	105	-2.7	0	0	35	24.108	0
GAR_G7	11.55	105	-3	0	0	33	24.162	0
GAR_G8	11.55	105	-3	0	0	33	23.827	0
GAR_G9	11.55	105	-2.7	0	0	35	23.927	0
GAR2S1	217.319	98.78	-7.9	100	20	0	0	0
GAR2S2	217.51	98.87	-7.8	0	0	0	0	0
GDF1	114.123	103.75	-19.1	0	0	0	0	0
GDF2	223.99	101.81	-17.7	0	0	0	0	0
GEN1	108.111	98.28	-21.8	0	0	0	0	0

HAG1	112.375	102.16	-25.6	13.7	1.4	0	0	0
HAS1	108.098	98.27	-21.8	13.4	18.7	0	0	-4.829
HWT2	219.701	99.86	-20.4	210	5	0	0	0
IBA1	104.927	95.39	-12.3	45	26.5	0	0	0
IBA2	207.491	94.31	-10	0	0	0	0	0
IZG1	103.922	94.47	-16.2	154	28.8	0	0	-4.463
JAP33	33.825	102.5	-12.6	0	0	0	0	0
JAP69_1	0.681	98.74	-11.2	0	1.178	1.9	0	0
JAP69_2	0.681	98.74	-11.2	0	1.178	1.9	0	0
JAP69_3	0.681	98.74	-11.2	0	1.178	1.9	0	0
JAP69_4	0.681	98.74	-11.2	0	1.178	1.9	0	0
JAP69_5	0.681	98.74	-11.2	0	1.178	1.9	0	0
JAP69_6	0.681	98.74	-11.2	0	1.178	1.9	0	0
JAP69_7	0.681	98.74	-11.2	0	1.178	1.9	0	0
JAP69_8	0.681	98.74	-11.2	0	1.178	1.9	0	0
JAS1	108.995	99.09	-13.3	0	0	0	0	0
JAS2	205.371	93.35	-10.7	0	0	0	0	0
KAB2	213.342	96.97	-8.7	0	0	0	0	0
KAB5	511.34	102.27	-7	0	0	0	0	0
KHE1	101.998	92.73	-11.9	88.2	46.2	0	0	0
KHN1	102.329	93.03	-10.7	0	0	0	0	0
KHN11_GT1	11	100	-16.6	0	0	13	10.341	0
KHN11_ST1	11.8	100	-5	0	0	33	2.872	0
KHN11_ST2	11.8	100	-5	0	0	33	2.872	0
KHN11_ST3	11	100	-5.3	0	11.921	60	0	0
KHN11_ST4	11	100	-5.3	0	11.921	60	0	0
KHN11_ST5	11.115	101.04	-2.8	0	75	110	0	0
KHN11_ST6	11.115	101.04	-2.8	0	75	110	0	0
KHN3	31.352	95.01	-20.1	64	7.437	0	0	-4.513
KL366	67.949	102.95	-33.4	2	1	0	0	0
KLX1	104.827	95.3	-13.9	0	16.8	0	0	0
KLX2	205.092	93.22	-10.9	0	0	0	0	26.072
KSL11	11.083	100.76	-39.1	10.9	5.6	5.8	5.7	-7.309

KSL66	70.164	106.31	-37.9	0	0	0	0	0
KUK1	102.286	92.99	-11.7	0	0	0	0	0
LOM1	104.69	95.17	-14.4	79.9	42.5	0	0	-81.597
MAN1	114.525	104.11	-26.1	10	2.2	0	0	0
Mar-01	115.283	104.8	-25.3	110	31.1	0	0	0
MAR11_1	11.47	104.27	-25.7	0	0	0	0	0
MAR11_2	11.404	103.67	-26.3	0	0	0	0	0
Mar-02	214.145	97.34	-19.2	0	0	0	0	166.909
MHD1	104.306	94.82	-16.6	163	60	0	0	-67.728
MHD2	201.589	91.63	-11.6	0	0	0	0	0
MNA1	104.978	95.43	-26.1	15.7	5.7	0	0	0
MRK2	204.311	92.87	-10.8	0	0	0	0	0
MRK5	512.282	102.46	-6.8	0	0	0	0	0
MRW5_S1	519.379	103.88	-3.4	0	0	0	0	0
MRW5_S2	519.393	103.88	-3.4	0	0	0	0	0
MSH2	217.978	99.08	-2.7	0	0	0	0	29.451
MUG1	102.984	93.62	-16.9	54.5	16.275	0	0	0
MUG1_1	102.978	93.62	-16.9	89.025	48.825	0	0	0
MWAIS2	218.185	99.18	-6.5	0	0	0	0	0
MWP14_1	13.524	98	0	0	8.344	68.064	0	0
MWP14_10	13.524	98	2.9	0	4.825	125	0	0
MWP14_2	13.524	98	0	0	9.245	67.939	0	0
MWP14_3	13.524	98	-9.8	125	4.267	0	0	0
MWP14_4	13.524	98	-9.7	125	2.669	0	0	0
MWP14_5	13.524	98	2.9	0	3.142	125	0	0
MWP14_6	13.524	98	2.9	0	4.865	125	0	0
MWP14_7	13.524	98	2.8	0	3.467	125	0	0
MWP14_8	13.524	98	2.8	0	5.113	125	0	0
MWP14_9	13.524	98	2.9	0	3.175	125	0	0
MWT2S1	216.187	98.27	-8.3	0	0	0	0	0
MWT2S2	216.187	98.27	-8.3	129	40	0	0	0
NHLF66	66.558	100.85	-34.2	4.1	2	0	0	0
OBE2	227.692	103.5	2.2	6.1	3.7	0	0	32.135

OMD1	103.233	93.85	-17.3	153	32.7	0	0	-2.202
POR2	220	100	-24.5	94	9.9	0	0	3.715
RBK1	109.42	99.47	1.4	30	5	0	0	0
RBK11	104.479	94.98	-25.6	11.2	5.4	0	0	0
RBK2	228.072	103.67	2.6	0	0	0	0	32.242
RNK2	226.054	102.75	-1.6	0.5	0.5	0	0	31.674
ROS11_1	11	100	-5.9	0	0.647	30	0	0
ROS11_2	11	100	-7	0	1.421	15	0	0
ROS11_3	11	100	-1.3	0	0	40	1.522	0
ROS11_4	11	100	-5.7	0	2.425	40	0	0
ROS11_5	10.708	97.34	-11.4	0	0	0	0	14.214
ROS11_5	11	100	-1.6	0	0	40	1.33	0
ROS11_6	11	100	-1.3	0	0	40	0.94	0
ROS11_7	11	100	-1.2	0	0	40	0.966	0
ROS2	221.024	100.47	-11	200	3.3	0	0	0
RWS66	69.852	105.84	-25.1	2	0.9	0	0	0
SENJ1	109.645	99.68	-24	78.6	5.3	0	0	0
SENJ11	11.459	104.18	-38.7	0	0	0	0	0
SENJ2	215.105	97.78	-19.9	0	0	0	0	28.68
SENP1	109.911	99.92	-24.4	3	1	0	0	0
SHEH	229.9	104.5	-11.3	0	28.184	200	0	0
SHG1	104.166	94.7	-15.5	112	41.5	0	0	0
SHN2	221.272	100.58	-8.4	11.5	5.8	0	0	0
SIN2	217.193	98.72	-19.1	50	15	0	0	29.239
TAN2	228.592	103.91	2.4	1.2	0.2	0	0	32.389
UMR2	228.561	103.89	2.3	2.6	1	0	0	32.38

As we can see from the above table voltage increased in all busses, but still less than 0.95 P.U in 12 busbars so we will add another STATCOM device at busbar (MHD2) The enhancement of the voltage at this busbar and by the way the grid is done by using Statcom device added to this busbar and setting the current (Ic &

IL) ,then the Statcoms started to generate MVAR and the voltage in this busbar increased and also at the other buses , in the next schedule we see the busbars voltage after the enhancement

Table 4.9 load flow analysis after enhancement by (MAR2) STATCOM

NAME	U KV	U %	U ang	P LOAD	Q LOAD	P GEN	Q GEN	Q SHUNT
ATB2	223.823	101.74	-8.1	55	15	0	0	0
ATB5	519.486	103.9	-5.6	0	0	0	0	0
B-1230801506	11.55	105	8.1	0	0	125	13.58	0
B-1230801512	11.55	105	8.1	0	0	125	13.58	0
B-1230801515	11.55	105	8.1	0	0	125	13.58	0
B-1230801518	11.55	105	8.1	0	0	125	13.58	0
BAG1	106.873	97.16	-15.1	14.6	12.7	0	0	-4.72
BNT1	108.257	98.42	-12.6	50	10	0	0	0
DEB2S1	219.661	99.85	-9	0	0	0	0	0
DEB2S2	219.661	99.85	-9	4.5	1.8	0	0	19.938
DON2S1	221.296	100.59	-9.6	0	0	0	0	0
DON2S2	221.296	100.59	-9.6	8.8	3.4	0	0	0
FAO1	111.71	101.55	-26.3	40	1.6	0	0	0
FAR1	105.3	95.73	-14.2	84	51.4	0	0	0
FRZ2	218.747	99.43	-7.8	7	3.5	0	0	0
GAD1	107.139	97.4	-15.2	0	0	0	0	0
GAD2	209.213	95.1	-11.6	0	0	0	0	0
GAM1	108.705	98.82	-12.1	0	0	0	0	0
GAM2	209.109	95.05	-10.7	0	0	0	0	0
GAR_G1	11.55	105	-2.8	0	0	33	20.889	0
GAR_G10	11.55	105	-2.8	0	0	33	20.7	0
GAR_G11	11.55	105	-2.8	0	0	33	20.7	0
GAR_G12	11.55	105	-2.5	0	0	35	20.799	0
GAR_G13	11.55	105	-1.2	0	0	55	27	0

GAR_G14	11.55	105	-1.2	0	0	55	27	0
GAR_G2	11.55	105	-2.8	0	0	33	20.889	0
GAR_G3	11.55	105	-2.5	0	0	35	20.99	0
GAR_G4	11.55	105	-2.8	0	0	33	20.889	0
GAR_G5	11.55	105	-2.8	0	0	33	20.889	0
GAR_G6	11.55	105	-2.5	0	0	35	20.99	0
GAR_G7	11.55	105	-2.8	0	0	33	21.021	0
GAR_G8	11.55	105	-2.8	0	0	33	20.7	0
GAR_G9	11.55	105	-2.5	0	0	35	20.799	0
GAR2S1	219.106	99.59	-7.6	100	20	0	0	0
GAR2S2	219.289	99.68	-7.6	0	0	0	0	0
GDF1	114.604	104.19	-18.5	0	0	0	0	0
GDF2	224.81	102.19	-17.1	0	0	0	0	0
GEN1	109.767	99.79	-21.3	0	0	0	0	0
HAG1	113.707	103.37	-24.9	13.7	1.4	0	0	0
HAS1	109.753	99.78	-21.3	13.4	18.7	0	0	-4.978
HWT2	220.903	100.41	-19.8	210	5	0	0	0
IBA1	106.654	96.96	-12	45	26.5	0	0	0
IBA2	210.057	95.48	-9.8	0	0	0	0	0
IZG1	106.149	96.5	-15.8	154	28.8	0	0	-4.656
JAP69_1	0.694	100.62	-11	0	1.178	1.9	0	0
JAP69_2	0.694	100.62	-11	0	1.178	1.9	0	0
JAP69_3	0.694	100.62	-11	0	1.178	1.9	0	0
JAP69_4	0.694	100.62	-11	0	1.178	1.9	0	0
JAP69_5	0.694	100.62	-11	0	1.178	1.9	0	0
JAP69_6	0.694	100.62	-11	0	1.178	1.9	0	0
JAP69_7	0.694	100.62	-11	0	1.178	1.9	0	0
JAP69_8	0.694	100.62	-11	0	1.178	1.9	0	0
JAS1	110.987	100.9	-12.9	0	0	0	0	0
JAS33	34.493	104.52	-13	12.4	7.5	0	0	0
KAB2	215.554	97.98	-8.5	0	0	0	0	0
KAB3_1	32.292	97.85	-8.6	0	0	0	0	0
KAB3_2	32.292	97.85	-8.6	0	0	0	0	0

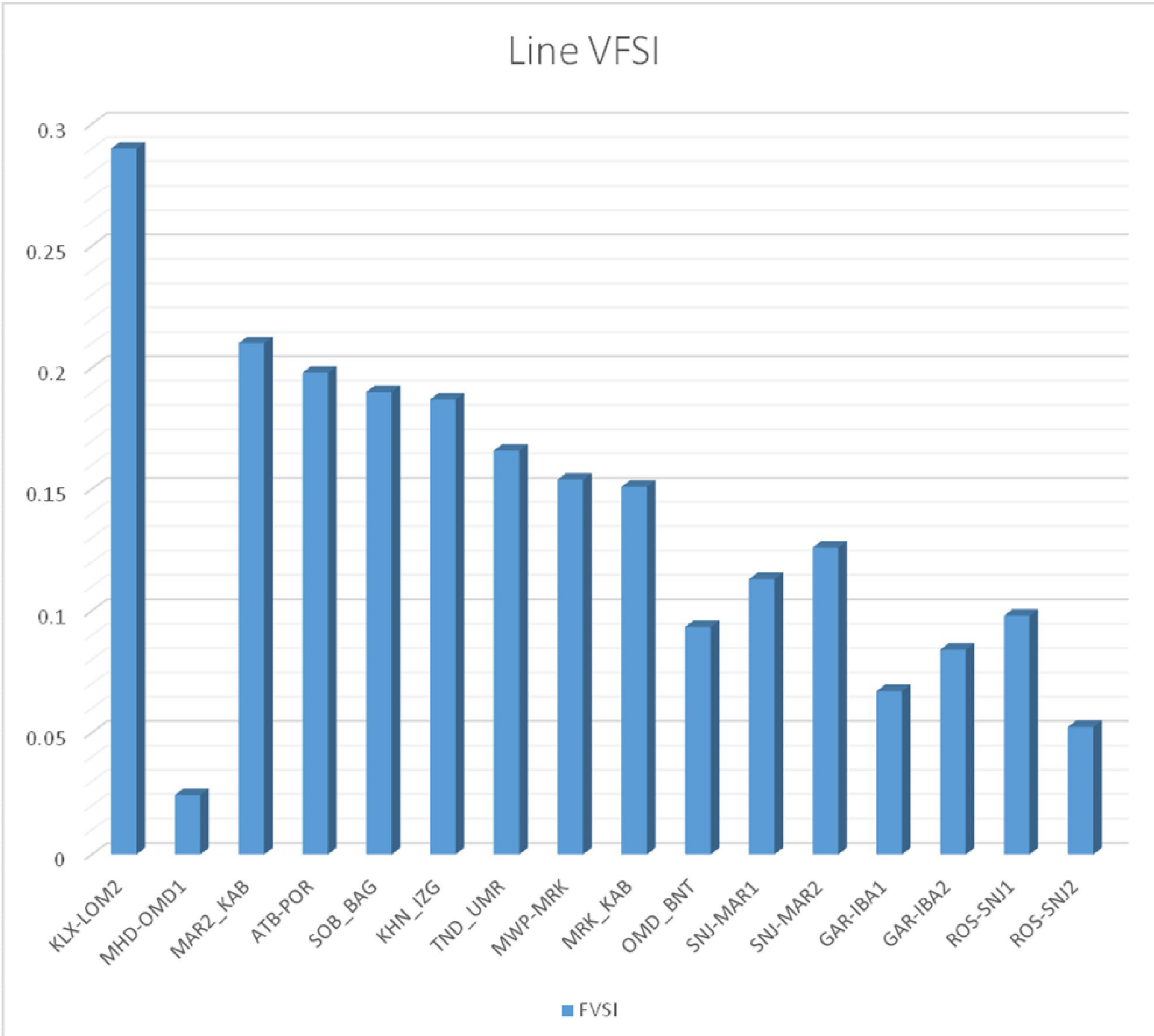
KAB5	517.139	103.43	-6.9	0	0	0	0	0
KHN11_GT1	11	100	-16	0	0	13	7.717	0
KHN11_ST1	11.8	100	-4.8	0	2.4	33	0	0
KHN11_ST2	11.8	100	-4.8	0	2.4	33	0	0
KHN11_ST3	11.126	101.15	-5.1	0	15	60	0	0
KHN11_ST4	11.126	101.15	-5.1	0	15	60	0	0
KHN11_ST5	11.334	103.03	-2.8	0	75	110	0	0
KHN11_ST6	11.334	103.03	-2.8	0	75	110	0	0
KHN3	31.763	96.25	-19.5	64	7.437	0	0	-4.632
KL366	68.409	103.65	-32.7	2	1	0	0	0
KLX1	106.589	96.9	-13.5	0	16.8	0	0	0
LOM1	106.512	96.83	-14.1	79.9	42.5	0	0	-83.018
MAN1	115.986	105.44	-25.5	10	2.2	0	0	0
Mar-01	116.729	106.12	-24.7	110	31.1	0	0	0
MAR11_1	11.614	105.58	-25.1	0	0	0	0	0
MAR11_2	11.548	104.99	-25.6	0	0	0	0	0
Mar-02	216.606	98.46	-18.7	0	0	0	0	168.828
MHD1	106.681	96.98	-16.3	163	60	0	0	-69.375
MHD2	207.761	94.44	-11.4	0	0	0	0	-89.963
MNA1	106.137	96.49	-25.4	15.7	5.7	0	0	0
MRK2	209.455	95.21	-10.6	0	0	0	0	0
MRK5	518.144	103.63	-6.7	0	0	0	0	0
MRW5_S1	521.456	104.29	-3.4	0	0	0	0	0
MRW5_S2	521.468	104.29	-3.4	0	0	0	0	0
MSH2	219.915	99.96	-2.5	0	0	0	0	29.977
MUG1	105.129	95.57	-16.5	54.5	16.275	0	0	0
MUG1_1	105.123	95.57	-16.5	89.025	48.825	0	0	0
MWAIS2	219.106	99.59	-6.4	0	0	0	0	0
MWP14_1	13.524	98	0	0	12.956	66.856	0	0
MWP14_10	13.524	98	3	0	9.369	125	0	0
MWP14_2	13.524	98	0	0	13.839	66.671	0	0
MWP14_3	13.524	98	-9.7	125	8.83	0	0	0
MWP14_4	13.524	98	-9.6	125	7.251	0	0	0

MWP14_5	13.524	98	3	0	7.681	125	0	0
MWP14_6	13.524	98	2.9	0	9.42	125	0	0
MWP14_7	13.524	98	2.9	0	8.085	125	0	0
MWP14_8	13.524	98	2.9	0	9.733	125	0	0
MWP14_9	13.524	98	3	0	7.725	125	0	0
MWT2S1	217.133	98.7	-8.1	0	0	0	0	0
MWT2S2	217.133	98.7	-8.1	129	40	0	0	0
NHLF66	67.03	101.56	-33.5	4.1	2	0	0	0
OBE2	228.431	103.83	2.4	6.1	3.7	0	0	32.343
OMD1	105.505	95.91	-16.8	153	32.7	0	0	-2.3
POR2	220	100	-24.1	94	9.9	0	0	5.874
RBK1	109.775	99.8	1.6	30	5	0	0	0
RBK11	105.6	96	-24.9	11.2	5.4	0	0	0
RBK2	228.804	104	2.8	0	0	0	0	32.449
RNK2	226.818	103.1	-1.4	0.5	0.5	0	0	31.888
ROS11_1	11	100	-5.5	0	1.532	30	0	0
ROS11_2	11	100	-6.6	0	2.308	15	0	0
ROS11_3	11	100	-0.9	0	0	40	0.776	0
ROS11_4	11	100	-5.2	0	3.774	40	0	0
ROS11_5	10.744	97.67	-11	0	0	0	0	14.31
ROS11_5	11	100	-1.2	0	0	40	0.555	0
ROS11_6	11	100	-0.9	0	0	40	0.197	0
ROS11_7	11	100	-0.8	0	0	40	0.226	0
ROS2	221.714	100.78	-10.6	200	3.3	0	0	0
SENJ1	110.698	100.63	-23.4	78.6	5.3	0	0	0
SENJ2	216.992	98.63	-19.4	0	0	0	0	29.185
SENP1	111.009	100.92	-23.7	3	1	0	0	0
SHEH	229.9	104.5	-10.7	0	34.568	200	0	0
SHG1	106.134	96.49	-15.1	112	41.5	0	0	0
SHN2	222.823	101.28	-8.2	11.5	5.8	0	0	0
SIN2	218.675	99.4	-18.6	50	15	0	0	29.64
TAN2	229.329	104.24	2.6	1.2	0.2	0	0	32.598
UMR2	229.299	104.23	2.5	2.6	1	0	0	32.59

From the above schedule show the final enhancement to the grid and as we can see there is no busbar voltage less than 0.95 P.U. Also when we can calculate FVSI for the weakest buses and the next schedule show the enhancement in FVSI values after using 4 STATCOM devices.

Table 4.10 FVSI values for the weakest lines after adding STATCOM

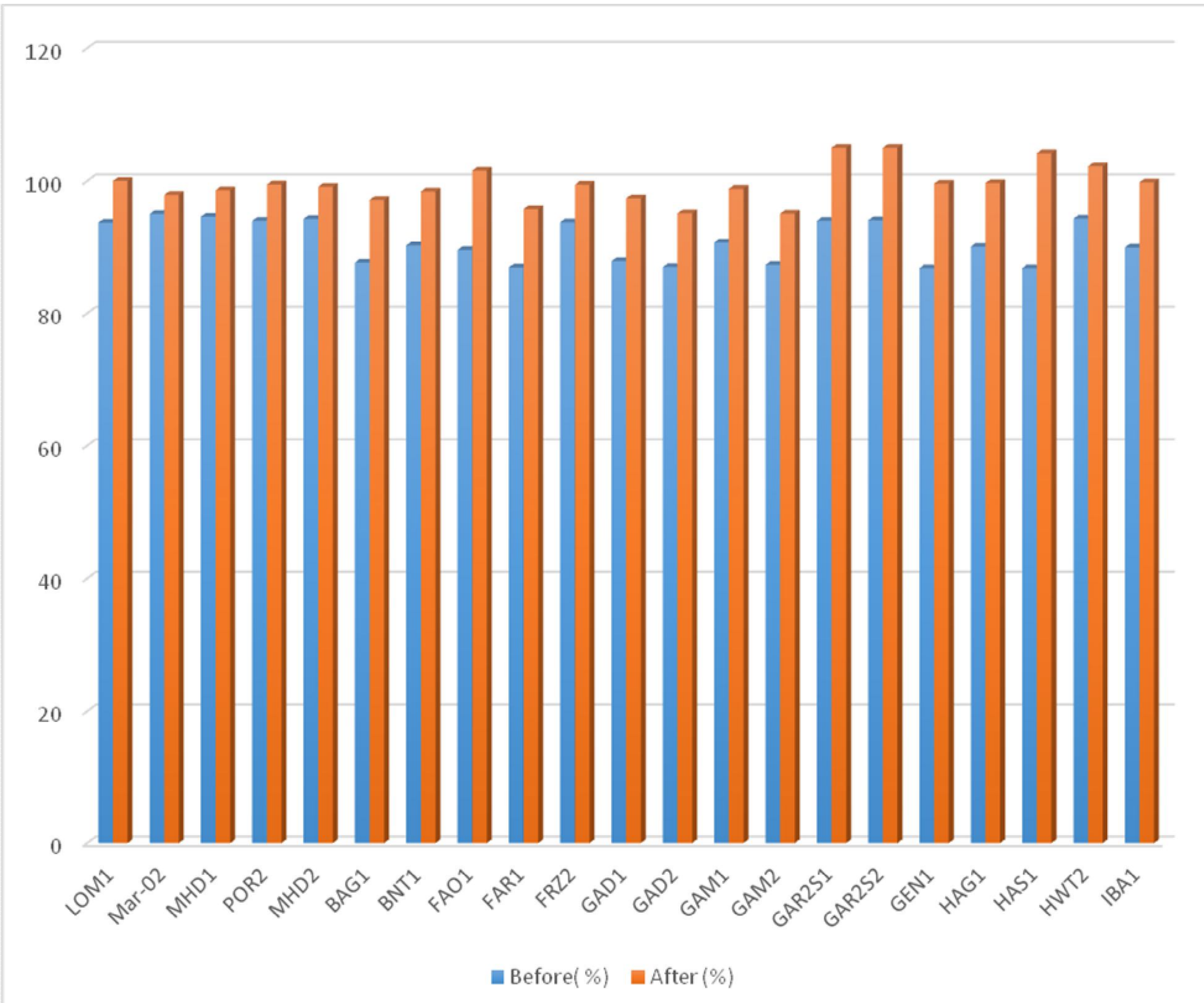
Rank	**Line name**	**FVSI**
1	KLX-LOM2	**0.29**
2	MHD-OMD1	**0.0243**
3	MAR2_KAB	**0.21**
3	ATB-POR	***0.198***
4	SOB_BAG	**0.19**
5	KHN_IZG	**0.187**
6	TND_UMR	**0.166**
7	MWP-MRK	**0.154**
8	MRK_KAB	***0. 151***
9	OMD_BNT	***0.09345***
10	SNJ-MAR1	***0.113***
11	SNJ-MAR2	***0.126***
12	GAR-IBA1	***0.067***
13	GAR-IBA2	***0.084***
14	ROS-SNJ1	***0.098***
15	ROS-SNJ2	***0.0523***



Line VFSI
0.3
0.25
0.2
0.15
0.1
0.05
0
KLX-LOM2
MHD-OMD1
MAR2_KAB
ATB-POR
SOB_BAG
KHN_IZG
TND_UMR
MWP-MRK
MRK_KAB
OMD_BNT
SNJ-MAR1
SNJ-MAR2
GAR-IBA1
GAR-IBA2
ROS-SNJ1
ROS-SNJ2
FVSI

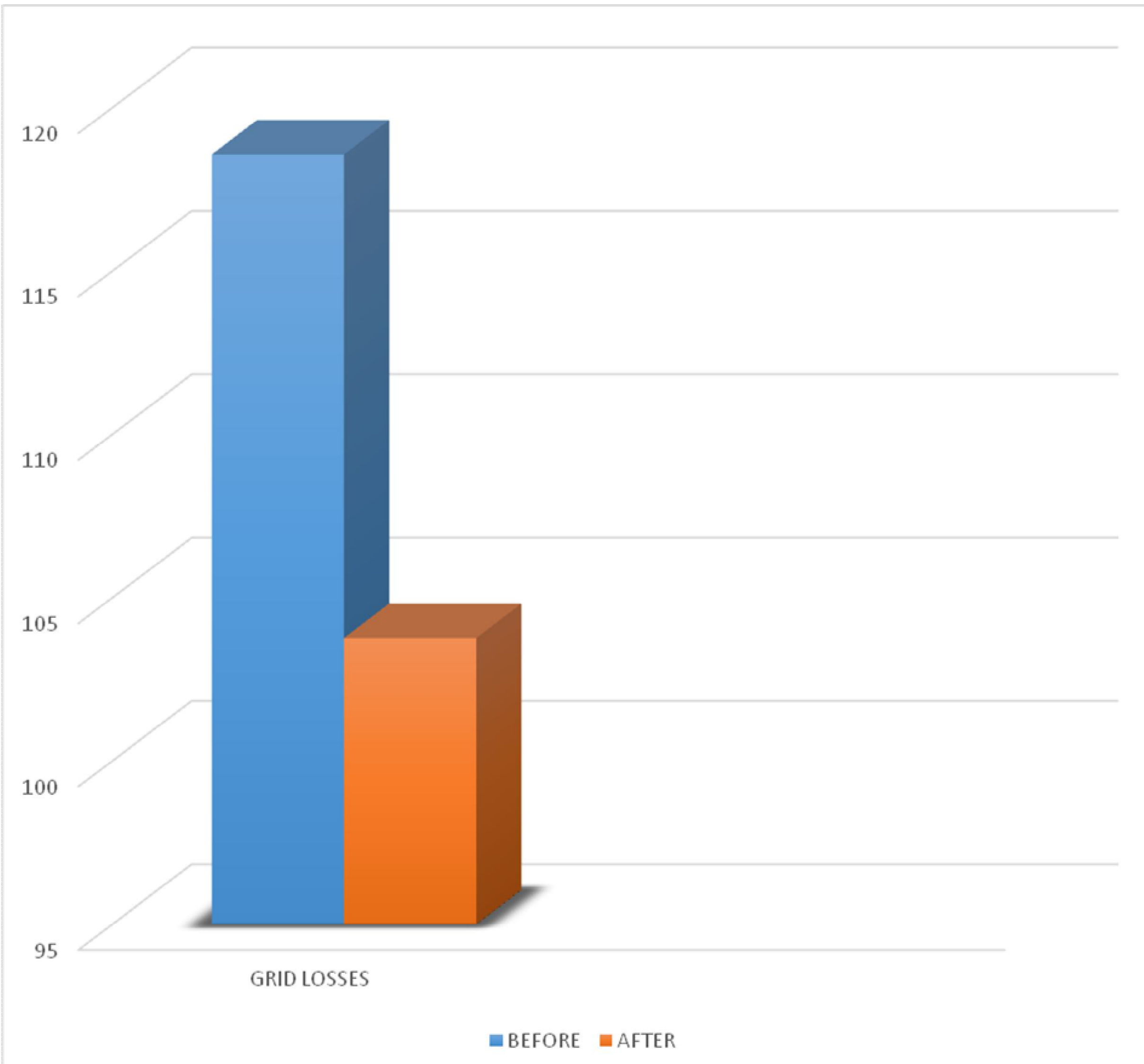
4.7 Voltage comparison between the busses which STATCOM connected to it before and after

This diagram shows the voltage comparison in the NG busbars before and after adding Statcom devices, the influence of adding the Statcoms is the increasing of the voltage % at all weak busses to be more than 95%.



4.8 Comparison between the losses in the three bus bars

This diagram show a comparison between the GRID active losses (P) before and after adding STATCOM devices, the diagram show that the P losses in the GRID is decreased after adding STATCOM devices by 14.796 MW.



Chapter Five

Conclusion and Recommendations

5.1 Conclusion

Sudanese Grid has become large and complicated, so it is subjected to sudden changes in load levels. Stability is an important concept which determines the stable operation of the power system. The modern trend is to employ by installing Flexible Alternating Current Transmission System (FACTS) devices in the system for effective utilization of transmission resources. The FACTS devices contribute to the power flow improvement besides, they extend their services in transient stability improvement as well, study and analyze the stability of the system through rotor angle and voltage. The object of this research is to improve the stability of the Sudanese National Grid System by using STATCOM devices in different optimal locations.

Case study is the Sudanese electrical network 66-bus bars. The load flow program was implemented using NEPLAN Program. Using Statcom devices in transmission lines when they reach the limits and need continues voltage control with a short time response in a continuity situation.

After we make a load flow analysis using Neplan program The results show that before using Statcom system voltage decreased in many buses at peak load. When Statcom are installed in Sudan national grid during peak load, we have reduced branch losses and voltage profile was improved. Reduction of losses, increase of power transfer capability and voltage profile can also be optimized. The load flow test shows that the lowest voltage level detected in the absence of STATCOM is 91.95% at bus (MHD2) compared with 97.02% for bus (MNA1) in presence of STATCOM. The results also show that the active losses decreased for example for the three busbars (POR1,GDF,LOM) before and after adding STATCOM devices, the results show that the P losses in the three busses is decreased after adding STATCOM devices and this also happened for the other buses. Also a comparison for number of STATCOM devices we can use and we find that the best choice is to use 4 devices of STATCOM because the economic reasons and also this can make an over voltage in some bus bars. More over with the STATCOM devices, it is possible to support the system during faults and transient period or to improve power quality

5.2 Recommendations

- Use another types of Facts devises (series and shunt types)
- Make a comparison between different types of FACTS devices in voltage magnitude and losses
- Make a economic operation study for using Statcom devices
- Make a study about the influence of Facts devices on the protection systems.

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Appendix A

Transmission lines data

ID	Name	Length	Number	Cable	Overhead	R(1)	X(1)	C(1)
		km				Ohm/...	Ohm/...	uF/...
1	MWT-DEB	139.3	1	0	0	0.076	0.403	0.00902
2	MWP-MWT	34.55	1	0	0	0.076	0.403	0.00902
3	MWP-DON	34.55	1	0	0	0.076	0.403	0.00902
4	DEB-DON	139.38	1	0	0	0.076	0.403	0.00902
5	IBA-KLX-2	14	1	0	0	0.067	0.302	0.01306
6	IBA-KLX-1	14	1	0	0	0.067	0.302	0.01306
7	GAR-IBA-1	60	1	0	0	0.067	0.302	0.01306
8	GAR-IBA-2	60	1	0	0	0.067	0.302	0.01306
9	KHN-KUK-1	4.5	1	0	0	0.0384	0.302	0.0095
10	KHN-KUK-2	4.5	1	0	0	0.0384	0.302	0.0095
11	KUK-KHE-1	3.2	1	0	0	0.067	0.269	0.01306
12	KUK-KHE-2	3.2	1	0	0	0.067	0.269	0.01306
13	KUK-KLX-2	14.6	1	0	0	0.087	0.379	0.0095
14	KUK-KLX-1	14.6	1	0	0	0.087	0.379	0.0095
15	KLX-LOM-2	3	1	0	0	0.067	0.269	0.01306
16	KLX-BAG	28	1	0	0	0.348	0.421	0.0086
17	KLX-LOM-1	3	1	0	0	0.067	0.269	0.01306
18	SHG-LOM-1	7.8	1	0	0	0.067	0.269	0.01306
19	SHG-LOM-2	7.8	1	0	0	0.067	0.269	0.01306
20	MUG-SHG-1	11	1	0	0	0.067	0.269	0.01306
21	JAS-SHG-1	39	1	0	0	0.067	0.269	0.013
22	JAS-SHG-2	39	1	0	0	0.067	0.269	0.013
23	MUG-BNT-2	3.8	1	0	0	0.067	0.269	0.01306
24	MUG-BNT-1	3.8	1	0	0	0.067	0.269	0.01306
25	BNT-OMD-2	5.9	1	0	0	0.067	0.269	0.01306
26	BNT-OMD-1	5.9	1	0	0	0.067	0.269	0.01306
27	MHD-OMD-1	9.3	1	0	0	0.067	0.269	0.01306
28	MHD-OMD-2	9.3	1	0	0	0.067	0.269	0.01306
29	MHD-IZG-2	8	1	0	0	0.067	0.269	0.01306
30	MHD-IZG-1	8	1	0	0	0.067	0.269	0.01306
31	IBA-IZB-2	11	1	0	0	0.067	0.269	0.01306

32	IBA-IZB-1	11	1	0	0	0.067	0.269	0.01306
33	MRK-MHD-2	21	1	0	0	0.067	0.302	0.01306
34	MRK-MHD-1	21	1	0	0	0.067	0.302	0.01306
35	MRK-GAM-1	37	1	0	0	0.067	0.302	0.01306
36	JAS-GAM-1	37	1	0	0	0.067	0.302	0.01306
37	JAS-GAM-2	37	1	0	0	0.067	0.302	0.01306
38	KHN-IZG-1	12	1	0	0	0.067	0.269	0.01306
39	MRK-KAB	36.8	1	0	0	0.028	0.276	0.013083
40	SHN-ATB-2	140	1	0	0	0.067	0.302	0.01306
41	SHN-ATB-1	140	1	0	0	0.067	0.302	0.01306
42	FRZ-SHN-2	115	1	0	0	0.067	0.302	0.01306
43	FRZ-SHN-1	115	1	0	0	0.067	0.302	0.01306
44	IBA-KHN-2	12	1	0	0	0.067	0.269	0.01306
45	IBA-KHN-1	12	1	0	0	0.067	0.269	0.01306
46	KLX-GAD-1	43	1	0	0	0.076	0.403	0.00902
47	KLX-GAD-2	43	1	0	0	0.076	0.403	0.00902
48	JAS-GAD-1	36	1	0	0	0.067	0.302	0.01306
49	JAS-GAD-2	36	1	0	0	0.067	0.302	0.01306
50	GIAD-BAG	3	1	0	0	0.348	0.421	0.0086
51	KHN-IZG-2	12	1	0	0	0.067	0.269	0.01306
52	MUG-SHG-2	11	1	0	0	0.067	0.269	0.01306
53	MRK-GAM-2	37	1	0	0	0.067	0.302	0.01306
54	GAR-FRZ-2	5	1	0	0	0.067	0.302	0.01306
55	GAR-FRZ-1	5	1	0	0	0.067	0.302	0.01306
56	KBA-FRZ-2	34	1	0	0	0.067	0.302	0.01306
57	KBA-IBA-1	30	1	0	0	0.067	0.302	0.01306
58	KBA-IBA-2	30	1	0	0	0.067	0.302	0.01306
59	ATB-POR	448.92	1	0	0	0.076	0.403	0.00902
60	KBA-FRZ-1	34	1	0	0	0.067	0.302	0.01306
61	GAM-BNT-2	16.5	1	0	0	0.067	0.269	0.01306
62	MWP-ATB	236.7	1	0	0	0.028	0.276	0.013083
63	MWP-MRK-1	346	1	0	0	0.028	0.276	0.013083
64	MWP-MRK-2	346	1	0	0	0.028	0.276	0.013083
65	GAM-BNT-1	16.5	1	0	0	0.067	0.269	0.01306
66	DON-WAW-2	166	1	0	0	0.067	0.302	0.01306
67	DON-WAW-1	166	1	0	0	0.067	0.302	0.01306

68	WAW-WHL-2	205	1	0	0	0.067	0.302	0.01306
69	WAW-WHL-1	205	1	0	0	0.067	0.302	0.01306
70	ROS-SNG-1	178	1	0	0	0.076	0.403	0.00902
71	ROS-SNG-2	178	1	0	0	0.076	0.403	0.00902
72	SNG-SNJ-2	50	1	0	0	0.076	0.403	0.00902
73	SNG-SNJ-1	50	1	0	0	0.076	0.403	0.00902
74	SNG-HWT-2	90	1	0	0	0.067	0.302	0.01306
75	MAR-NHS-2	60.3	1	0	0	0.076	0.403	0.00902
76	MAR-NHS-1	60.3	1	0	0	0.076	0.403	0.00902
77	MAR-SNJ-1	84	1	0	0	0.076	0.403	0.00902
78	MAR-SNJ-2	84	1	0	0	0.076	0.403	0.00902
79	SNG-HWT-1	90	1	0	0	0.067	0.302	0.01306
80	HWT- GDF-2	110	1	0	0	0.067	0.302	0.01306
81	GDF -SHK -1	75.12	1	0	0	0.067	0.302	0.01306
82	GDF - SHK -2	75.12	1	0	0	0.067	0.302	0.01306
83	HWT- GDF-1	110	1	0	0	0.067	0.302	0.01306
84	GRB - HLF -1	48.87	1	0	0	0.067	0.302	0.01306
85	GRB - HLF -2	48.87	1	0	0	0.067	0.302	0.01306
86	SHK - GRB -1	62.54	1	0	0	0.067	0.302	0.01306
87	SHK - GRB -2	62.54	1	0	0	0.067	0.302	0.01306
88	GRB - KSL -1	74.5	1	0	0	0.067	0.302	0.01306
89	GRB - KSL -2	74.5	1	0	0	0.067	0.302	0.01306
90	KSL - ARM-1	43.87	1	0	0	0.067	0.302	0.01306
91	KSL - ARM -2	43.87	1	0	0	0.067	0.302	0.01306
92	ROS - RNK -2	172.8	1	0	0	0.067	0.302	0.01306
93	ROS - RNK -1	172.8	1	0	0	0.067	0.302	0.01306
94	RBK - RNK -1	163	1	0	0	0.067	0.302	0.01306
95	RBK - RNK -2	172.8	1	0	0	0.067	0.302	0.01306
96	RBK - MSH -2	100	1	0	0	0.067	0.302	0.01306
97	RBK - TND -2	84	1	0	0	0.067	0.302	0.01306
98	RBK - TND -1	84	1	0	0	0.067	0.302	0.01306
99	TND - UMR -1	78.3	1	0	0	0.067	0.302	0.01306
100	TND - UMR -2	78.3	1	0	0	0.067	0.302	0.01306
101	RBK - MSH -1	100	1	0	0	0.067	0.302	0.01306
102	UMR - OBD -2	126	1	0	0	0.067	0.302	0.01306
103	UMR - OBD -1	126	1	0	0	0.067	0.302	0.01306

104	GAD-NHS-1	80.7	1	0	0	0.067	0.302	0.01306
105	GAD-NHS-2	80.7	1	0	0	0.067	0.302	0.01306
106	GAD-NHS-110KV	80.7	1	0	0	0.348	0.421	0.0086
107	NHS-GND-2	15	1	0	0	0.067	0.302	0.01306
108	NHS-GND-1	15	1	0	0	0.067	0.302	0.01306
109	NHS-HAS	60	1	0	0	0.348	0.421	0.0086
110	HAS - MAR	55	1	0	0	0.348	0.421	0.0086
111	SNJ-SNP	10	1	0	0	0.348	0.421	0.0086
112	KLX-AFR-2	9.5	1	0	0	0.067	0.269	0.013
113	KLX-AFR-1	9.5	1	0	0	0.067	0.269	0.013
114	AFR-FAR-1	4.5	1	0	0	0.067	0.269	0.013
115	AFR-FAR-2	4.5	1	0	0	0.067	0.269	0.013
116	JAS- MSH -1	100	1	0	0	0.067	0.302	0.01306
117	JAS - MSH-2	100	1	0	0	0.067	0.302	0.01306
118	MAR-HAG	35	1	0	0	0.348	0.421	0.0086
119	SNP-HAG	60	1	0	0	0.348	0.421	0.0086

Generators Data

	Name	Sr	Ur	cosphi	xd sat	xd' sat	xd" sat	x(2)	Ufmax/ur	P Gen	Q Gen	Q min	Q max
Unit	-	MVA	kV	-	%	%	%	%	-	MW	Mvar	Mvar	Mvar
1	GAR GT01	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
2	GAR GT02	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
3	GAR ST01	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
4	GAR GT03	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
5	GAR GT04	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
6	GAR ST02	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
7	GAR GT05	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
8	GAR GT06	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
9	GAR GT07	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
10	GAR GT08	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
11	GAR ST03	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
12	GAR ST04	41.3	11	0.9	160	24	16	16	1.3	30	5	-10	15
13	GAR ST05	41.3	11	0.9	160	24	16	16	1.3	30	12	0	0
14	GAR ST06	41.3	11	0.9	160	24	16	16	1.3	30	12	-15	15
15	KHN ST06	137.5	13.8	0.9	122	17.4	13.4	13.4	1.3	100	22	-75	105
16	KHN ST05	137.5	13.8	0.9	122	17.4	13.4	13.4	1.3	100	22	-75	105
17	KHN ST04	75	11	0.9	227	23	14.8	14.8	1.3	50	22	0	0
18	KHN ST03	75	11	0.9	227	23	14.8	14.8	1.3	50	22	0	0
19	KHN ST01	41.25	11	0.9	227	23	14.8	14.8	1.3	30	1	-7	17
20	MWP HT01	140	13.8	0.9	88.3	27.5	18	19.6	1.3	121	7	-109	67

21	MWP HT02	140	13.8	0.9	88.3	27.5	18	19.6	1.3	120
22	MWP HT03	140	13.8	0.9	88.3	27.5	18	19.6	1.3	120
23	MWP HT04	140	13.8	0.9	88.3	27.5	18	19.6	1.3	120
24	MWP HT05	140	13.8	0.9	88.3	27.5	18	19.6	1.3	120
25	MWP HT06	140	13.8	0.9	88.3	27.5	18	19.6	1.3	120
26	MWP HT08	140	13.8	0.9	88.3	27.5	18	19.6	1.3	120
27	MWP HT09	140	13.8	0.9	88.3	27.5	18	19.6	1.3	120
28	MWP HT010	140	13.8	0.9	88.3	27.5	18	19.6	1.3	120
29	MWP HT07	140	13.8	0.9	88.3	27.5	18	19.6	1.3	120
30	ROS HT01	44	11	0.9	123	44	30	30	1.3	40
31	ROS HT03	44	11	0.9	123	44	30	30	1.3	40
32	ROS HT02	44	11	0.9	123	44	30	30	1.3	40
33	ROS HT04	44	11	0.9	123	44	30	30	1.3	30
34	ROS HT07	44	11	0.9	123	44	30	30	1.3	30
35	ROS HT06	44	11	0.9	123	44	30	30	1.3	30
36	ROS HT05	44	11	0.9	123	44	30	30	1.3	30
37	KOSTI ST03	147	11	0.85	122	17.4	13.4	13.4	1.3	125
38	KOSTI ST04	147	11	0.85	122	17.4	13.4	13.4	1.3	125
39	KOSTI ST01	147	11	0.85	122	17.4	13.4	13.4	1.3	125
40	KOSTI ST02	147	11	0.85	122	17.4	13.4	13.4	1.3	125
41	SNP HT02	10	110	0.8	90	30	12	12	1.3	8
42	SNP HT01	10	110	0.8	90	30	12	12	1.3	8
43	KHN GT	141	13.8	0.9	122	17.4	13.4	13.4	1.3	70