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Static Voltage Stability Improvement with Embedded Statcom FACTS Controller

تحسين استقرارية الجهد الساكنة بتضمين متحكم التعويض المتزامن الساكن

A Dissertation submitted in partial fulfillment for the requirements of the degree of M.Sc. in Electrical Engineering (Power)

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الآيـــــــــة

"يَا بُنَيَّ إِنَّهَا إِن تَكُ مِثْقَالَ حَبَّةٍ مِّنْ خَرْدَلٍ فَتَكُن فِي صَخْرَةٍ أَوْ فِي السَّمَاوَاتِ أَوْ فِي الْأَرْضِ يَأْتِ بِهَا اللَّهُ إِنَّ اللَّهَ لَطِيفٌ خَبِيرٌ"

سورة لقمان الآية (16)

DEDICATION

To

My Mother…

A strong and gentle soul who taught me to trust in Allah, believe in hard work and that so much could be done with little.

My Father…

For earning an honest living for us and for supporting and encouraging me to believe in myself.

My Brothers and Sisters…

Whose affections, love and prays make me able to get such success an honor.

My close Friend, Ahmed…

For being my guardian during my life and educational career.

Along with all hard working and respected teachers.

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Last but not least, I would like to thank my family and all my friends without whose support, this work would not be possible.

ABSTRACT

The dissertation outlines the Modal analysis and V-Q sensitivity analysis as important techniques of static voltage stability analysis in power systems in order to check the system stability. Flexible AC transmission systems (FACTS) controllers are described alongside with their role in enhancing system performance. Static synchronous compensator (STATCOM) is discussed in detail as one of the most important shunt compensators. A 110 kV level of Sudan National electrical grid is implemented as case study. Modal analysis and V-Q sensitivity analysis are applied to the system in order to assess and evaluate its static voltage stability and also to determine the weakest buses that need to be compensated by using STATCOM. FACTS devices are very costly and need to be placed optimally in the system, Novel line stability index is used to identify the best locations of compensation devices. The system is analyzed at its base case then the weakest buses and areas are identified as well as the optimal locations of STATCOM to be implemented. A new study of the system is conducted after compensation. The results of the study show that STATCOM improves static voltage stability and enhances the system performance.

المستخلص

تستعرض الأطروحة تحليل النمط و تحليل حساسية الجهد والقدرة غير الفعالة كطرق مهمة لتحليل استقرارية الجهد الساكنة في أنظمة القدرة الكهربائية وذلك لفحص استقرارية تلك الأنظمة. أنظمة نقل التيار المتردد المرنة (FACTS) تم وصفها بجانب دورها في تحسين أداء المنظومة. كما تناقش الأطروحة بالتفصيل، المعوض المتزامن الساكن (STATCOM) كأحد أهم معوضات التوازي للقدرة المتفاعلة. تم تقديم دراسة لجزء من الشبكة القومية الكهربائية السودانية لمستوى جهد 110 كيلو فولت ، كما تم تطبيق تحليل النمط، وتحليل حساسية الجهد والقدرة المتفاعلة على منظومة الدراسة لفحص وتقييم استقرارية جهودها وتحديد قضبان التوصيل الأضعف التي تحتاج إلى تعويض باستخدام الـ (STATCOM) ، و نظراً لأن أجهزة الأنظمة المرنة لنقل التيار المتردد مكلفة و يتحتم توصيلها في المنظومة على النحو الأمثل، فإن مؤشر استقرارية الخط (NLSI) تم استخدامه في هذه الأطروحة لتحديد الأماكن الأفضل لأجهزة التعويض. تمت دراسة النظام في حالته الراهنة بدون تعويض وتم تحديد قضبان التوصيل والمناطق الأضعف والمواقع المثلى للمعوضات ليتم تطبيقها على النظام. ومن ثم أُجريت دراسة للنظام بعد التعويض، نتائج الدراسة تظهر أن المعوض المتزامن الساكن يزيد من استقرارية الجهد الساكنة ويُحسن أداء المنظومة.

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FACTS	Flexible AC Transmission System.
STATCOM	Static Synchronous Compensator.
TCR	Thyristor Controlled Reactor.
TSC	Thyristor Switched Capacitor.
SVC	Static Var Compensator.
TSSC	Thyristor Switched Series Compensator.
TSSR	Thyristor Switched Series Reactor.
TCSC	Thyristor Controlled Series Compensator.
TCSR	Thyristor Controlled Series Reactor.
TCBR	Thyristor Controlled Braking resistors.
TCPST	Thyristor Controlled Phase Shifting Transformers.
LCC	Line Commutated Converter Compensator.
SSSC	Static Synchronous Series Compensator.
UPFC	Unified Power Flow Controller.
IPFC	Interline Power Flow Controller.
SCC	Self-Commutated Compensator.
VSM	Voltage Stability Margin.
VSI	Voltage Stability Index.
FVSI	Fast Voltage Stability Index.
Lmn	Line Stability Index.
NLSI	Novel Line Stability Index.

Chapter One

INTRODUCTION

1.1 Background:

Power system stability may be broadly defined as that property of a power system that enables to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [1, 2, 3].

In the evaluation of stability, the concern is the behavior of the power system when subjected to a transient disturbance. The disturbance may be small or large. Small disturbances in the form of load changes take place continually, and the system adjust itself to the changing conditions. The system must be able to operate satisfactorily under these conditions and successfully supply the maximum amount of load. The system response to a disturbance involves much of the equipment. For example, a short-circuit on a critical element followed by its isolation by protective relays will cause variations in power transfers, machine rotor speeds, and bus voltages; the voltage variations will actuate both generator and transmission system voltage regulators; the speed variation will actuate prime mover governors; the change in tie line loadings may actuate generation controls; the changes in voltage and frequency will affect loads in the system in varying degrees depending on their individual characteristics. The understanding of stability problems is greatly facilitated by classification of stability into various categories [1].

During the daily operation, power systems may experience both over-voltage and under-voltage violations that can be overcomed by voltage/Var control [4]. Providing adequate reactive power supports at the appropriate location not only to reduce the power loss and improving the voltage profile, but also solves voltage instability problems. Recent development and use of FACTS devices added flexibility to the transmission system by reducing the voltage instability and improving safe and secure operation of the system [5].

1.2 Problem Statement:

Electricity market activities and a growing demand for electricity have led to heavily stressed power systems. This requires operation of the networks closer to their stability limits. Power system operation is affected by stability related problems, leading to unpredictable system behavior. Cost efficient solutions are preferred over network extensions. In many countries, permits to build new transmission lines are very expensive, which means the existing network has to be enforced to fulfill the changing requirements [6]. On other hand, the continuous increasing consumption of electrical energy due to increasing demand of the electrical power usage worldwide, the power systems generally face the problem of voltage instability which leads to the voltage collapse.

The voltage instability may happens because of heavily loaded transmission lines, the large distance between voltage sources and load centers, in addition to the insufficiency of reactive power compensation [1]. As a result the power systems are more susceptible to suffer from those problems.

1.3 Objectives:

Voltage instability does not mean the problem of low voltage in steady-state condition. As a matter of fact, it is possible that the voltage collapse may be precipitated even if the initial operating voltages may at acceptable levels [7]. In Sudan power system, the power demand increases enormously, this growth of demand influences voltage stability of the system, the voltage must be maintained within the stability limit for proper operation of the system.

This dissertation focuses on the role of regulated compensation on improving the static voltage stability limits of Sudan electric power system, by implementation of STATCOM FACTS controller to a part of Sudan electric power system (110 kV grid) in order to:

- Upgrade the weakest buses, lines and areas of the system.
- Insurance of stable operation of the system under various load conditions.
- Improve system reliability and security.
- Increase voltage stability margin of the system.

1.4 Methodology / Approach:

- Apply load flow and static voltage stability analyses to the system in order to study and check the system performance, using NEPLAN simulation software.
- Investigation of the weakest areas and optimal placement of STATCOM controller using Novel Line Stability Index (NLSI).
- Implementation of STATCOM according to the results that obtained from the proposed voltage stability index.
- Analysis of the obtained results and check the changes and improvements of voltage stability which made by STATCOM FACTS controller with respect to the base case of the system.

1.5 Dissertation Layout:

Chapter two represents a literature review, discussing the voltage stability and voltage collapse problem in an electric power system. A review of voltage stability analysis methods based on static criteria is presented and discussed. A brief representation of FACTS controllers and detailed discussion of STATCOM is also included.

Chapter three outlines the indices related to static voltage stability analysis as well as the identification of the weak buses in the power system and placing of the compensators. Novel line stability index is proposed based on the transmission line impedance and the active and reactive power at the receiving end.

In chapter four, a part of Sudan 110 kV system model is implemented. The load flow and modal analysis method is applied to the case study, then the optimal locations of Statcom FACTS controller are identified according to the results of application of NLSI to the system and the obtained results are analyzed and discussed.

Finally, the conclusions of the dissertation are pointed out in Chapter five as well as recommendations for future work.

Chapter Two

LITERATURE REVIEW

2.1 Introduction:

A healthy power system should be stable at any time while satisfying various operating criteria. The modern power system is challenged with the increasing load demands from the industrial, commercial and residential sectors. The large increase of load demands has caused congestion in transmission lines which further lead to instability the in power system operation. The significance of this phenomenon has increased nowadays as many major blackouts are caused by power system instability. Un treated large and weak networks with recurring voltage variations are inevitably prone to voltage collapse. Thus, maintaining voltage stability is one of the major concerns in power system operation. The enhancement of voltage stability through FACTS controllers has been widely adopted by utility companies worldwide. The promotion of FACTS controllers in power systems offer benefits, such as reduction in power losses, improvement in voltage profile and reduction of on-peak operating costs. The trend in electricity charge promotes the location and time base pricing schemes [8].

In this chapter, a review of voltage stability analysis methods is presented in order to outline the techniques that used to identify the critical buses in a power system, i.e. buses which are close to their voltage stability limits, and thus enable certain measures to be taken by the operators in order to avoid any incidence of voltage collapse. Next, a review of power electronic based devices that are used to enhance the power system performance in terms of voltage stability are stated. STATCOM which used in this dissertation is discussed in full details.

2.2 Voltage Stability and Voltage Collapse:

Voltage stability is defined as the ability of a power system to maintain steady voltages at all the buses in the system after being subjected to a disturbance from a given initial operating condition [1, 9, 33]. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. Voltage instability stems from the attempt of load dynamics to restore power consumption beyond the capability of the combined transmission and generation system [10, 15]. Instability that may result appears in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and the other elements by their protection leading to cascading outages that in turn may lead to loss of synchronism of some generators. [33].

Power system voltage stability involves generation, transmission and distribution. Voltage stability is closely associated with other aspects of power system steady-state and dynamic performance. Load characteristics, voltage control, reactive power compensation and management, rotor angle (synchronous) stability, protective relaying, and control center operations all influence voltage stability [1].

It is useful to classify voltage stability into four categories; these categories are discussed below [12, 33]:

- **Large-disturbance voltage stability** refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. This ability is determined by the system and load characteristics, and the interactions of both continuous and discrete controls and protections. The study period of interest may extend from a few seconds to tens of minutes.

- **Small-disturbance voltage stability** refers to the system's ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load. This form of stability is influenced by the characteristics of loads, continuous controls, and discrete controls at a given instant of time.
- **Short-term voltage stability** involves dynamics of fast acting load components such as induction motors, electronically controlled loads and HVDC converters. The study period of interest is in the order of several seconds, and analysis requires solution of appropriate system differential equations.
- **Long-term voltage stability** involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads and generator current limiters. The study period of interest may extend to several or many minutes, and long-term simulations are required for analysis of system dynamic performance. Instability is due to the loss of long-term equilibrium, post-disturbance steady-state operating point being small disturbance unstable, or a lack of attraction towards the stable post disturbance equilibrium. The disturbance could also be a sustained load build up.

Voltage collapse typically occurs in power system which are usually heavily loaded, faulted and/or have reactive power shortages [13, 36, 39]. Voltage collapse is system instability and it involves large disturbances (including rapid increase in load or power transfer) and mostly associated with reactive power deficits.

Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant part of system. The main factors causing voltage instability are [36]:

1. The inability of the power system to meet demands for reactive power in heavily stressed system to keep voltage in the desired range.
2. Characteristics of the reactive power compensation devices.
3. Action and Coordination of the voltage control devices.
4. Generator reactive power limits.
5. Load characteristics.
6. Parameters of transmission lines and transformer.

2.3 Load Characteristics:

Typically, the voltage stability problems are analyzed based on estimation of the maximum loadability and the computation of critical power system loading that eventually lead to voltage collapse events.

Voltage collapse as discussed earlier can easily occur in a heavily loaded power system when the system operates close to the stability limits. With the increasing of load demand, interest in voltage stability studies is often determined by the maximum amount of active power that can be delivered to the end users.

For a simple 2 bus system shown in Figure 2.1, the change in load characteristic affects the voltage, current and active power at the load bus can be illustrated by Figure 2.2. At receiving bus, as the load demand increased, the amount of active power delivered by the system to the bus also increases until it reaches a maximum value.

The power transferred reaches the maximum value when the load impedance Z_L is equal to source impedance Z_S. Figure 2.2 indicates that point where $Z_L = Z_S = 1$ is the critical loading point for the system to operate satisfactorily. Further increase beyond the critical loading point would adversely cause the system voltage to collapse [8].

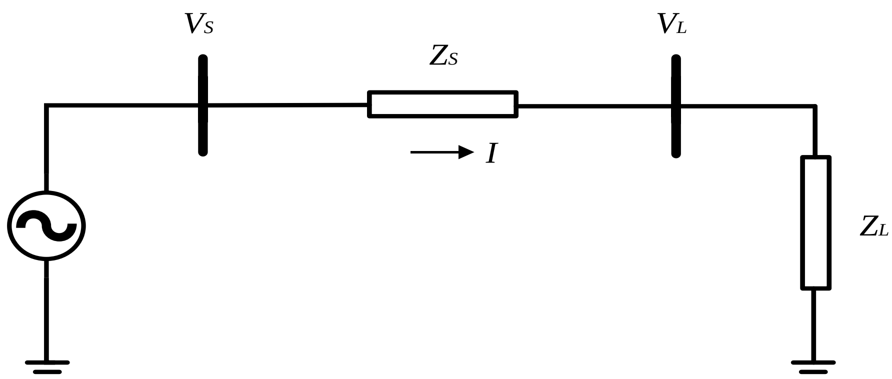


Figure 2.1: 2-bus system example

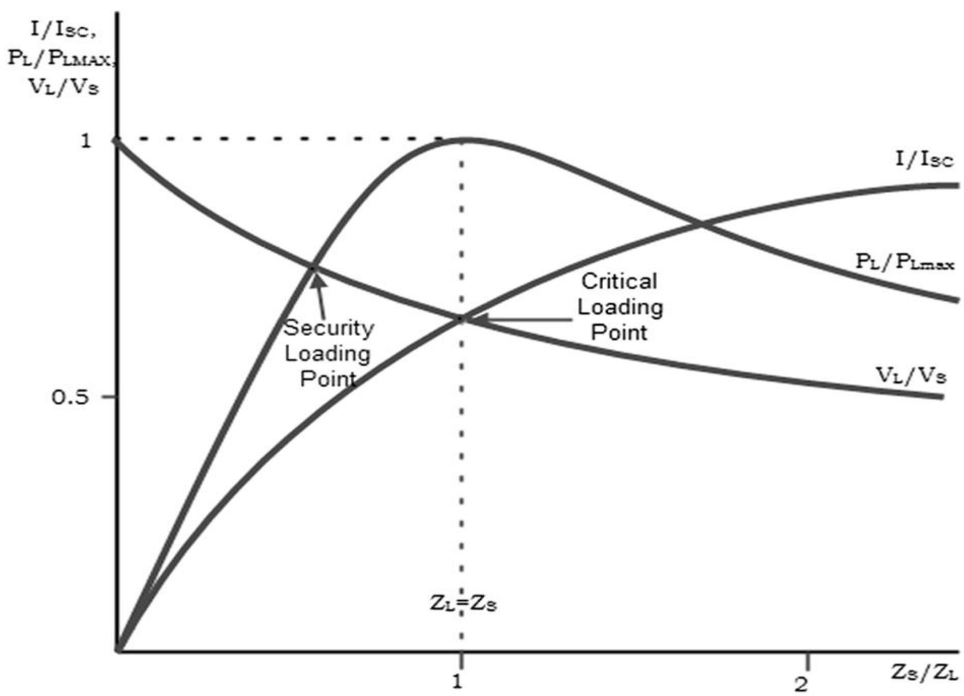


Figure 2.2: Load demand Function.

2.4 Voltage Stability Analysis:

The analysis of voltage stability for a given system state involves the examination of two aspects [1, 14]:

1. Proximity to voltage instability: How close is the system to voltage instability?

2. Mechanism of voltage instability: How and why does thus instability occur? what are the key factors contributing to instability? What are the voltage weak areas? What measures are most effective in improving voltage stability?

Voltage instability is a non-linear phenomenon. It is impossible to capture the phenomenon as a closed form solution. Following a disturbance, power simulations provide a method of study of a voltage instability problem [36]. There are two general types of tools for voltage stability analysis; dynamic analysis tools and static analysis tools. Dynamic analysis uses time-domain simulations to solve non-linear systems of differential algebraic equations, while static analysis is based on solution of conventional or modified power flow equations. Static analysis involves only the solution of algebraic equations, and is computationally considered more efficient than dynamic analysis. Therefore, static analysis is ideal for voltage stability studies of the bulk systems in which voltage stability limits for many pre-contingency and post-contingency cases must be determined. For these reasons static analysis methods of voltage stability are considered [16, 20].

2.4.1 Dynamic Voltage Stability Analysis:

Dynamic or time-domain method is useful in understanding the mechanism of voltage collapse and the coordination of protection controls dynamic analysis of power systems involve solution for first order differential equations can be solved in time-domain using numerical techniques and network power flow analysis methods. The study period is typically on the order of several minutes [1, 8].

2.4.2 Static Voltage Stability Analysis:

The static approach captures snapshots of the system conditions at various time frames along the time domain trajectory. In this method, the overall system equations reduce to purely algebraic equations allowing the use of static analysis techniques. Practical applications are developed on the basis of *V-Q* sensitivity. The advantages of the modal analysis and sensitivity analysis are that they give voltage stability related information from a system – wide perspective and clearly identify areas that have potential problems [1]. Several methods have been used for static voltage stability analysis to measure voltage stability proximity estimating the point of voltage collapse. A number of methods proposed in the literature use the singularity of power flow Jacobian matrix as base, sign or indicator of voltage collapse. Several methods are developed using eigenvalue or Jacobian matrix singularity monitoring the smallest eigenvalue, are based on a reducing Jacobian determinants, identifying the critical buses using a tangent vector, or computing eigenvalues and eigenvectors of a reduced Jacobian matrix and named as modal analysis. Other methods took another approach determining maximum loadability at line while others are specifying system stability margins at bus attempting to determine the weaken bus [17]. Modal analysis and V-Q sensitivity analysis are adopted to analyze the proposed system in this dissertation.

2.4.2.1 Modal Analysis:

It involves the computation of a small number of eigenvalues and associated eigenvectors of a reduced Jacobian matrix J_R, each eigenvalue and its associated eigenvectors define one mode of voltage stability. The eigenvalue determines whether that mode is voltage stable. The bus participation factor, which is calculated based on the eigenvectors of J_R, identify the physical elements which are associated with each mode. The mode with a small or negative eigenvalue is the voltage stability critical mode [20].

Reduced Jacobian Matrix:

Consider the linearized power flow equation expressed [1] as:

$$\begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \end{bmatrix} = \begin{bmatrix} \mathbf{J_{P\theta}} & \mathbf{J_{PV}} \\ \mathbf{J_{Q\theta}} & \mathbf{J_{QV}} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\theta} \\ \Delta \mathbf{V} \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

Where

$\Delta \mathbf{P}$ = incremental change in bus real power injection.

$\Delta \mathbf{Q}$ = incremental change in bus reactive power injection.

$\Delta \boldsymbol{\theta}$ = incremental change in bus voltage angle.

$\Delta \mathbf{V}$ = incremental change in bus voltage magnitude.

The elements of the Jacobian matrix give the sensitivity between power flow and bus voltage changes. System voltage stability is affected by both P and Q. In this analysis, at each operating point, P is kept constant and voltage stability is analyzed by considering the incremental relationship between Q and V. Based on these considerations, in Equation (2.1), let $\Delta P = 0$. then

$$\mathbf{\Delta Q = J_R \Delta V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.2)}$$

Where

$$\mathbf{J_R = [J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV}]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.3)}$$

And $\mathbf{J_R}$ is the reduced Jacobian matrix of the system. From Equation (2.2), we can write

$$\mathbf{\Delta V = J_R^{-1} \Delta Q} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.4)}$$

Voltage stability characteristics of the system can be identified by computing the eigenvalues and eigenvetors of the reduced Jacobain matrix $\mathbf{J_R}$ defined by Equation (2.3). Let

$$\mathbf{J_R = \xi\ \Lambda\ \eta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.5)}$$

From Equation (2.5)

$$\mathbf{J_R^{-1} = \xi\ \Lambda^{-1} \eta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.6)}$$

Substituting in equation (2.4) gives

$$\mathbf{\Delta V = \xi\ \Lambda^{-1} \eta \Delta Q} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.7)}$$

Or

$$\mathbf{\Delta V} = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \mathbf{\Delta Q} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.8)}$$

Where ξ_i is the i^{th}column right eigenvector and η_i the i^{th} row left eigenvector of and Λ is diagonal eigenvalue matrix .Each eigenvalue λ_i and the corresponding right and left eigenvectors ξ_i and η_i define the mode of the *Q*-*V* response. The modal analysis is performed using equation,

$$\mathbf{v = \ \Lambda^{-1} q} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.9)}$$

Where

$\mathbf{v} = \boldsymbol{\eta}\Delta\mathbf{V}$ the vector of modal voltage variations.

$\mathbf{q} = \boldsymbol{\eta}\Delta\mathbf{Q}$ the vector of modal reactive power variations.

Equation (2.9) represents uncoupled first order equations. For the mode i we have,

$$\mathbf{v_i} = \frac{\mathbf{1}}{\boldsymbol{\lambda}_\mathbf{i}}\mathbf{q_i} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.10)}$$

The stability criterion is formulated as follows. If $\lambda_i > 0$, then the system is voltage stable. If $\lambda_i < 0$, then the system is voltage unstable. The magnitude of λ_i determines the degree of stability of the modal voltage. The smaller the magnitude of positive λ_i, the closer the modal voltage to being unstable. When $\lambda_i = 0$, i^{th} modal voltage collapses because any change in that modal reactive power causes infinite change in the corresponding modal voltage [1].

Bus Participation Factors:

In (2.8), let $\Delta\boldsymbol{Q} = \boldsymbol{e_k}$,where $\mathbf{e_k}$ has all its elements zero except the $\mathbf{k_{th}}$ one being 1.Then,

$$\Delta\mathbf{V} = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.11)}$$

V-Q sensitivity at bus k

$$\frac{\partial V_k}{\partial Q_k} = \sum_i \frac{\xi_{ki}\eta_{ik}}{\lambda_i} = \sum_i \frac{P_{ki}}{\lambda_i} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.12)}$$

And

$$P_{ki} = \xi_{ki}\eta_{ik} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.13)}$$

where P_{ki} = The participation factor of bus k to mode i.

From Equation (2.12), P_{ki} indicates the contribution of the i^{th} eigenvalue to the V-Q sensitivity at bus k. the bigger the value of P_{ki} the more λ_i contributes in determining V-Q sensitivity at bus k. For all the small eigenvalues, bus participation factors determine the areas close to voltage instability.

Branch Participation Factors:

Branch participation factors, indicate, for each mode which branches consume the most reactive power response to an incremental change in reactive load. The relative participation of branch j in mode i is given by participation factor as:

$$P_{ji} = \frac{\Delta Q_{loss}\, for\ branch\ j}{maximum\ \Delta Q_{loss}\, for\ all\ branches} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(2.14)}$$

Branches with high participation factors are either weak links or are heavily loaded.

2.4.2.2 V-Q Sensitivity Analysis:

The voltage sensitivity method is the most direct approach using the voltage sensitivity to system parameter. This method calculates the relationship between voltage change and reactive power changes at different buses using reduced Jacobian matrix [20, 34]. Equations (2.1) through (2.4) represent the derivation for V-Q sensitivity analysis.

The elements of the inverse of the reduced Jacobian matrix J_R are V-Q sensitivities. The diagonal components $\partial V_i/\partial Q_i$ are the self-sensitivities and the non-diagonal elements $\partial V_k/\partial Q_i$ are the mutual sensitivities. Positive sensitivities represent stable operation and as stability decreases, the magnitude of the sensitivity increases becoming infinite at the maximum load ability limit. Negative sensitivities: unstable operation.

2.5 Reactive Power Compensation:

The management of reactive power at the load bus, for optimum performance of power system loads, being the prime objective of load compensation, the scope of load compensation can be subdivided into the following three components which are power factor correction, improving voltage regulation and balancing of loads. Different techniques are used for controlling the voltage in the system. Generator excitation control as well as switching of capacitors and/or inductors are enough for cyclic load variation. Some of the compensator devices may serve as a reactive power compensator while a few may act as both real and reactive power compensators. Broadly, the compensators may be classified in the following two groups [21]:

1. Passive or classical compensators.
2. Active (FACTS) compensators based power electronic technologies.

2.6 Ideal Shunt Compensation:

A simple and lossless ac system is composed of two ideal generators, and a short transmission line, as shown in Figure 2.3, is considered as basis to discuss the operating principles of a shunt compensator [19]. The transmission line is modeled by an inductive reactance X_L. In the circuit, a continuously controlled voltage source is connected in the middle of the transmission line. It is assumed that the voltage phasors V_S and V_R have the same magnitude and are phase-shifted by δ. V_M has also the same magnitude as V_S and V_R, and its phase is exactly $(-\delta/2)$ with respect to V_S and $(+\delta/2)$ with respect to V_R. In this situation, the current I_{SM} flows from the source and the current I_{MR} flows into the receptor. The phasor I_M is the resulting current flowing through the ideal shunt compensator; this current I_{SM}, in this case, is orthogonal to the voltage V_M, which means that the ideal shunt compensator voltage source does not has to generate or absorb active power and have only reactive power in its terminals [22]. And in this case the active power transferred from V_S to V_R is given by,

$$P = \frac{2V^2 \sin(\delta/2)}{X_L} \quad \text{.....................................} \quad (2.15)$$

Since 2 $\sin(\delta/2)$ is always greater than sin δ for δ in the range of [0, 2π], the ideal shunt compensator does improve the stability by increasing power transfer capability of the transmission line and it helps produce a substantially flat voltage profile at all levels of power transmission and meet the reactive power requirements of transmission [22, 23].

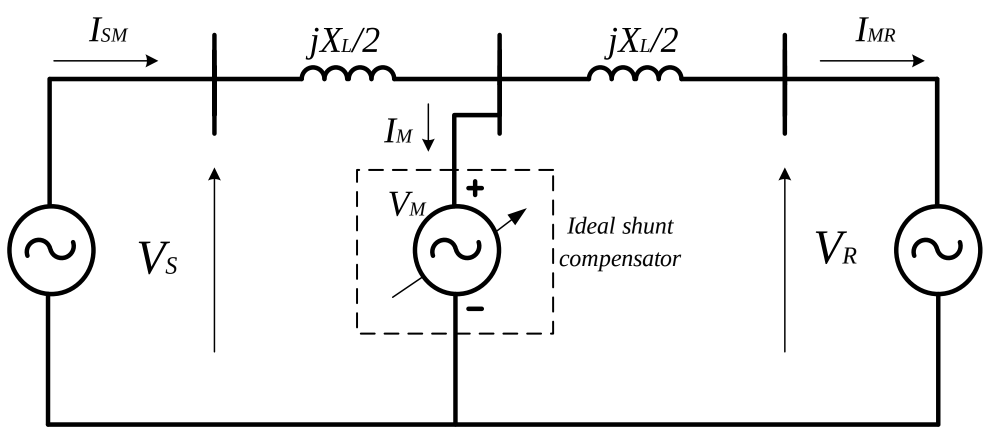


Figure 2.3: Ideal shunt compensator connected in the middle of the line.

2.7 FACTS Controllers:

FACTS (Flexible AC transmission System) is defined as an alternating transmission system incorporating semiconductor based power electronic and other static controllers in order to enhance power transfer capacity and increase controllability of transmission. It increases the ability to accommodate changes in operating conditions simultaneously, maintaining steady state and transient stability margins [21]. The development of FACTS-devices has started with the growing capabilities of power electronic components. Devices for high power levels have been made available in converters for high and even highest voltage levels. The overall starting points are network elements influencing the reactive power or the impedance of a part of the power system [6].

It is well known that these devices are capable of controlling voltage magnitude, phase angle and circuit reactance. By controlling these, we can improve the reactive power margin, regulate bus voltage and thereby ensure voltage stability of the system. Therefore, this method provides a promising one to improve voltage stability [26].

2.8 Classification of FACTS Devices According to the Operating Technology:

FACTS controllers can be classified into two families according to the power electronics technology which used [48]:

A. Thyristor-based devices are:

- Thyristor Controlled Reactors (TCR).
- Thyristor Switched capacitor (TSC).
- Static Var Compensator (SVC).
- Thyristor Switched Series Compensator (TSSC/TSSR).
- Thyristor Controlled Series Compensator (TCSC/TCSR).

- Thyristor Controlled Braking resistors (TCBR).
- Thyristor Controlled Phase Shifting Transformers (TCPST).
- Line Commutated Converter Compensator (LCC).

B. Converter-based devices are:

- Static synchronous compensator (STATCOM).
- Static Synchronous Series Compensator (SSSC).
- Unified Power Flow Controller (UPFC).
- Interline Power Flow Controller (IPFC).
- Self-Commutated Compensator (SCC).

2.9 Classification of FACTS Controllers Based on Their Connection in The System:

2.9.1 Series Controllers:

Series controllers, in FACES technology, arc used to inject voltage in series with the line. In the simplest form, a variable impedance multiplied by the current flow through it represents an injected series voltage in the line. If the series voltage is in phase quadrature with the line current, the series controller Only supplies or absorbs variable reactive power, Real power is involved for any other phase relationship between the injected voltage and the line current. symbolic representation of series FACTS controller is shown in Figure 2.4 [21].

Static Synchronous Series Compensator (SSSC) and Thyristor Controlled Series Compensator (TCSC/TCSR) represent an examples of series connected FACTS controllers [6].

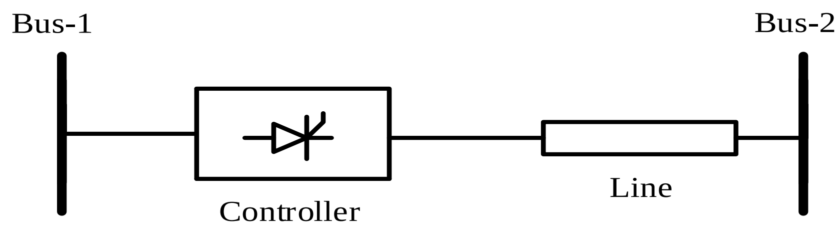


Figure 2.4: Series controller.

2.9.2 Shunt Controllers:

Similar to series controllers, shunt controllers have variable impedance or a variable source or a combination of both. All shunt connected FACTS devices inject current into the bus at the point of connection. the shunt impedance may be variable to vary the injected current. As long as this injected current is in phase quadrature with line voltage, the shunt controller only supplies or absorbs variable reactive power. Any other phase relationship of the generated current with line voltage will involve real power flow [21].

The most common shunt connected FACTS devices are Static Var Compensator (SVC) and Static Synchronous compensator (STATCOM) which used in the dissertation. The shunt FACTS controller symbolically represented in figure 2.5 below.

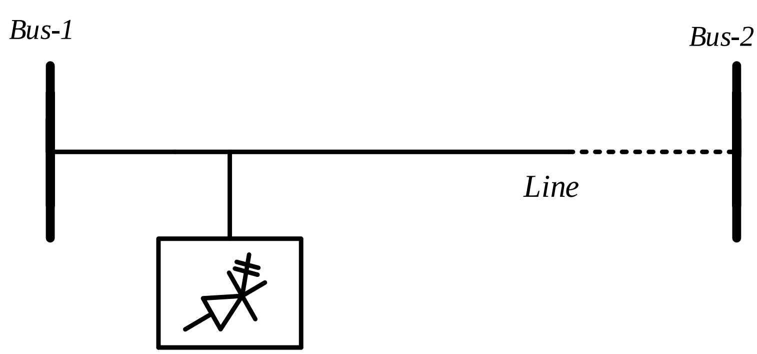


Figure 2.5: Symbolic representation of shunt controller.

2.9.3 Series-Series Controller:

Any standard series controller (FACTS device) may be suitably connected with another type of series FACTS controller to form a series-series controller. Though not very common in use, the series-series controller (Fig. 2.6) may be applied for control of power in double circuit ac lines [21].

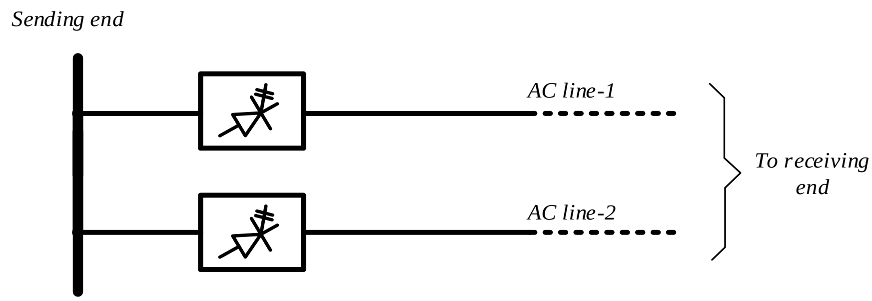


Figure 2.6: schematic of series – series controller

2.9.4 Shunt-Series Controller:

Shunt-Series controller is a combination of separate series and shunt controllers which are controlled in a coordinated manner to provide series and shunt reactive power compensation. Transfer of active power is done via DC link [24]. Example of the series-shunt compensator is the unified power flow controller (UPFC) [6]. Figure 2.7 represents the symbolic of series-shunt compensation.

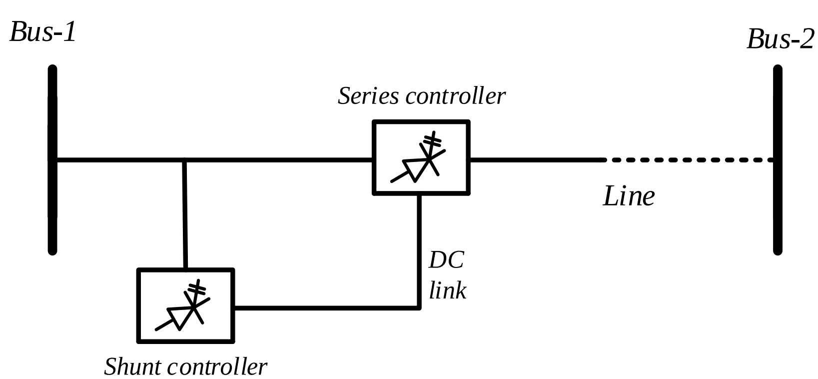


Figure 2.7: Schematic of shunt – series controller.

2.10 Static Synchronous Compensator (STATCOM):

The STATCOM is a FACTS controller based on voltage sourced converter (VSC). A VSC generate a synchronous voltage of fundamental frequency [49], controllable magnitude and phase angle. If a VSC is shunt connected to a system via a coupling transformer as shown in Figure 2.8, 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 [19, 29, 42].

2.10.1 Operation Principle of STATCOM:

The control of reactive power in the STATCOM is done by controlling its terminal voltage [22, 25]. For the voltage source converter, its ac output voltage is controlled, such that, it is just right for the required reactive current flow for any ac bus voltage, and DC capacitor voltage is automatically adjusted as required to serve as a voltage source for the converter. The basic operational principle of STATCOM is as follows [38]:

• The voltage source converter which is connected to a DC capacitor generates a controllable AC voltage source behind the transformer.

• The voltage difference across the reactance of the transformer produces active and reactive power exchanges between the STATCOM and the power system.

• The STATCOM output voltage magnitude can be controlled by controlling the voltage across the DC capacitor.

The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point [27, 44]. This can be seen in the V-I characteristics diagram shown in figure 2.9 for the maximum currents being independent of the voltage in comparison to the SVC [28]. This means, that even during most severe contingencies, the STATCOM keeps its full capability [6].

2.10.2 Modeling of STATCOM:

In this section, the implementation of STATCOM's model in the Newton-Raphson power flow will be discussed [21, 31]. A schematic representation of the STATCOM equivalent circuit are shown in Figure 2.10.

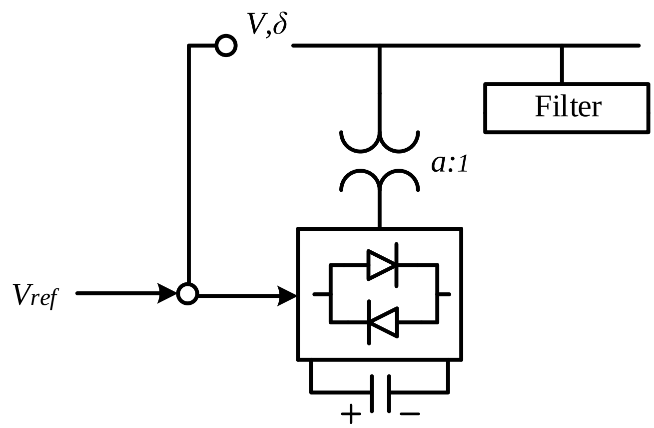


Figure 2.8: Structure of STATCOM.

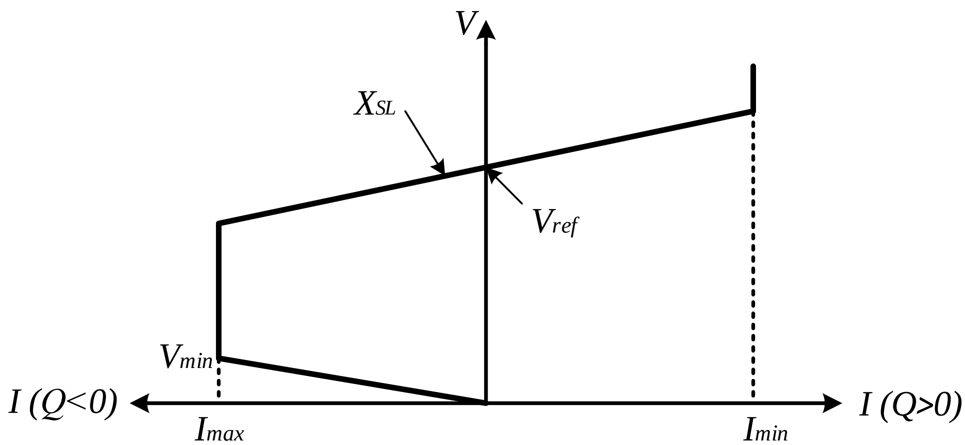


Figure 2.9: V-I characteristics of STATCOM.

Let,

$V_{sc}\angle\delta_k$ = bus voltage at bus k,

$V_{sc}\angle\delta_{sc} =$ inverted voltage (ac) at the output of STATCOM,

$X_{sc} =$ STATCOM reactance,

$Q_{sc} =$ reactive power exchange for the STATCOM with the bus.

It is assumed that the shunt-connected transformer is ideal. STATCOM's operating is through this way: The active power flow between the AC source and the VSC is controlled by the phase angle and the reactive power flow is determined mainly by the magnitude of the bus voltage (V_k), and the VSC output fundamental voltage, V_{sc}.

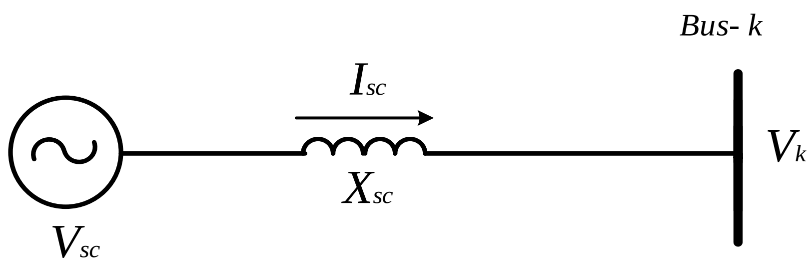


Figure 2.10: Equivalent circuit of shunt operated STATCOM.

For $V_{sc} > V_k$, the VSC generates reactive power and consumes reactive power when $V_{sc} < V_k$. During normal operation, a small amount of active power must flow into the VSC to compensate for the power losses inside the VSC, and δ_{sc} is kept slightly larger than 0 (lagging). STATCOM equivalent circuit shown in Fig. 2.10 is used to drive the mathematical model of the controller for inclusion in power flow algorithm. The power flow equations for bus *i* of the power system with no FACTS controllers given by

$$P_k = \sum_{m=1}^{n} (V_k^2\, G_{kk} - V_k V_m [G_{km} \cos(\delta_k - \delta_m) + B_{km} \sin(\delta_k - \delta_m)]) \dots\dots\dots\dots\dots (2.16)$$

$$Q_k = \sum_{m=1}^{n} (-V_k^2\, B_{kk} + V_k V_m [G_{km} \cos(\delta_k - \delta_m) - B_{km} \sin(\delta_k - \delta_m)]) \dots\dots\dots\dots (2.17)$$

With the addition of STATCOM connected at bus k the power flow equations of the system remain the same as the power flow equations of the system without STATCOM for all buses given by Eq. (2.16) and (2.17), except for bus k which are given below. The power flow equations for the STATCOM in 2-bus system (Figure 2.10) are obtained below from first principles and assuming the following voltage source representation:

$$E_{sc} = V_{sc}(\cos\delta_{sc} + j\sin\ \delta_{sc}) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2.18)$$

Based on the shunt connection shown in Figure 2.9, the following may be written:

$$S_{sc} = V_{sc}I_{sc}^{*} = V_{sc}Y_{sc}(V_{sc}^{*} - V_{k}^{*}) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.19)$$

Then, the following active and reactive power equations are obtained for the converter and bus *k*, respectively:

$$P_{sc} = V_{sc}^{2}\ G_{sc} - \ V_{sc}V_{k}[G_{sc}\cos(\delta_{sc} - \delta_{k}) + B_{sc}\sin(\delta_{sc} - \delta_{k})] \ldots\ldots.. (2.20)$$

$$Q_{sc} = -V_{sc}^{2}\ B_{sc} + \ V_{sc}V_{k}[B_{sc}\cos(\delta_{sc} - \delta_{k}) - G_{sc}\sin(\delta_{sc} - \delta_{k})] \ldots\ldots (2.21)$$

$$P_{k} = V_{k}^{2}\ G_{sc} - \ V_{k}V_{sc}[G_{sc}\cos(\delta_{k} - \delta_{sc}) + B_{sc}\sin(\delta_{k} - \delta_{sc})] \ldots\ldots\ldots (2.22)$$

$$Q_{k} = -V_{k}^{2}\ B_{sc} + \ V_{k}V_{sc}[B_{sc}\cos(\delta_{k} - \delta_{sc}) - G_{sc}\sin(\delta_{k} - \delta_{sc})] \ldots\ldots. (2.23)$$

These equations for the 2-bus power system are obtained. Thus, in general, for an n-bus power system the active and reactive power equations for bus k (the bus that STATCOM is connected) are obtained from equations (2.16), (2.17), (2.22) and (2.23) as bellow:

$$P_{k} = V_{k}^{2}\ G_{sc} - \ V_{k}V_{sc}[G_{sc}\cos(\delta_{k} - \delta_{sc}) + B_{sc}\sin(\delta_{k} - \delta_{sc})] + \sum_{m=1}^{n}(V_{k}^{2}\ G_{kk} - \ V_{k}V_{m}[G_{km}\cos(\delta_{k} - \delta_{m}) + B_{km}\sin(\delta_{k} - \delta_{m})]) \ldots\ldots (2.24)$$

$$Q_k = -V_k^2\, B_{sc} + \; V_k V_{sc}[B_{sc}\cos(\delta_k - \delta_{sc}) - G_{sc}\sin(\delta_k - \delta_{sc})]$$

$$+ \sum_{m=1}^{n} (-V_k^2\, B_{kk} + \; V_k V_m[G_{km}\cos(\delta_k - \delta_m) - B_{km}\sin(\delta_k - \delta_m)]) \ldots . (2.25)$$

With addition of STATCOM, two variables (V_{sc}, δ_{sc}) are added to state variables, so we need two additional equations. One equation is STATCOM's active power (In this representation, The STATCOM's active generation is assumed zero) and another equation is introduced in,

$$F = V_k - V_{SP} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.26)$$

Where V_{SP} is the voltage that STATCOM must be set for bus k. Using these equations, the linearized STATCOM's model is given as,

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{sc} \\ \Delta F \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \delta_k} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_{sc}} & \frac{\partial P_k}{\partial V_{sc}} V_{sc} \\ \frac{\partial Q_k}{\partial \delta_k} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_{sc}} & \frac{\partial Q_k}{\partial V_{sc}} V_{sc} \\ \frac{\partial P_{sc}}{\partial \delta_k} & \frac{\partial P_{sc}}{\partial V_k} V_k & \frac{\partial P_{sc}}{\partial \delta_{sc}} & \frac{\partial P_{sc}}{\partial V_{sc}} V_{sc} \\ \frac{\partial F}{\partial \delta_k} & \frac{\partial F}{\partial V_k} V_k & \frac{\partial F}{\partial \delta_{sc}} & \frac{\partial F}{\partial V_{sc}} V_{sc} \end{bmatrix} \begin{bmatrix} \Delta \delta_k \\ \frac{\Delta V_k}{V_k} \\ \Delta \delta_{sc} \\ \frac{\Delta V_{sc}}{V_{sc}} \end{bmatrix} \ldots\ldots\ldots\ldots (2.27)$$

At the end of iteration i, the variable voltage V_{sc} can be corrected as

$$V_{sc}^{(i+1)} = \; V_{sc}^{(i)} + \Delta V_{sc}^{(i)} \ldots\ldots\ldots\ldots\ldots\ldots (2.28)$$

The STATCOM is represented by a synchronous voltage source with maximum and minimum voltage magnitude limits that is [V_{min}, V_{max}] p.u and its phase angle is in range [0, 2π] rad. In each iteration we check the STATCOM's voltage limits as bellow:

$If \quad V_{sc} \geq \; V_{max}$ then $F = V_{sc} - V_{max}$

$If \quad V_{sc} \leq V_{min}\; then \;\; F = V_{sc} - V_{min}$

Chapter Three

OPTIMAL LOCATION OF STATCOM

3.1 Introduction:

Although power production, transmission and distribution are unbundled there still exist common interests for these companies: power system adequacy and security. The transmission networks need to be utilized ever more efficiently. The transfer capacity of an existing transmission network needs to be increased without major investments but also without compromising the security of the power system. The more efficient use of transmission network has already led to situation in which many power systems are operated more often and longer close to voltage stability limits. A power system stressed by heavy loading has a substantially different response to disturbances from that of a non-stressed system [32].

The main focus in voltage stability studies in power system is the identification of weak or critical buses. There are counter measures to avoid voltage instability. One of the most important is FACTS devices compensation to extend the voltage stability margin (VSM) [8, 11]. In order to optimize and to obtain the maximum benefits from their use, the main issues to be considered are the type of FACTS devices, the settings of FACTS devices and optimal location of FACTS devices. The optimal location can be selected on the basis of voltage stability indices (VSIs) for improvement of voltage stability of power system. Voltage stability index can be used for determining the weakest line in a power system [37].

Thus, several voltage stability indices were derived from static power flow analysis. The values of these indices were calculated for each transmission line and bus based on load flow calculation results [41]. Voltage stability indices are relatively simple, accurate and fast generating voltage stability indications with low computation time needed to avoid such voltage collapse events. The introduced indices can be applied in real-time application producing quick voltage stability indications, allowing controls to take necessary action to prevent such incidents. The introduced indices might fulfil the needs of electric sectors and meet application's requirements to prevent future blackout incidents [17].

3.2 Classification of VSIs:

Many VSIs have been proposed in literature. These indices have been classified based on the following ways [11]:

1. Jacobian matrix and system variables based VSIs.
2. Bus, line and overall VSIs.

Jacobian matrix based VSIs can calculate the voltage collapse point and determine the VSM. But the computation time is high and any topological change leads to change the Jacobian matrix and this matrix must be recalculated. On the other hand, the VSIs which are based on system variables require less computation and are adequate for real-time applications. The disadvantage of these indices is that they cannot accurately estimate the VSM so they can just present critical lines and buses. In many applications, VSIs are used to detect the weakest bus and line of power system or triggering the countermeasures against voltage instability. Therefore, the classification of VSIs according to the bus, line and overall indices, can be very useful [11].

3.3 Line Voltage Stability Indices:

Voltage stability analysis can be evaluated by the voltage stability index referred to a line. All of the line VSIs are formulated based on the two bus representation of a system as Figure 3.1 where the shunt admittances are neglected. So, the theoretical base of most of the line VSIs are the same and the difference is in the assumptions used in each index. In proving most of the line VSIs, the discriminant of the voltage quadratic equation is set to be greater than or equal to zero to achieve the stability [11], fast voltage stability index (FVSI), line stability index (L_{mn}) and Novel line stability index (NLSI), which used in this dissertation, representing an examples of line VSIs [43].

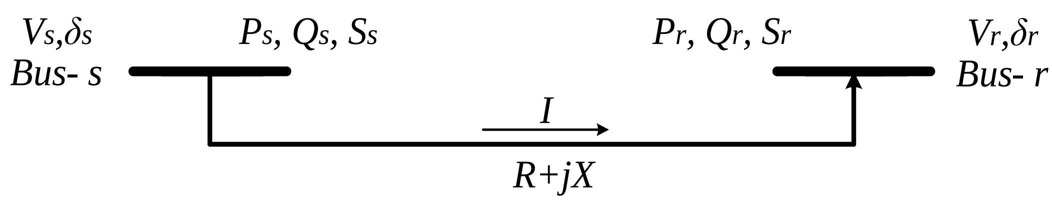


Figure 3.1: Two-bus power system model.

3.4 Novel line Stability Index (NLSI):

The NLSI is based on the concept in which the discriminant of the voltage quadratic equation is set to be greater than or equal to zero. Any line in the system whose NLSI is close to unity indicates that the line is approaching its stability limit.

The mathematical formulation for the Novel voltage stability index is derived by the current equation through a line in a 2 bus system [32, 35] shown in Figure 3.1 above. By taking bus s as the sending bus, bus r as the receiving bus and choosing the sending bus as the reference and ($\delta_s - \delta_r = \delta$), then the power equation at bus 2 is as follows;

$$\overrightarrow{S_r} = \overrightarrow{V_r}\,\vec{I}^* \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.1)}$$

And the current I is given by,

$$\vec{I} = \overrightarrow{Y_{sr}}\left(\overrightarrow{V_s} - \overrightarrow{V_r}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.2)}$$

Substitute equation (3.2) in (3.1),

$$S_r = \overrightarrow{V_r}\left(\overrightarrow{Y_{sr}}\left(\overrightarrow{V_s} - \overrightarrow{V_r}\right)\right)^* \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.3)}$$

So,

$$P_r + jQ_r = V_r\angle\delta\left(\frac{V_s - V_r\angle -\delta}{R - jX}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.4)}$$

Rearranging equation (3.4) and substitute $V_2\angle\delta = V_2(\cos\delta + jsin\,\delta)$, gives these following equations;

$$V_sV_r sin\,\delta - RQ_r + XP_r = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.5)}$$

$$V_r^2 + V_sV_r cos\,\delta + RP_r + XQ_r = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.6)}$$

The quadratic equation for the receiving bus is given by;

$$V_r = \frac{-V_s cos\,\delta \pm \sqrt{(V_s cos\,\delta)^2 - 4(RP_r + XQ_r)}}{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.7)}$$

Where, P_s, Q_s are the active and reactive power at the sending buses. P_r, Q_r are the active and reactive power at the receiving buses. R, X are the line resistance and reactance respectively. δ is angle difference between the sending and receiving buses.

To obtain real value for V_r, the discriminate of equation (3.6) must be greater than or equal to zero. There for we can obtain this statement;

$$V_s^2 cos^2\delta \geq 4(RP_r + XQ_r) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.8)}$$

Then;

$$1 \geq \frac{4(RP_r+XQ_r)}{V_s^2 cos^2 \delta} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(3.9)}$$

And;

$$\frac{RP_r+XQ_r}{0.25\, V_s^2 cos^2 \delta} \leq 1 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(3.10)}$$

Since the difference in the angle between the sending bus and the receiving bus δ, is normally very small, therefore, $cos\ \delta \approx 1$. And the novel line stability index (NLSI) can be expressed as,

$$NLSI = \frac{RP_r+XQ_r}{0.25\, V_s^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(3.11)}$$

Any line in the system that exhibits NLSI closed to unity indicates that the line is approaching its stability limit hence may lead to system violation. Therefore, NLSI has to be maintained less than unity in order to maintain a stable system [32].

3.5 Voltage Stability Indices and System Loading:

There have been a number of incidents in the past few years which were diagnosed as voltage instability problem due to the increase in loading and decrement of stability margin. The stability margin (VSM) can be defined as the distance between the base loading of the system and the maximum loading limit of the system [47]. The contingencies occur in the system would lead to the decrease in stability margin and the system approaches a very critical stage, which may lead the system to a total collapse. Various techniques were reported in the literature to identify and estimate the maximum loadability [17, 32] to indicate its importance in power system studies. One of the conventional techniques is the repetitive power flow in which load was increased in steps until load flow diverges. At this point, it was assumed that the system is at its maximum loading point prior to the system collapse [9].

The computation of VSIs at various loading of the system allows the prediction of voltage collapse point and estimation of VSM. In this application, the loads were remained constant and increased in small steps, until the system collapsed. At this point, the voltage collapse is predicted and voltage stability margin is calculated. Two load scenarios were considered in this study: in the first on load components were increased simultaneously at all buses once with loading factor λ until the system collapsed then calculate the VSI at the point of collapse The power factors were kept constant [17] and,

$$New\ load = Initial\ load * (1 + \lambda) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.12)$$

In the other scenario, the active and reactive power of buses gradually increased at constant power factor from basis quantity until the load flow equation diverged. This is the maximum power that a bus can supply before voltage instability happened. NLSI for each line of system is obtained according to increase of load. The line that has largest index and smallest lodability is introduced as the critical line [32, 41].

Chapter Four

SIMULATION RESULTS AND DISCUSSIONS

4.1 Test System Description:

The system studied in this dissertation, is a part of Sudanese national grid as shown in single line diagram of figure 4.1, it consists of slack bus (Marawy), three generator buses (Gerri, Khartoum north and Jabel awlya) and 26 load buses, all elements connected through 28 transmission lines at three voltage levels (500, 220 and 110 kV). The data of this system is available in appendix B. Loads are considered as constant power and the voltage limits are (0.95 – 1.05) pu. Software used for this study is NEPLAN.

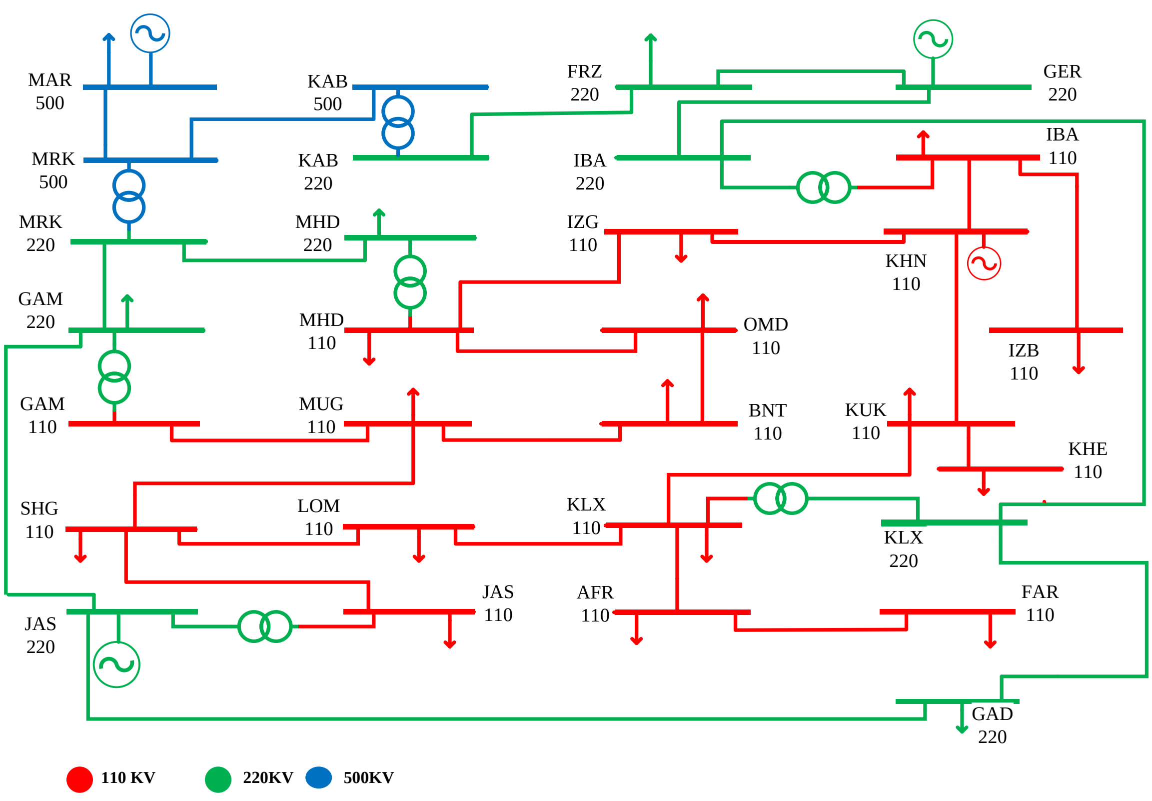


Figure 4.1: Case study system.

4.2 Results and Discussions:

NEPLAN software is used to calculate the load flow solution then analyze the voltage stability based on modal analysis and Q-V sensitivity analysis. Two cases are considered: the base case without compensation and the compensated case by implementation of multiple STATCOM to the system. The optimal location of the STATCOMs is selected by identification of weakest buses using Novel line stability index (NLSI). A comparison is made between the two of cases to investigate the impact of STATCOM on voltage stability of the system.

4.2.1 Base case:

Table 4.1 shows the voltage profile of the base case after performing load flow. All busses are within tolerance except FAR 110 which is below the voltage limits.

Table 4.1: Voltage profile at base case.

BUS	*V (kv)*	*V (p.u.)*	*Ang(°)*	*BUS*	*V (kv)*	*V (p.u)*	*Ang(°)*
AFR 110	104.878	0.9534	-15.8	OMD110	105.76	0.9615	-15.4
BNT 110	105.271	0.9570	-15.6	SHG110	105.44	0.9586	-15.4
FAR 110	**103.51**	**0.9410**	**-16.6**	FRZ 220	220.21	1.0009	-8.2
GAM110	106.827	0.9712	-14.4	GAM 220	219.09	0.9959	-11.4
IBA 110	108.817	0.9892	-14.4	GER 220	220	1.0000	-8.2
IZB 110	108.074	0.9825	-15.0	GIAD 220	218.11	0.9914	-12.2
IZG 110	108.137	0.9831	-14.9	IBA 220	216.18	0.9826	-12.1
JAS110	108.05	0.9823	-13.7	JAS220	220	1.0000	-11.7
KHE 110	107.541	0.9776	-15.2	KAB 220	221.96	1.0089	-7.6
KHN110	110	1.0000	-15.0	KLX 220	215.4	0.9791	-12.6
KLX110	106.077	0.9643	-15.0	MHD 220	218.4	0.9927	-11.2
KUK 110	107.841	0.9804	-15.0	MRK 220	220.47	1.0021	-10.3

BUS	***V (kv)***	***V (p.u.)***	***Ang(°)***	***BUS***	***V (kv)***	***V (p.u)***	***Ang(°)***
LOM 110	105.772	0.9616	-15.2	KAB 500	509.78	1.0196	-6.1
MHD110	107.474	0.9770	-14.6	MAR 500	500	1.0000	0.0
MUG110	105.277	0.9571	-15.5	MRK 500	510.81	1.0216	-5.9

Figure 4.2 below shows the voltage magnitude of the busses of level 110 kV transmission system, which show that most of the buses are near to the lower limit and FAR bus is out of tolerance as obtained from the load flow.

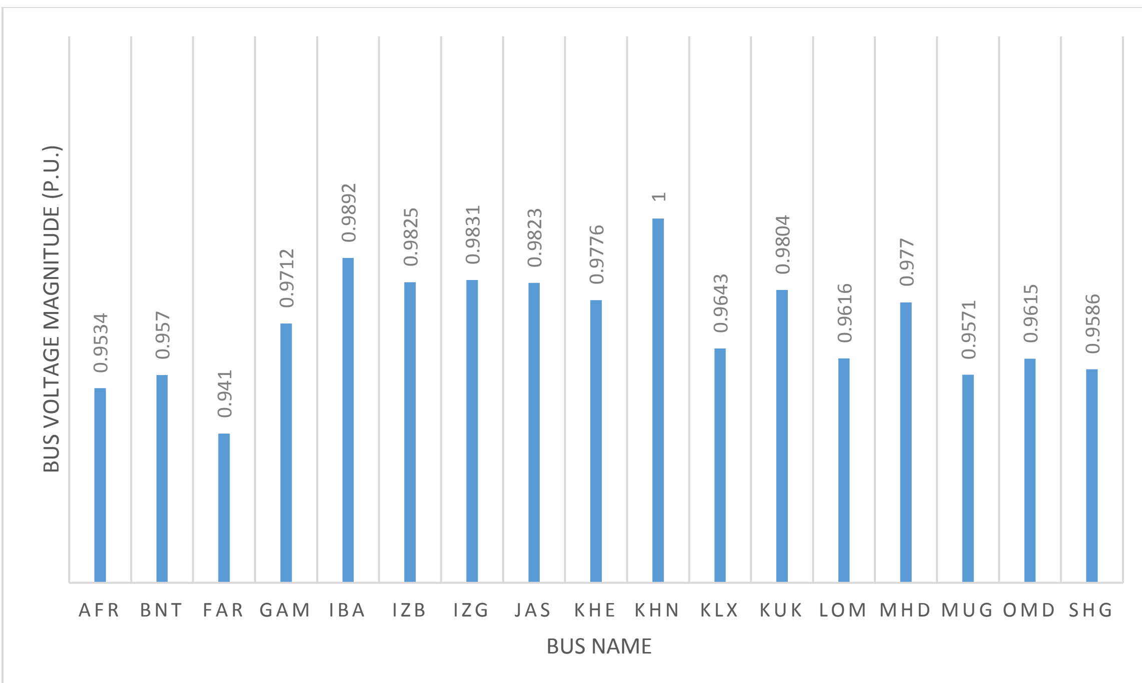


Figure 4.2: Voltage magnitude of 110 kV busses.

For 110 kv transmission system, the total active power losses are 7.954 MW and the total reactive power losses are 6.685 MVAr. Active losses, reactive losses and loading of each line are shown in table 4.2 and represented at figures 4.3, 4.4 and 4.5 below:

Table 4.2: Active losses, reactive losses and line loading of 110 kv system.

Line	*Loading (%)*	*P loss (MW)*	*Q loss (MVAr)*	*Line*	*Loading (%)*	*P loss (MW)*	*Q loss (MVAr)*
BNT-OMD	14.76	0.0803	-0.1769	IZB-IBA	19.87	0.2718	0.1634
KLX-AFR	24.53	0.4139	0.8615	GAM-MUG	27.76	0.6805	1.7753
MHD-IZG	16.06	0.1308	-0.1734	AFR-FAR	21	0.3851	0.4887
MUG-SHG	4.08	0.0117	-0.9491	IBA-KHN	21.51	0.3455	0.3787
KUK-KLX	23.77	0.2458	0.0736	KUK-KHE	24.92	0.125	0.2588
JAS-SHG	15.38	0.5934	-0.9725	MHD-OMD	36.89	0.7927	2.7056
BNT-MUG	6.03	0.0087	-0.3065	KLX-LOM	21.66	0.0883	0.1216
KHN-IZG	23.19	0.4096	0.675	LOM-SHG	8.81	0.0384	-0.5406
KUK-KHN	63.02	3.3319	2.3017				

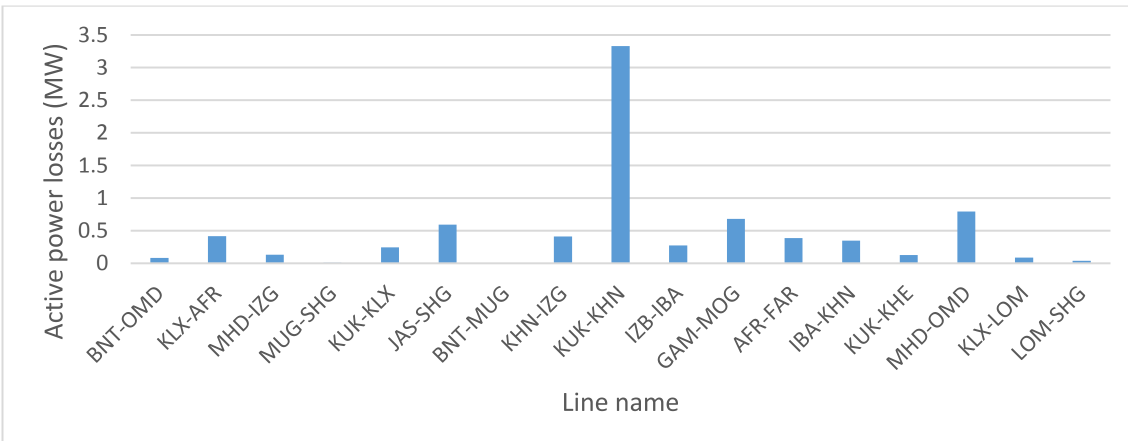


Figure 4.3: Active power losses at base case

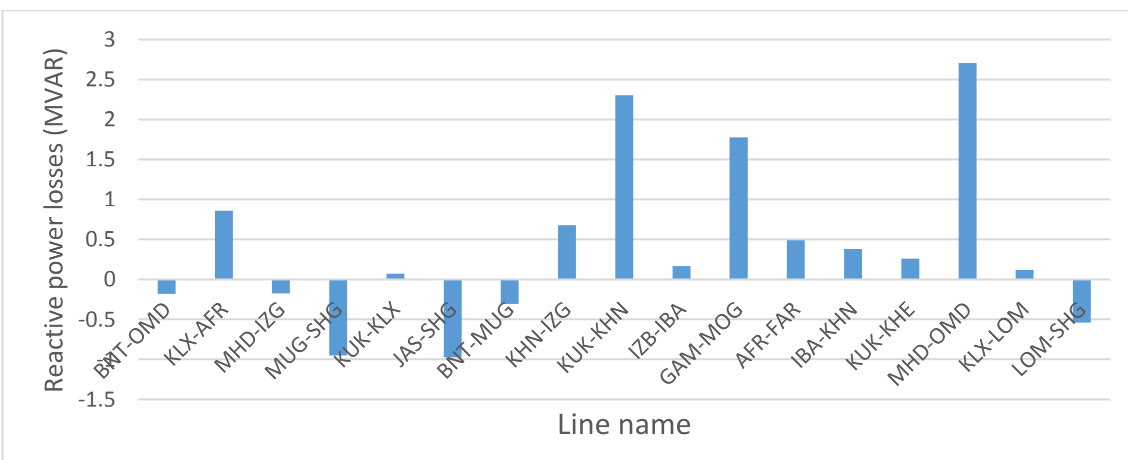


Figure 4.4: Reactive power losses at base case.

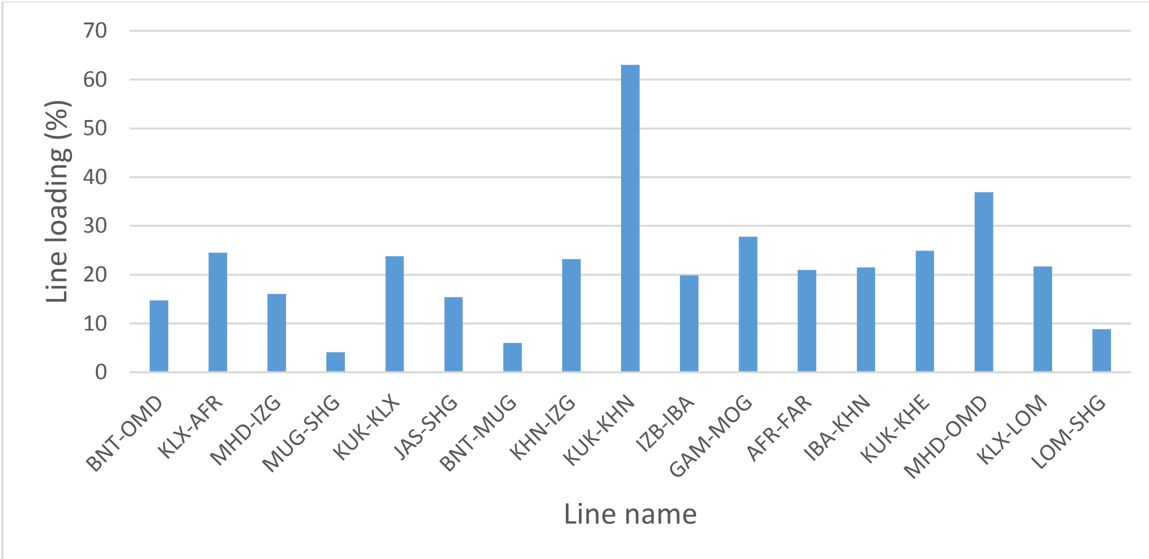


Figure 4.5: Line loading of the system at base case.

Voltage stability analysis study of the base case is done using modal analysis and Q-V sensitivity analysis, table 4.3 shows the calculated eigenvalues of the reduced Jacobian matrix.

Table 4.3: eigenvalues of the system at base case

No.	***Eigenvalue***	***No.***	***Eigenvalue***
1	9.4943	14	150.396
2	17.873	15	190.4197
3	31.1477	16	212.6815
4	33.9768	17	222.8866
5	40.6997	18	260.938
6	55.9769	19	336.7779
7	62.4663	20	421.7587
8	72.3017	21	535.578
9	78.0873	22	565.8586
10	89.6857	23	586.7884
11	111.9099	24	601.6711
12	123.8033	25	676.5811
13	125.8583	26	737.6641

It is clear from the above table that all eigenvalues are positive so the system is voltage stable, the critical mode is that corresponds to the smallest eigenvalue (9.4943). To identify the weakest buses of the system, right eigenvector components and bus participation factors corresponding to that minimum critical eigenvalue are given in tables 4.4 and 4.5. The buses that have the highest eigenvector components as well as the highest participation factors are considered as weakest buses and prone to voltage instability.

Table 4.4: Right eigenvector at the critical mode

Bus	***Magnitude of component***
IBA 220	0.0844
KLX 220	0.1089
OMD110	0.2522
BNT 110	0.2825
KLX110	0.2532
AFRA110	0.375
GIAD 220	0.0281
MHD110	0.1731
IZG 110	0.1098
FRZ 220	0.002
KAB 220	0.0168
MRK 220	0.0958
GAM 220	0.0785
MUG110	0.2875
SHG110	0.2804
KUK 110	0.0603
JAS110	0.1661
GAM110	0.2579
IBA 110	0.0402
IZB 110	0.0468
FARG110	0.4662
KHE 110	0.0631
MRK 500	0.0487
KAB 500	0.0461
MHD 220	0.1168
LOM 110	0.2684

Table 4.5: Bus participation factors at the critical mode.

Bus	***Participation Factor***
FAR 110	0.2148
AFR 110	0.1401
MUG110	0.0825
BNT 110	0.0797
SHG110	0.0785
LOM 110	0.0721
GAM110	0.0667
KLX110	0.0642
OMD110	0.0638
MHD110	0.0304
JAS110	0.0277
MHD 220	0.0141
IZG 110	0.0123
KLX 220	0.0121
MRK 220	0.0095
IBA 220	0.0074
GAM 220	0.0063
KHE 110	0.0041
KUK 110	0.0038
MRK 500	0.0026
KAB 500	0.0023
IZB 110	0.0023

It can be observed that the most critical buses in the system are the buses of 110 kV level (FAR, AFR, MUG, BNT, SHG, LOM, GAM, KLX and OMD), that also can be seen from the results of the V-Q sensitivity analysis of the system.

Table 4.6 shows the self-sensitivities of the buses, as discussed in chapter 2, buses that have the largest values of self V-Q sensitivities are considered as the weakest buses that need improvement of voltage stability by reduction of their sensitivities. The maximum loading factor of the base case is 1.805, at that point, system reaches its stability limits and collapses at the values beyond that point.

Table 4.6: Self V-Q sensitivities at base case

Bus	***V-Q Sensitivity***
FARG110	0.0467
AFRA110	0.027
JAS110	0.0266
IZB 110	0.0247
GAM110	0.0231
BNT 110	0.0175
OMD110	0.0173
MUG110	0.0165
SHG110	0.0153
MHD 220	0.0144
LOM 110	0.0137
MHD110	0.0131
KLX110	0.0121
KAB 500	0.0117
MRK 220	0.0109
IZG 110	0.0108
IBA 110	0.0104
KAB 220	0.0102
MRK 500	0.0098
KHE 110	0.0097
KLX 220	0.0096
GIAD 220	0.0092
IBA 220	0.0085
GAM 220	0.0083
KUK 110	0.0055
FRZ 220	0.0015

4.2.2 Identification of the Optimal Locations of STATCOM:

Novel line stability index (NLSI) is used to identify the optimal placement of STATCOM to obtain the best results from the compensation. The system load is increased at small steps until it reached its maximum loading, then line index is applied to the 110 kV transmission system. The obtained results are shown in table 4.7 below:

Table 4.7: Results of NLSI application at 1.805 loading factor.

Line	***NLSI***	***Line***	***NLSI***
AFR-FAR	**0.11924**	SHG-MUG	**0.120746**
KLX-AFR	0.040723	GAM-MUG	**0.153562**
KLX-KUK	0.071448	BNT-MUG	0.045786
KHN-KUK	0.027549	MHD-OMD	**0.079336**
KHN-IBA	0.027161	BNT-OMD	0.058086
IBA-IZB	0.04749	MHD-IZG	0.050713
KLX-LOM	0.014457	KHN-IZG	0.051149
LOM-SHG	0.06236	KUK-KHE	0.019869
JAS-SHG	**0.257747**		

The results of NLSI shows that lines (SHG-JAS, MUG-GAM, MUG-SHG, AFR-FAR and OMD-MHD) are the weakest lines which connected to the weakest buses. Figures (4.6 to 4.10) shows the plotted NLSIs of the critical buses versus the reactive power loading. The load at each bus is gradually increased from basis quantity until the load flow equation diverged. This is the maximum power that a bus can supply before voltage instability happened.

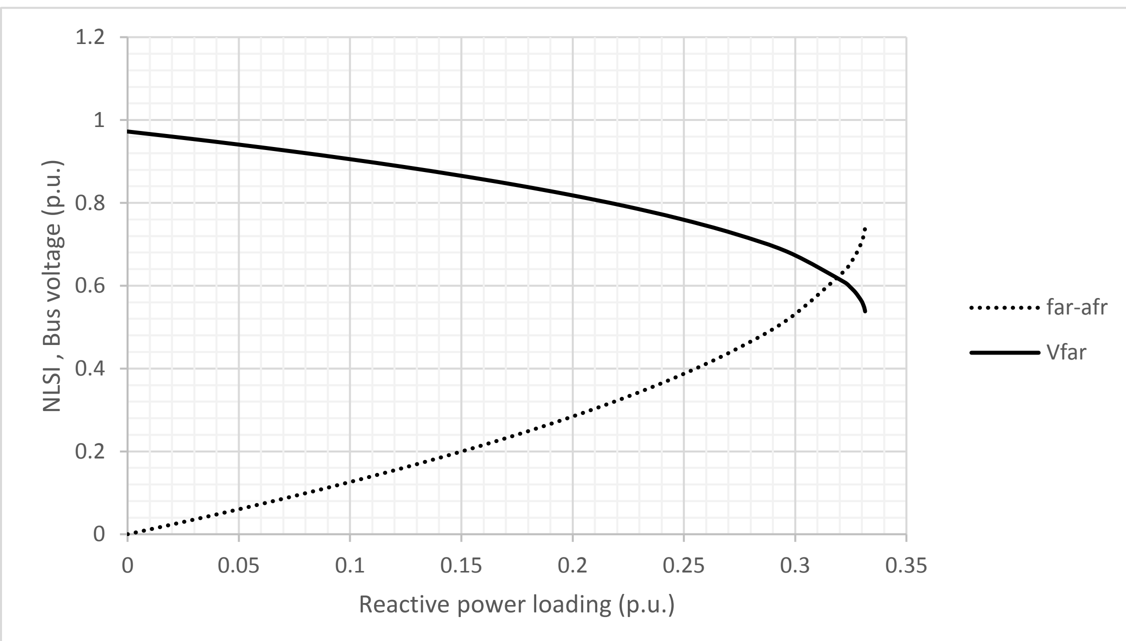


Figure 4.6: NLSI at bus FAR.

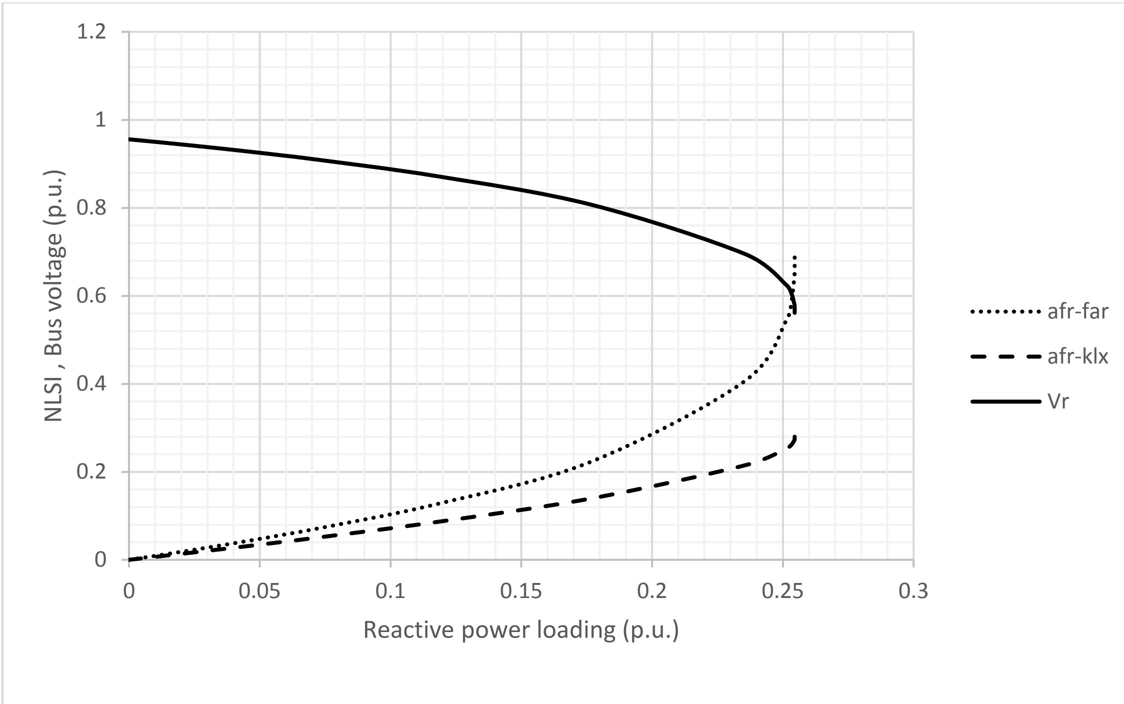


Figure 4.7: NLSI at bus AFR.

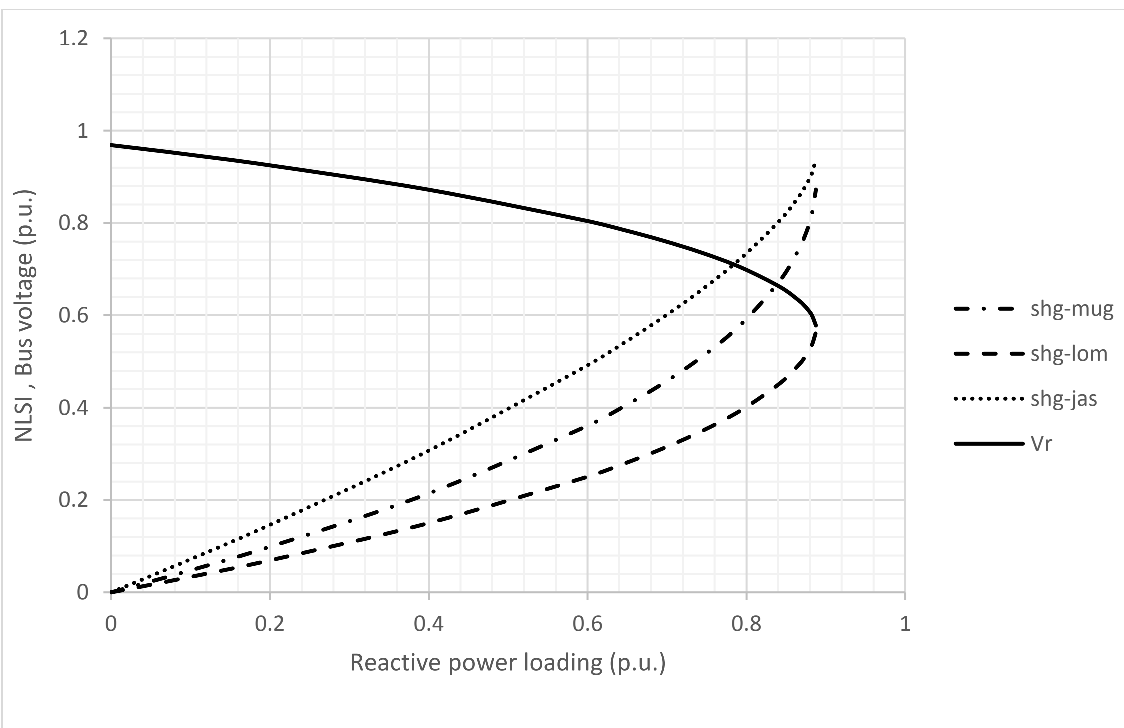


Figure 4.8: NLSI at bus SHG.

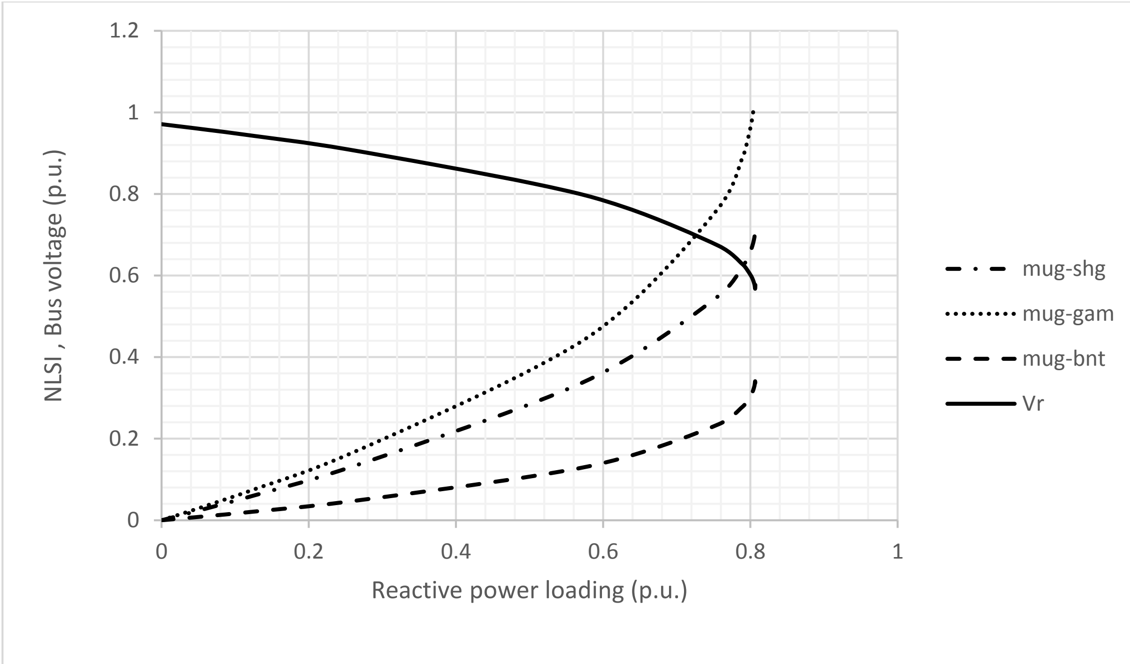


Figure 4.9: NLSI at bus MUG.

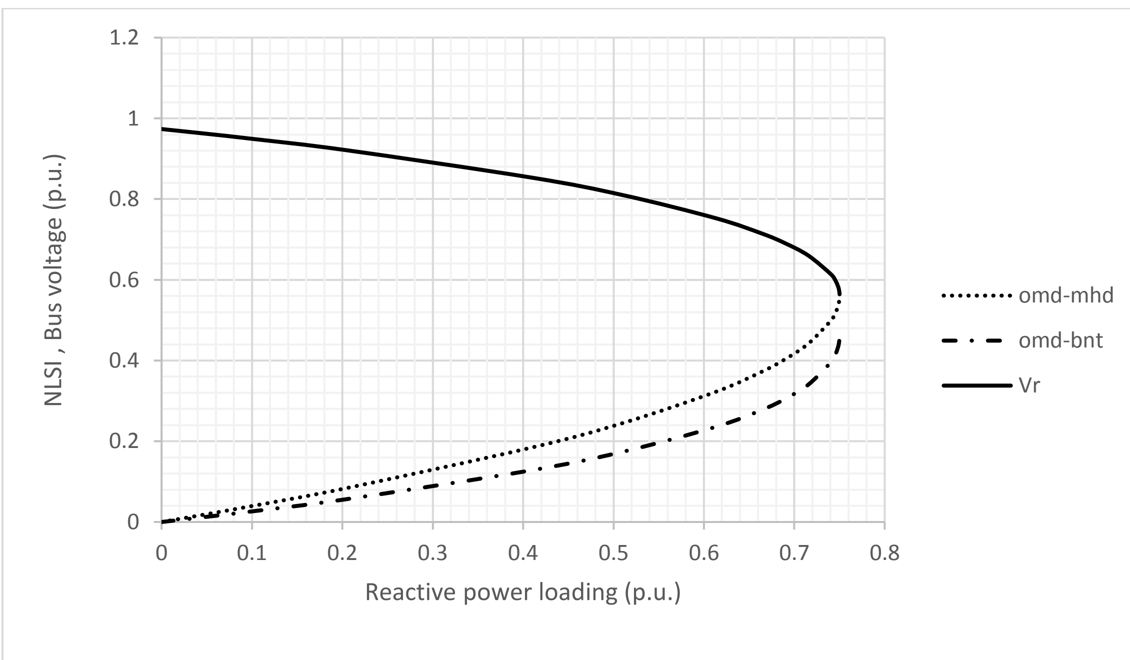


Figure 4.10: NLSI at bus OMD.

From the above results, STATCOM is to be connected at bus SHG, MUG, OMD and at the middle of line AFR-FAR.

4.2.3 Results with STATCOM:

Multiple STATCOM compensation is applied to the base case, the locations of STATCOM are specified at the previous section. The MVAr injection by STATCOMs are:

- 118.67 MVAr at bus SHG.
- 98.67 MVAr at the middle of line AFR-FAR.
- 99.109 MVAr at bus MUG.
- 92.349 MVAr at bus OMD.

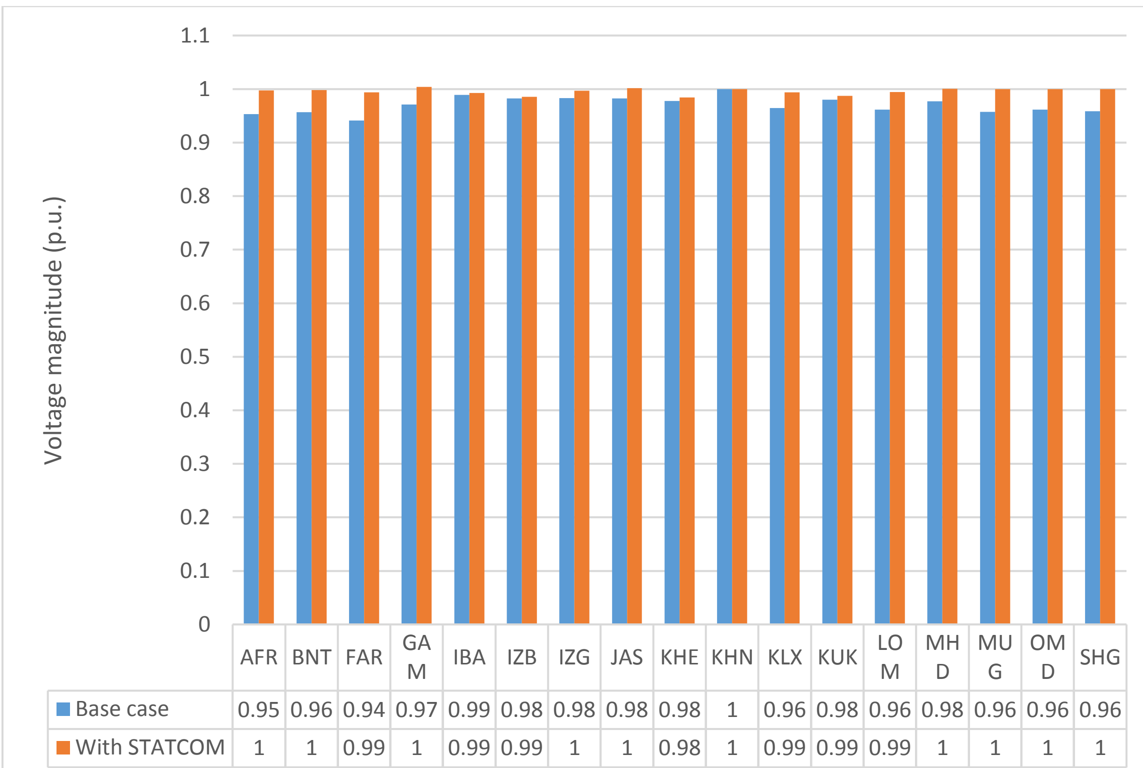
Power flow and voltage stability analysis are applied for the compensated system. Table 4.8 shows the voltage profile of the compensated case.

Table 4.8: Voltage profile of the compensated case.

Bus	*V (kv)*	*V (p.u.)*	*Ang(°)*	*Bus*	*V (kv)*	*V (p.u.)*	*Ang(°)*
IZB 110	108.432	0.9857	-14.6	GER 220	220	1	-8.1
KLX 220	217.863	0.9903	-12.4	IBA 220	218.025	0.991	-12
MAR 500	500	1	0	IBA 110	109.173	0.9925	-14
MRK 500	512.963	1.0259	-5.9	OMD 110	110	1	-15.3
KHN110	110	1	-14.5	MUG 110	110	1	-15.5
IZG 110	109.674	0.997	-14.6	GAM 220	220.933	1.0042	-11.3
KUK 110	108.57	0.987	-14.8	GAM 110	110.449	1.0041	-14.3
KHE 110	108.272	0.9843	-15	BNT 110	109.813	0.9983	-15.5
MRK 220	222.58	1.0117	-10.2	SHG 110	110	1	-15.4
MHD 220	221.098	1.005	-11.1	JAS 220	220	1	-11.5
MHD110	110.028	1.0003	-14.4	JAS 110	110.166	1.0015	-13.5
KAB 500	511.737	1.0235	-6.1	LOM 110	109.406	0.9946	-15.1
KAB 220	222.234	1.0102	-7.5	KLX110	109.35	0.9941	-14.9
GAD 220	218.697	0.9941	-12	AFR 110	109.7	0.9973	-15.8
FRZ 220	220.24	1.0011	-8	FAR 110	109.35	0.9941	-16.6
M 110	110	1	-16.3				

Bus M is the additional bus at the middle of line AFR-FAR for compensation.

It can be observed that the voltage of busses has been improved by implemented STATCOMs. The comparison shown in figure 4.11 shows the enhancement of voltage at level 110 transmission system, the voltage at the compensated buses is set to 1 p.u., as discussed in chapter 2, the buses which have been compensated by STATCOMs keep their voltage magnitude at acceptable limits, in case of additional loads the STATCOM tries to maintain voltages within tolerance and that depends on the maximum injected reactive current.



	AFR	BNT	FAR	GAM	IBA	IZB	IZG	JAS	KHE	KHN	KLX	KUK	LOM	MHD	MUG	OMD	SHG
Base case	0.95	0.96	0.94	0.97	0.99	0.98	0.98	0.98	0.98	1	0.96	0.98	0.96	0.98	0.96	0.96	0.96
With STATCOM	1	1	0.99	1	0.99	0.99	1	1	0.98	1	0.99	0.99	0.99	1	1	1	1

Figure 4.11: voltage magnitude of 110 kV system with and without STATCOM.

STATCOM also reduces the total line losses and loading, the active losses at 110 kV level are reduced from 7.954 MW to 4.909 MW, also reactive power losses with STATCOM are -2.147 MVAr while they were 6.685 MVAr at the base case, table 4.9 and figures (4.12, 4.13 and 4.14) show the impact of STATCOM on the line active losses, line reactive losses and line loading.

Table 4.9: active losses, reactive losses and line loading with STATCOM.

Line Number	***Line name***	***Loading (%)***	***Active losses (MW)***	***Reactive losses (MVAr)***
1	BNT-OMD	10.38	0.04	-0.1644
2	KLX-AFR	22.68	0.354	0.5127
3	MHD-IZG	8.74	0.038	-0.1209
4	MUG-SHG	2.93	0.006	-0.8651
5	KUK-KLX	11.33	0.0533	-0.8026
6	JAS-SHG	13.87	0.4666	-0.7749
7	BNT-MUG	5.42	0.017	-0.2999
8	KHN-IZG	4.66	0.0157	-0.5172
9	KUK-KHN	45.9	1.7703	1.0714
10	IZB-IBA	19.73	0.27	0.1483
11	GAM-MOG	25.28	0.5621	1.138
12	IBA-KHN1	15.42	0.1768	-0.3857
13	KUK-KHE	24.75	0.1233	0.2471
14	MHD-OMD	29.48	0.5085	1.3686
15	KLX-LOM	17.99	0.0609	-0.0201
16	LOM-SHG	7.32	0.1015	-0.3126
17	M-AFR	19.8	0.1718	0.0811
18	FAR-M	19.88	0.1731	0.0891

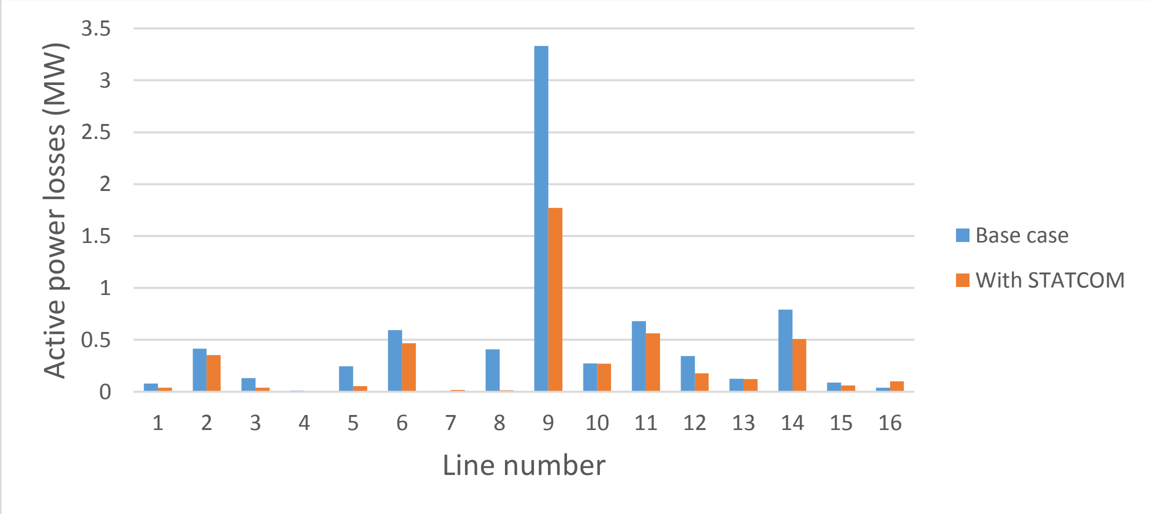


Figure 4.12: Impact of STATCOM on active power losses.

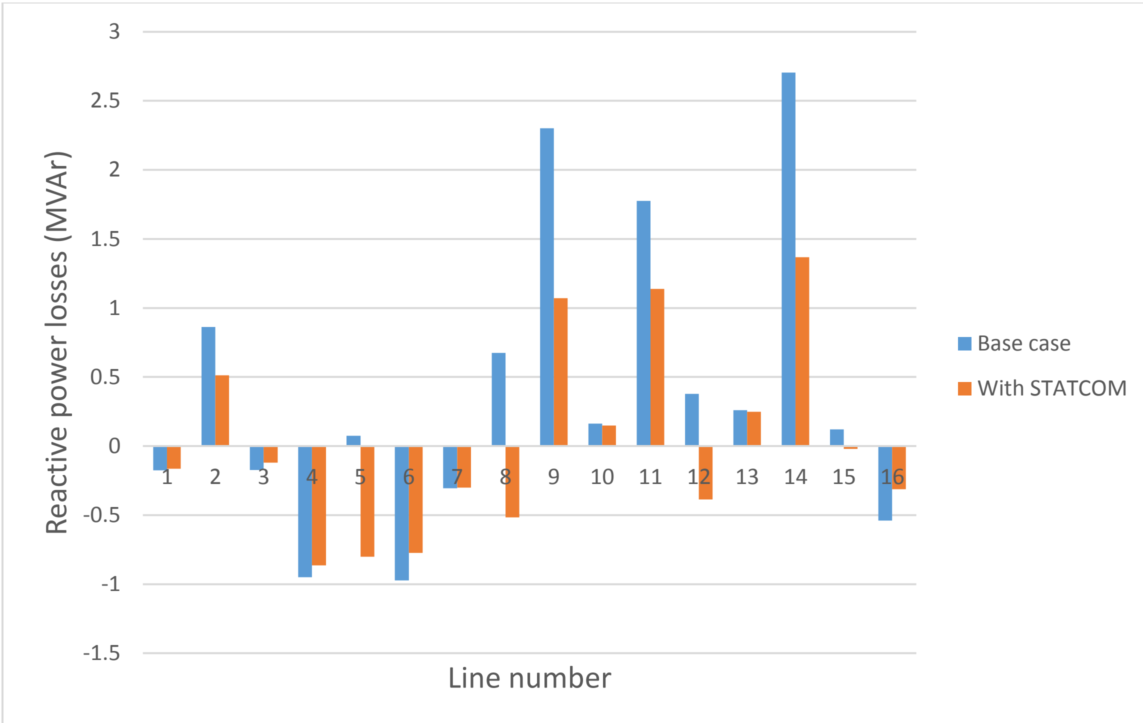


Figure 4.13: Impact of STATCOM on reactive power losses.

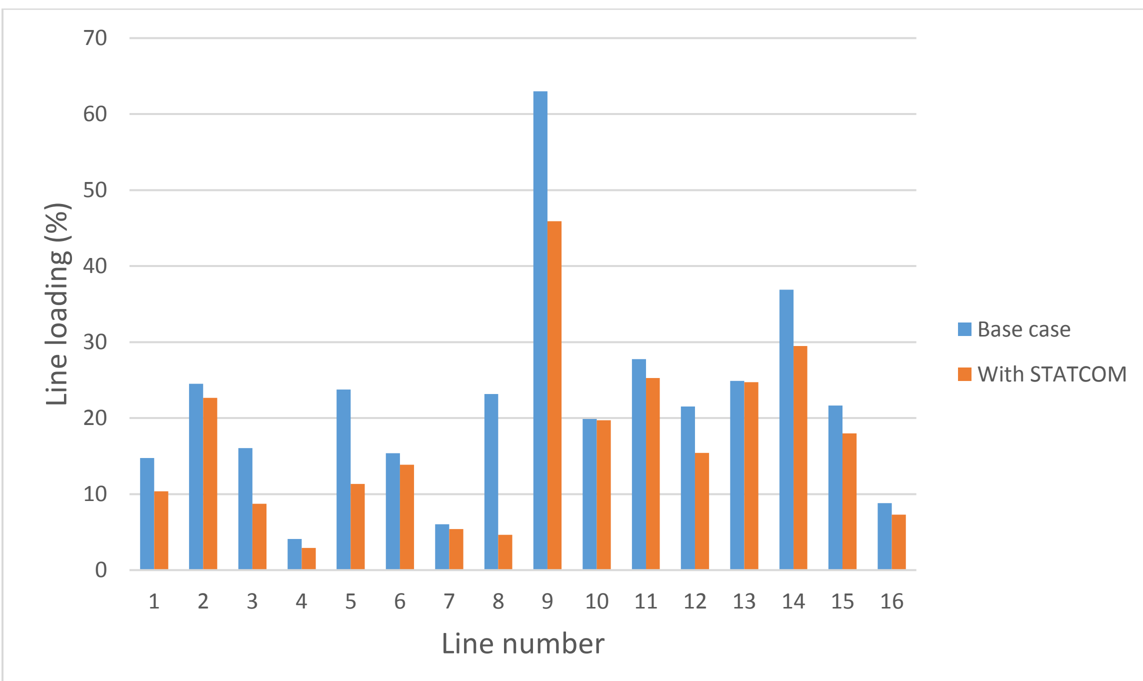


Figure 4.14: Impact of STATCOM on line loading.

Tables 4.10, 4.11 show the eigenvalues and eigenvectors corresponding to the smallest eigenvalue for the compensated case, the smallest eigenvalue which indicate to the critical mode in this case is 31.0073 while in the base case is 9.4943, that is an indicator for voltage stability improvement at the system.

Table 4.10: Eigenvalues for the compensated case.

No.	***Eigenvalue***
1	31.0073
2	31.8892
3	43.7407
4	60.9126
5	65.8013
6	77.7088
7	78.9721
8	96.4499
9	111.3248
10	113.2666
11	125.9582
12	126.8555
13	192.355
14	209.6882
15	223.522
16	298.9703
17	345.651
18	425.7313
19	540.6699
20	589.3424
21	605.7875
22	688.7675
23	737.7883
24	1000000
25	1000000
26	1000000
27	1000000

Also the magnitudes of the right eigenvector components are reduced in comparison with the base case as shown in table 4.11, which illustrates the increasing of voltage stability at busses, the busses where STATCOM is connected result in zero right eigenvector component magnitude.

Table 4.11: Right eigenvector at the critical mode with STATCOM.

Bus	***Component magnitude***
MUG	0
OMD	0
SHG	0
IBA	0.2466
KLX	0.2272
AFR	0.0348
FAR	0.0001
BNT	0
KLX	0.075
GIA	0.0743
MHD	0.0053
IZG	0.0039
FRZ	0.0007
KAB	0.006
MRK	0.016
GAM	0.0094
KUK	0.0204
JAS	0.0039
GAM	0.0052
IBA	0.4564
IZB	0.8132
KHE	0.0234
MRK	0.0138
KAB	0.0143
MHD	0.0168
LOM	0.0592
M	0

V-Q sensitivity analysis is also performed for the compensated case, the recorded results at table 4.12 show that the self-sensitivities at all buses even that buses are quite away from the compensated busses are reduced and the buses where STATCOM installed have recorded zero sensitivities, the comparative diagram of figure 4.15 illustrates the effect of STATCOM on the system bus sensitivities.

Table 4.12: Self V-Q sensitivities of the compensated case.

Bus	***V-Q sensitivity***	***Bus***	***V-Q sensitivity***
FAR 110	0.0088	KHE 110	0.0093
AFR 110	0.0062	IZG 110	0.0085
JAS 110	0.0229	IBA 110	0.0103
IZB 110	0.0245	KAB 220	0.0102
GAM 110	0.0131	KLX 220	0.0086
BNT 110	0.0029	GIAD 220	0.0091
OMD110	0	IBA 220	0.008
MUG 110	0	GAM 220	0.0077
SHG110	0	MRK 220	0.0077
KUK 110	0.0052	FRZ 220	0.0015
LOM 110	0.0056	MHD 220	0.0128
MHD110	0.0068	KAB 500	0.0096
KLX110	0.0055	MRK 500	0.0096
M	0		

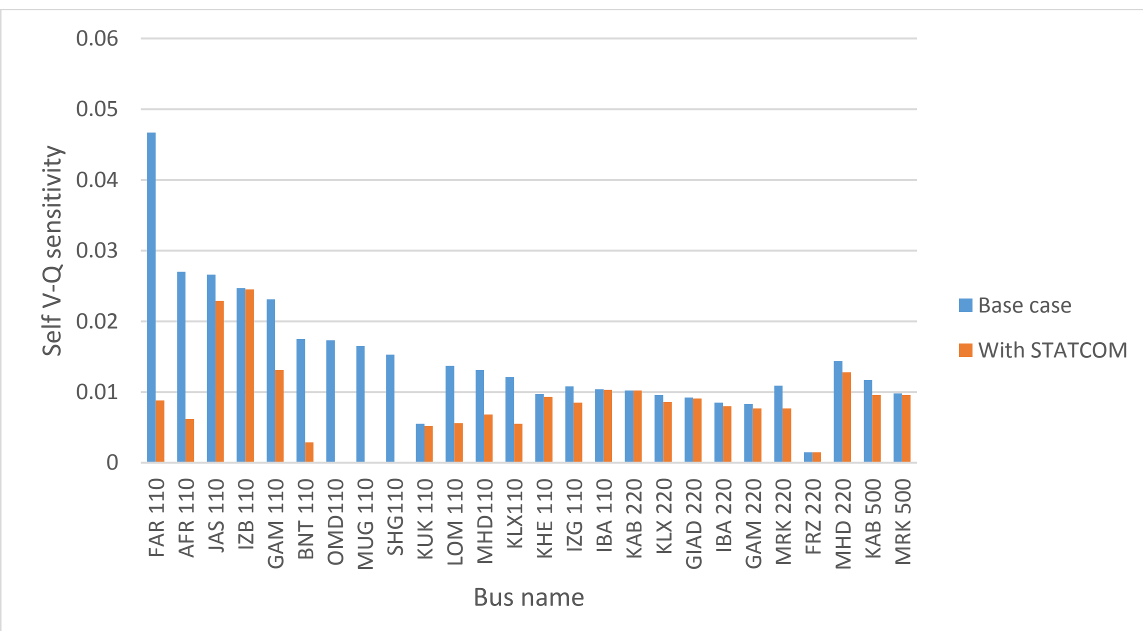


Figure 4.15: Impact of STATCOM on self V-Q sensitivity.

By increasing the load at system 110 kV load buses, based on constant power factor load increase, the voltage collapse is reached. The critical λ value is equal to 2.074 while the maximum loading factor at the base case is 1.805, therefore, the STATCOM is very effective in increasing the stability margin of the system.

In summary of the above results, a STATCOM allocated at the critical buses using NLSI, leads to an acceptable voltage profile for all system, also the system losses and loading are reduced.

From the two studied cases, it is noticeable that eigenvalues have been increased, on the other hand eigenvectors and V-Q sensitivities have been decreased. By allocating a suitable size STATCOMs, the system operation has been more stable and secured.

Chapter five

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion:

The problem of voltage instability in power systems has become a challenging issue for the operators and planners due to the growth and expansion of these networks, the dissertation represents an important and effective solution for this problem which is the multiple shunt compensation of reactive power using STATCOM controller.

Different techniques are applied to assess the voltage stability for the case study to investigate the system performance, the modal analysis and V-Q sensitivity analysis show that the weakest busses and/or areas are in the transmission system of 110 kV level, this what has been verified by application of Novel line stability index (NLSI) to identify the optimal locations for STATCOM.

After implementing the compensation devices and comparing the simulation results, it can be concluded that the criterion for selection of optimal placement of STATCOM using VSI maintains the voltage profile, minimizes the voltage deviations and reduces the power losses. And as a result of the above, the system capacity is increased (additional loads can be added), the stability limits are also increased, thus the efficiency of power system is effectively improved.

5.2 Recommendations:

- From the FACTS view point, future prospects are mostly dependable on a number of practical applications of the FACTS controllers, the implementation of multiple controllers and using of the combined controllers such as UPFC, IPFC are to be considered.
- An advanced technique of placing and sizing of FACTS controllers is needed, the optimization algorithms such as Particle Swarm optimization and CAT Swarm optimization should be adopted.
- The distributed generation units (DGs) represent multi-dimensional benefits, these systems have great effect in power system operation, stability and control, they provide a considerable economic development if properly coordinated in operation with the main generation units.

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APPENDICES:

Appendix A: *Test system data.*

A.1 Bus data:

Bus	***Type***	***Nominal voltage (kv)***	***Pgen (MW)***	***Qgen (MVAr)***	***Pd (MW)***	***Qd (MVAr)***
MAR500	Slack	500	-	-	0.5	0.3
GER220	PV	220	280	-	0	0
KHN220	PV	110	125	-	0	0
JAS110	PV	220	127	-	0	0
MHD110	PQ	110	0	0	32.9	14.2
JAS110	PQ	110	0	0	16	7.2
SHG110	PQ	110	0	0	80	49.58
OMD110	PQ	110	0	0	89.5	51.1
MUG110	PQ	110	0	0	107	63.1
BNT110	PQ	110	0	0	74.9	42.5
IBA110	PQ	110	0	0	32	20.9
LOM110	PQ	110	0	0	50	30.99
KLX110	PQ	110	0	0	35	21.5
AFR110	PQ	110	0	0	17.05	3.927
FRG110	PQ	110	0	0	80	49.58
IZB110	PQ	110	0	0	88.4	28.8
KUK110	PQ	110	0	0	40	24.87
IZG110	PQ	110	0	0	47	42.3
GAM110	PQ	110	0	0	0	0
KHE110	PQ	110	0	0	108	42.8
IBA220	PQ	220	0	0	0	0
GAD220	PQ	220	0	0	60.3	37.37
MHD220	PQ	220	0	0	54.7	25.4
KLX220	PQ	220	0	0	0	0
GAM220	PQ	220	0	0	20.2	9.8
MRK220	PQ	220	0	0	0	0
FRZ220	PQ	220	0	0	16.8	11.1
KAB220	PQ	220	0	0	0	0
KAB500	PQ	500	0	0	0	0
MRK500	PQ	500	0	0	0	0

A.2 Transmission lines data:

No.	***From***	***To***	***Nom. Voltage (kV)***	***length (km)***	***No. of lines***	***R (Ω/km)***	***X (Ω/km)***	***C (μF/km)***
1	MHD110	IZG110	110	8	2	0.067	0.302	0.01306
2	IBA110	IZB110	110	11	2	0.067	0.302	0.01306
3	KHN110	KUK110	110	4.5	2	0.384	0.302	0.009502
4	KUK110	KHE110	110	3.2	2	0.067	0.302	0.01306
5	IBA110	KHN110	110	12	2	0.067	0.302	0.01306
6	LOM110	KLX110	110	3	2	0.067	0.302	0.01306
7	LOM110	SHG110	110	7.8	2	0.067	0.302	0.01306
8	OMD110	BNT110	110	5.9	2	0.067	0.302	0.01306
9	KLX110	AFR110	110	11	2	0.067	0.302	0.01306
10	MRK220	GAM220	220	37	2	0.067	0.302	0.01306
11	GAM220	JAS220	220	39.88	2	0.067	0.302	0.01306
12	KAB500	MRK500	500	36.8	1	0.028	0.276	1.31E-05
13	MAR500	MRK500	500	345	2	0.028	0.276	0.013079
14	GER220	IBA220	220	60	2	0.067	0.302	0.01306
15	FRZ220	KAB220	220	38	2	0.067	0.302	0.01306
16	KUK110	KLX110	110	14.6	2	0.087	0.379	0.009502
17	MUG110	SHG110	110	11	2	0.067	0.302	0.01306
18	SHG110	JAS110	110	39	2	0.067	0.302	0.01306
19	IZG 110	KHN110	110	12	2	0.067	0.302	0.01306
20	MUG110	GAM110	110	14	2	0.067	0.302	0.01306
21	MUG110	BNT 110	110	3.8	2	0.067	0.302	0.01306
22	FAR110	AFR110	110	14	2	0.067	0.302	0.01306
23	GER220	FRZ220	220	5	2	0.067	0.302	0.01306
24	OMD110	MHD110	110	9.3	2	0.067	0.302	0.01306
25	IBA220	KLX220	220	14	2	0.067	0.302	0.01306
26	KLX220	GAD220	220	43	1	0.076	0.403	0.00902
27	GAD220	JAS220	220	36	2	0.067	0.302	0.01306
28	MHD220	MRK220	220	21	2	0.067	0.302	0.01306

A.3 Transformers data:

Name	***Vector group***	***S (MVA)***	***Vr1 (kV)***	***Vr2 (kV)***	***Vkr (%)***
MRK1	YNd11	300	500	220	16
MRK2	YNd11	300	500	220	16
MRK3	YNd11	300	500	220	16
KAB1	YNd11	300	500	220	16
KAB2	YNd11	300	500	220	16
KLX1	YNd11	100	220	110	6.16
KLX2	YNd11	100	220	110	6.16
KLX3	YNd11	100	220	110	6.16
MHD1	YNd11	150	220	110	12.68
MHD2	YNd11	150	220	110	12.68
MHD3	YNd11	150	220	110	12.68
IBA1	YNd11	150	220	110	9.65
IBA2	YNd11	150	220	110	9.65
IBA3	YNd11	150	220	110	9.65
GAM1	YNd11	150	220	110	12.91
GAM2	YNd11	150	220	110	12.91
JAS1	YNd11	150	220	110	12.7
JAS2	YNd11	150	220	110	12.7

A.4 Bus Name Abbreviations:

MAR	Marawy
GER	Gerri
KHN	Khartoum North
JAS	Jabel Awlya
AFR	Afra
BNT	Banat
FAR	Faroug
FRZ	Free Zone
GAM	Gammoeyia
IBA	Id Babikir
IZB	Izba
IZG	Izergab
KAB	Kabbashi
KHE	Khartoum East
KLX	Kilo X
KUK	Kuku
LOM	Local Market
MHD	Mahdeyia
MRK	Markhiyat
MUG	Mugran
OMD	Omdurman
SHG	Shagara

Appendix B: *STATCOM Parameters.*

Name	*Connected Bus*	V_{ref} (%)	X_{sl} (ohm)	I_{max} C (A)	I_{max} L (A)
STAT 1	SHG110	100	5	1000	1000
STAT 2	MUG110	100	5	1000	1000
STAT 3	OMD110	100	5	1000	1000
STAT 4	M 110	100	5	1000	1000

Appendix C: *Eigenvalues and Eigenvectors.*

In practical applications, equations of the form [50]:

$$\boldsymbol{Ax} = \boldsymbol{\lambda x}$$

occur, where $\boldsymbol{A}$ is a square matrix and $\boldsymbol{\lambda}$ is a number. Whenever $\boldsymbol{x} \neq \boldsymbol{0}$, the values of $\boldsymbol{\lambda}$ are called the eigenvalues of the matrix $\boldsymbol{A}$; the corresponding solutions of the equation $Ax = \lambda x$ are called the eigenvectors of A.

From above, if $\boldsymbol{Ax} = \boldsymbol{\lambda x}$ then $\boldsymbol{Ax} - \boldsymbol{\lambda x} = \boldsymbol{0}$ i.e. $(\boldsymbol{A} - \boldsymbol{\lambda I})\boldsymbol{x} = \boldsymbol{0}$ where $\boldsymbol{I}$ is the unit matrix. If $\boldsymbol{x} = \boldsymbol{0}$ then

$$|\boldsymbol{A} - \boldsymbol{\lambda I}| = \boldsymbol{0}$$

$|\boldsymbol{A} - \boldsymbol{\lambda I}|$ is called the characteristic determinant of $\boldsymbol{A}$ and $|\boldsymbol{A} - \boldsymbol{\lambda I}| = \boldsymbol{0}$ is called the characteristic equation.

Solving the characteristic equation will give the value(s) of the eigenvalues, as demonstrated in the following worked example.

Example C.1: Determine the eigenvalues and eigenvectors of the matrix

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{3} & \boldsymbol{4} \\ \boldsymbol{2} & \boldsymbol{1} \end{bmatrix}$$

The eigenvalue is determined by solving the characteristic equation $|A - \lambda I| = 0$

i.e. $$\left|\begin{bmatrix} 3 & 4 \\ 2 & 1 \end{bmatrix} - \lambda \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\right| = 0$$

i.e. $$\left|\begin{bmatrix} 3 & 4 \\ 2 & 1 \end{bmatrix} - \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix}\right| = 0$$

i.e. $$\begin{vmatrix} 3-\lambda & 4 \\ 2 & 1-\lambda \end{vmatrix} = 0$$

(Given a square matrix, we can get used to going straight to this characteristic equation),

Hence, $$(3-\lambda)(1-\lambda)-(4)(2)=0$$

i.e. $$3-3\lambda-\lambda+\lambda^2-8=0$$

and, $$\lambda^2-4\lambda-5=0$$

and, $$(\lambda-5)(\lambda+1)=0$$

from which, $\lambda - 5 = 0$ i.e $\lambda = 5$ or $\lambda + 1 = 0$ i.e. $\lambda = -1$

Hence, the eigenvalues of the matrix $\begin{bmatrix} 3 & 4 \\ 2 & 1 \end{bmatrix}$ are $\lambda_1 = 5$ and $\lambda_2 = -1$

To determine **eigenvectors**, using equation $(\boldsymbol{A} - \boldsymbol{\lambda I})\boldsymbol{x} = \mathbf{0}$ for $\lambda_1 = 5$

then $$\begin{bmatrix} 3-5 & 4 \\ 2 & 1-5 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

i.e. $$\begin{bmatrix} -2 & 4 \\ 2 & -4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

from which,

$$-x_1 + 4x_2 = 0$$

And

$$2x_1 - 4x_2 = 0$$

From either of these two equations, $x_1 = 2x_2$x1 = 2x2

Hence, whatever value x_2 is, the value of x_1 will be two times greater. Hence the simplest eigenvector is: $x_1 = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$

using equation $(\boldsymbol{A} - \boldsymbol{\lambda I})\boldsymbol{x} = \boldsymbol{0}$ for $\lambda_2 = -1$

then $$\begin{bmatrix} 3 - -1 & 4 \\ 2 & 1 - -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

i.e. $$\begin{bmatrix} 4 & 4 \\ 2 & 2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

from which,

$$4x_1 + 4x_2 = 0$$

$$2x_1 + 2x_2 = 0$$

From either of these two equations, $x_1 = -x_2$ or $x_2 = -x_1$

Hence, whatever value x_1 is, the value of x_2 will be -1times greater. Hence the simplest eigenvector is: $x_2 = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$

Summarizing, $x_1 = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$ is an eigenvector corresponding to $\lambda_1 = 5$

and $x_2 = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$ is an eigenvector corresponding to $\lambda_2 = -1$