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Static Voltage Stability Enhancement for Sudan National Electric Grid (SNEG) Through SVC

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الآيـة

قال تعالى :

﴿يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ ۚ وَاللَّهُ بِمَا تَعْمَلُونَ خَبِيرٌ﴾

(المجادلة 11)

DEDICATION

First and last thank for our GOD.

We extremely grateful to our fathers, and our mothers who raised us and taught us to study hard and to give priority in my life to the quest for knowledge, it is out of the question to find the right words to thank our darling parents.

To All our class mate our the way of study.

To Everyone who gave us award or advice or smile.

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We would like to express our appreciation to our honorable supervisor of this dissertation Dr. Mohammed Osman Hassan , Department of Electrical Engineering, they have been extremely helpful to us during the entire period of our studies in the School of Electrical and nuclear Engineering. Without This helps and encouragement this dissertation would not have been written.

ABSTRACT

The increase in power system demand has forced the power system to operate closer to its stability limit, voltage instability in the electrical networks has been given much attention by power system researchers and planners in recent years, being regarded as one of the major sources of power system insecurity. Maintaining a stable and secure operation of power system is therefore very important and challenging issue. One of the major causes of voltage instability is decrease in reactive power which occurs in stressed condition of the power system.

There are several techniques and tools for voltage stability analysis in power system, in this dissertation two methods of analysis are used, V-Q sensitivity and modal analysis. Flexible Alternating Current Transmission System (FACTS) devices play an important role in improving the performance of power system, but these devices are very costly and hence need to be placed optimally in power system. This dissertation evaluates the performance of Sudan National Grid against the growing demand and reactive power resources and enhancement of voltage stability of Sudan national Grid by using static VAR compensator (SVC).

The simulation is carried out by using NEPLAN Software. The results obtained showed the effect of SVC on the voltage and power losses.

المستخلص

الزيـادة فـي الطلـب للطاقـة أجبـرت أنظمـة الطاقـة الكهربائيـة بـان تعمـل فـي حـدود الاسـتقرارية ، عـدم اسـتقرارية الجهـد فـي الشـبكات الكهربائيـة اصـبح مـن المسـائل ذات الاهتمـام الأكبـر مـن قبـل البـاحثين ، والـذي اصـبح يصـنف مـن الأسـباب الرئيسـية الـذي يـؤدي الـى عـدم اسـتقرارية الجهـد أنظمـة الطاقـة ، وبالتـالي عمليـة إبقـاء نظـام القـدرة الكهربائيـة مسـتقروفي وضـع تشـغيل آمـن اصـبح مسـألة تحدي.احـد الأسـباب التـي تـؤدي الـى عـدم اسـتقرارية الجهـد هـو الـنقص فـي القـدرة الـرد فعليـة ، هنالـك العديـد مـن التقنيـات والأدوات التـي تسـتخدم لتحليـل الجهـد فـي نظـم القـدرة الكهربائيـة. فـي هـذه الأطروحـة تـم اسـتخدام طريقـة الحساسـية . الـنظم المرنـة الحديثـة لنقـل التيـار المتـردد تلعـب دورا هامـا فـي تحسـين أداء نظـام الطاقـة، ولكـن هـذه الأجهـزة مكلفـة جـدا ، بالتـالي يجـب ان توضـع علـى النحـو الأمثـل فـي نظـام الطاقة.هـذه الاطروحـة تعمـل علـى تقيـيم أداء الشـبكة القوميـة السـودانية عنـد زيـادة الحمـل مـع تحسـين الجهـد عنـد اسـتخدام معـوض القـدرة الـرد فعليـة السـاكن. تـم تنفيـذ المحاكـاة باسـتخدام برنـامج NEPLAN ، وأظهـرت النتـائج التـي تـم التوصـل عليهـا علـى فاعليـة معـوض القـدرة الـرد فعليـة السـاكن فـي تحسـين الجهـد وتقليـل المفاقيـد فـي الطاقـة الكهربائية.

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LIST OF ABBREVIATIONS

SVG	static VAR generators
SVC	static VAR compensator
SSSC	Static synchronous series compensator
TCSC	Thyristor Controlled Series Capacitor
TCSR	Thyristor controlled series reactor
SSG	static synchronous generator
SMES	superconducting magnetic energy storage
TCR	Thyristor controlled reactor
SVC	static VAR compensator
UPFC	unified power flow controller
VSC	Variable Source Converter
VSI	Voltage-Source Inverter
P	Active Power
Q	Reactive Power
VAR	Volt Ampere Reactive
TSC	Thyristor Series Capacitor
FACTS	Flexible AC transmission system
DC	Direct Current
AC	Alternating Current

LIST OF SYMOLS

J	Jacobian matrix
P	real power
V	voltage magnitude
Q	reactive power
Δ	The change
θ	voltage angle
Ξ	Right eigenvector matrix of J_R
η	Left eigenvector matrix of J_R
Λ	Diagonal eigenvector matrix of J_R

CHAPTER ONE

INTRODUCTION

4.1 Background

Modern power systems are operating under very stressed conditions and this is making the system to operate closer to their operating limits. Operation of power system is becoming difficult owing to the following reasons:

1- Increased competition in power sector.

2- Social and environmental burdens; resulting to limited expansion of transmission network.

3- Lack of initiatives to replace the old voltage and power control mechanisms.

4- Imbalance in load-generation growth.

All these factors are causing power system stability problems. A power system operating under stressed conditions shows a dierent behavior from that of a non-stressed system. As the system is operating close to the stability limit, a relatively small disturbance may causes the system to become unstable. As the power system is normally a interconnected system, it's operation and stability will be severely affected.

4.2 Problem Statement

The electric power system is undergoing change as result of power demand increase, thus it operates beyond its stability limit. The voltage magnitude of buses in the power systems should be within acceptable limits in the normal condition and after being subjected to a disturbance from a given initial operating condition [1].

Voltage instability phenomena are the ones in which the receiving end voltage decreases well below its normal value and does not come back even after setting restoring mechanisms such as VAR compensators, or continues to oscillate for lack of damping against the disturbances. Voltage collapse is the process by which the voltage falls to a low, unacceptable value as a result of an avalanche of events accompanying voltage instability [1].

4.3 Objective

The main objectives of this dissertation are:

- evaluate the performance of Sudan national Grid against the growing demand and associated stress on reactive power resources.
- enhancement of voltage stability of Sudan national grid through static VAR compensator (SVC).

4.4 Methodology

From the load flow solutions of national grid of the Sudan VQ sensitivity bus participation factors and eigenvalues are obtained at the base case (voltage stability limits) to identify the weakest buses . Static VAR compensator is then installed at the weakest bus according to the proposed indices . NEPLAN software Tool is used to implement this study and obtain the result.

4.5 Dissertation Outline

Chapter two presents the literature review, include Basic Concepts Related to voltage stability, voltage stability problem, voltage collapse and analysis techniques, Chapter three starts with Basic type of FACTS of controllers, FACTS controllers based on power electronic devices, and full details of SVC. Chapter Four presents the results of voltage stability enhancement of Sudan national Grid based on the proposed indices. The conclusion of this dissertation and recommendations for future work are outlined in Chapter Five

CHAPTER TWO

LITERAURE 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 early 1970 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 [2].

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 have 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

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.

2.2 Voltge Collapse Definition and causes

There are several definitions of voltage collapse in the literature, but all the definition considers different issues according to the author. According to definitions presented by IEEE voltage collapse is a process by which voltage instability leads to voltage drop in a significant part of the power system. Several reasons are there which leads to typical voltage instability in the power system, may be static or dynamic [3].

2.2 Classification of Power System Stability

A definition of power system stability as given in [1] is:

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains.

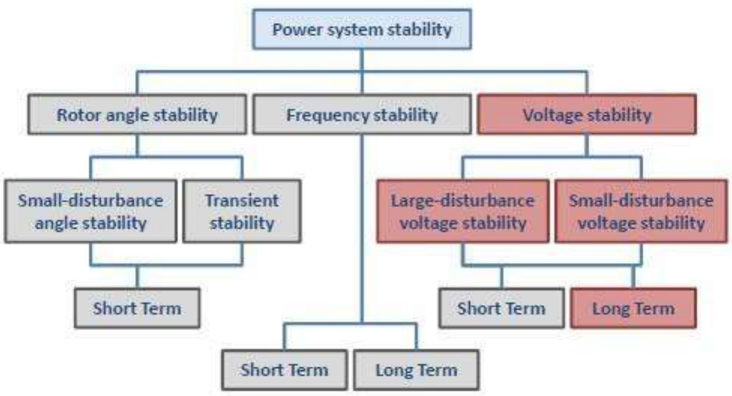

Figure 2.1: Classification of power system stability [4].

2.3 Voltage Stability Analysis

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 nonlinear 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 [5].

2.3.1 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 [5]. Consider the linearized power flow equation expressed as:

Where:

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

ΔP=incremental change in bus real power

ΔQ=incremental change in bus reactive power

$\Delta\theta$= incremental change in bus voltage angle

ΔV=incremental change in bus voltage magnitude

Let ΔP=0. Then:

$$\Delta Q = J_R \Delta V \quad (2.2)$$

Where:

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

J_R is the reduced Jacobin Matrix of the system form equation, (2.3) we may write:

$$\Delta V = J^{-1}\,\Delta Q \qquad (2.4)$$

The sensitivity at bus represents the slope of the Q-V curve at the given operating point. A positive V-Q sensitivity is indicative of stable operation; the smaller the sensitivity, the more stable the system. As stability decreases, the magnitude of the sensitivity increases, Conversely, a negative V-Q sensitivity is indicative of unstable operation. A small negative sensitivity represents a very unstable operation. Because of the nonlinear nature of the V-Q relationships, the magnitudes of the sensitivities for different system conditions do not provide a direct measure of the relative degree of stability [6].

2.3.2 Modal Analysis

Voltage stability characteristics of the system can be identified by computing the Eigenvalues and Eigenvectors of the reduced Jacobian Matrix defined by the equation [5].

$$J_R = \xi \eta \Lambda \qquad (2.5)$$

where:

ξ = Right eigenvector matrix of J_R

η = Left eigenvector matrix of J_R

Λ= Diagonal eigenvector matrix J_R

Where:

$$J_R = [J_{QV} - J_{Q\theta} J^{-1} J_{PV} \qquad (2.6)$$

And J_R is the reduced Jacobian matrix, by taking inverse of equation (2.5) We can write:

$$J^{-1}=\xi\Lambda^{-1}\eta \quad (2.7)$$

Substitute equation (2.7) into equation (2.4) we get:

$$\Delta V=\xi\Lambda^{-1}\eta\Delta \quad (2.8)$$

$$\Delta V=\sum(\xi_i * \eta_i / \lambda_i)\ \Delta Q \quad (2.9)$$

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.

Since $\xi^{-1}=\eta$, from equation (2.8) by multiplying both sides by η, may be written as:

$$\eta\ \Delta V=\Lambda^{-1}\eta\Delta Q \quad (2.10)$$

$$\text{Or } V= \Lambda^{-1}q \quad (2.11)$$

Where:

$V= \eta\ \Delta V$ is the vector of modal voltage variations

$Q = \eta\Delta Q$ is the vector of modal reactive power variations [5].

$$V_I = \frac{1}{\lambda_i} q_i \quad (2.12)$$

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 [5,7].

1- Bus Participation Factor:

Left and right eigenvectors corresponding to the critical modes in the system can provide information concerning the mechanism of voltage instability. The bus participation of the bus can be defined as [7].

$$P_{ki} = \xi_{ki}\,\eta_{ki} \tag{2.13}$$

2- Branch participation Factor

Branch participation factors indicate, for each mode, which branches consume the most reactive power in response to an incremental change in reactive load. Branches with high participations are either weak links or are heavily loaded. Branch participations are useful for identifying remedial measures to alleviate voltage stability problems and for contingency selection [6].

To compute the branch participation factor associated with mode i assume that the vector of modal reactive power variations q has all elements equal to zero except for the i^{th}, which equals l. Then from Equation 2.12 the vector of bus reactive power variations is:

$$V = \Lambda^{-1} q \tag{2.14}$$

$$\Delta Q^{(i)} = \eta^{-1} q = \xi\, q = \xi_i \tag{2.15}$$

Where ξ_i is the i^{th} right eigenvector of J_R assume that all right eigenvector is normalized so that?

$$\sum_j \xi^2 = 1 \qquad (2.16)$$

With the vector of bus reactive power variations equal to $\Delta Q^{(i)}$the vector of bus voltage variations, $\Delta V^{(i)}$ is:

$$\Delta V^{(i)} = \frac{1}{\lambda} \Delta Q^{(i)} \lambda$$

$$\Delta Q^{(i)} = -J^{-1} J_{PV}\, \Delta V^{(i)} \qquad (2.18)$$

The relative participation of branch j in mode i is given by the participation factor:

$$P_{ji} = \frac{\Delta Q_{losses} \text{ for branch j Maximum}}{\Delta Q_{losses} \text{ for all branches}} \qquad (2.19)$$

2.3.3 Q-V Curve

Q-V curve technique is a general method of evaluating voltage stability. It mainly presents the sensitivity and variation of bus voltages with respect to the reactive power injection. Q-V curves as shown in fig 2.1, are used by many utilities for determining proximity to voltage

collapse so that operators can make a good decision to avoid losing system stability. In other words, by using Q-V curves, it is possible for the operators and the planners to know the maximum reactive power that can be achieved or added to the weakest bus before reaching minimum voltage limit or voltage instability furthermore, the calculated MVAR margins could relate to the size of shunt capacitor or static VAR compensation in the load area [8].

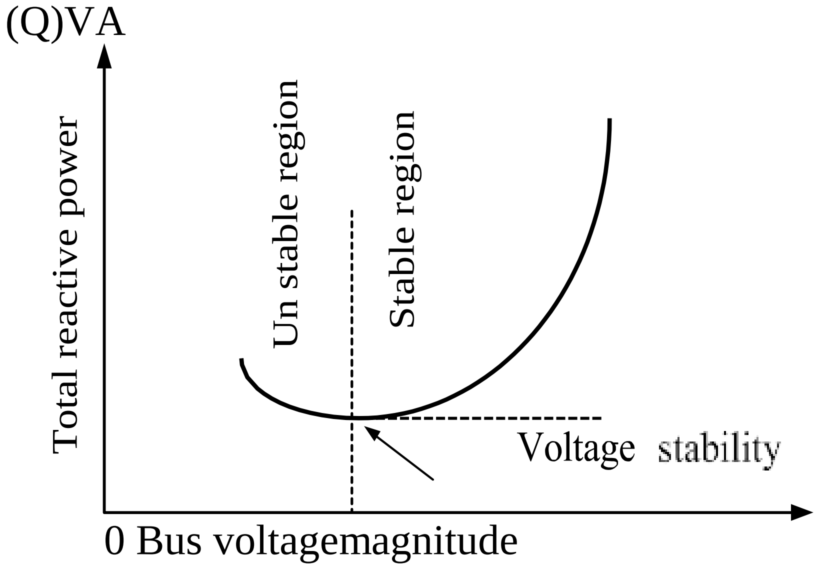

Figure 4.2 : Q -V Curve

2.3.4 P-V Curves

PV curves are useful for conceptual voltage stability analysis an for studying small or radial systems. This method is also used for larg and meshed systems where P is the total load in an area and V is th voltage at a critical or representative bus [9].

In principle, PV curve is a representation of voltage change as result of increased active power transfer between two systems. Tracin PV curves requires a parametric study involving a series of power flow while monitoring the changes in one set of power flow variables wit respect to another. As power transfer is increased in steps, voltage decreases at some buses on or near the transfer path. The transfer capacit where voltage reaches a low value criterion is the low voltage transfe limit. Transfer can continue to increase until the solution identifies th proximity to the voltage instability, which is a "nose point" on the P curve where the voltage drops steeply in response of an increase in th transfer power flow.

Load flow solution will not converge beyond thi limit, indicating a voltage collapse transfer limit, as in figure2.3 [10].

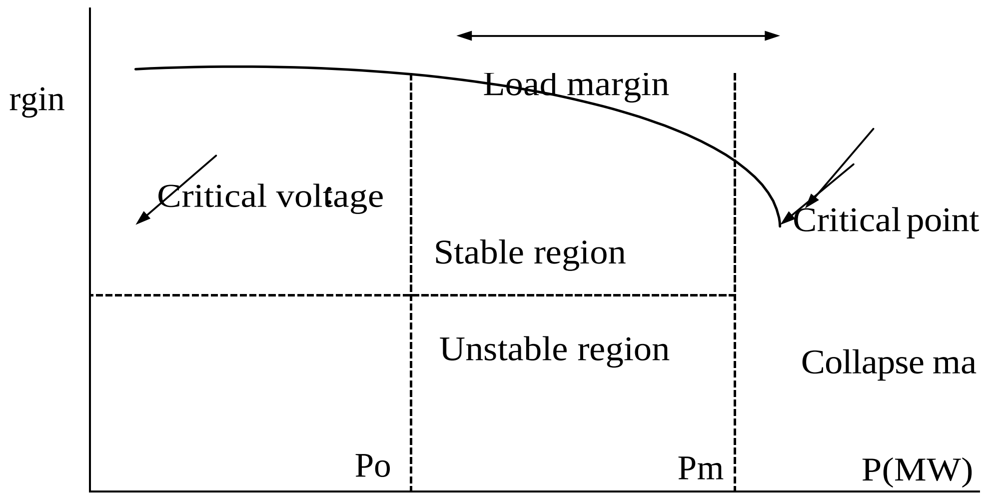

Figure 2.3 typical P-V curves

2.4.5 Continuation Power Flow

The Jacobian matrix becomes singular at the voltage stability limit Consequently, conventional power flow algorithms are prone t convergence problem at operating conditions near the stability limit. Th continuation power flow analysis overcomes this problem b reformulating the power flow equations so that they remain well conditioned at all possible loading conditions. This allows the solution o power-flow problem for stable as well as unstable point [11].

The purpose of the continuation power flow is to find a continuation of power flow solution for a given load change scenario. An early succes was the ability to find a set of solution from a base case up to the critical

monitoring the changes in one set of power flow variables wit respect to another. As power transfer is increased in steps, voltage point.

The general principle behind the continuation power flow is rathe simple. It employs a predictor corrector scheme [5]. The basic equation are similar to those of a standard power-flow analysis except that th increase in load is added as a parameter:

$$F(\theta,V) = \lambda K \qquad (2.20)$$

The above set of nonlinear equations is solved by specifying a value for such that $0 \leq \lambda \leq \lambda_{critical}$. When $\lambda = 0$ represents the base load condition and $\lambda = \lambda_{critical}$ represents the critical load. Equation (2.18) rearranged as:

$$F(\theta,V,\lambda) = 0 \qquad (2.21)$$

2.4.6Steady State Power System Voltage Stability Analysis and Control with FACTS

Voltage stability analysis and control become increasingly important as the systems are being operated closer to their stability limits including voltage stability Limit. This is due to the fact that there is lack of network investments and there are large amounts of power transactions across regions for economical reasons in electricity market environments. It has been recognized that a number of the system blackouts including the recent blackouts that happened in North America and Europe are related to voltage instabilities of the systems.

For voltage stability analysis, a number of special techniques such as power flow based methods and dynamic simulations methods have been proposed and have been used in electric utilities. Power flow based methods, which are considered as steady state analysis methods, include the standard power flow methods, continuation power flow methods, optimization methods modal methods singular decomposition methods etc [3]

CHAPTER THREE
FACTS CONTROLLERS

3.1 Introduction

Flexible AC Transmission Systems, called FACTS, gained in the recent years a well-known term for higher controllability in power systems by means of power electronic devices. Several FACTS-devices have been introduced for various applications worldwide. A number of new types of devices are in the stage of being introduced in practice. Even more concepts of configurations of FACTS-devices are discussed in research and literature. FACTS-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations. The basic applications of FACTS-devices are, power flow control, increase of transmission capability, voltage control, reactive power compensation, stability improvement, power quality improvement, power conditioning, flicker mitigation, interconnection of renewable and distributed generation and storages [15].

3.2 Basic Types of FACTS controllers

FACTS controllers are power electronics based systems and other static equipment that provide control of one or more transmission system parameters, the four basic categories of FACTS controllers are as follows:

1. Series controllers.
2. Shunt controllers.
3. Combined series-series controllers.
4. Combined shunt- series controllers.

3.2.1 Series Controllers

The series controllers may be a variable capacitor, inductor, or a power electronic based variable frequency source, this types of FACTS controllers are used to inject voltage in series with the line, the series controllers can be divided into three categories, Static synchronous series compensator (SSSC), and Thyristor Controlled Series Capacitor (TCSC), Thyristor controlled series reactor (TCSR) [16].

3.2.2 Shunt Controllers:

The shunt controller, also, may be either a variables source or a variable impedance or a combination connected in shunt and they all inject current into the bus at the point of connection if the injected current is in phase quadrature with the line voltage the controller handles reactive power for any other phase relationship of the current with the line voltage, it handles both real and reactive power, this types of controller include, Static Synchronous Compensator (STATCOM), static synchronous generator (SSG), superconducting magnetic energy storage (SMES), static VAR compensator (SVC), Thyristor-controlled reactor (TCR), and Thyristor controlled dynamic brake [2,4].

3.2.3 Series - Series Controllers

Any standard series controller may be suitably connected with another type of series FACTS controller to form a series- series controller we may think of thyristor controlled series capacitor (TCSC) in series with a thyristor switched series capacitor it is reasonable to arrange this series connection such that one module could be smooth thyristor control while the other could be thyristor switched control, the series-series controller may be applied for control of power in double circuit ac lines [16].

3.2.4 Combined Series-shunt controller

A combined series-shunt controller has separate series and shunt contro=llers in a transmission line whose operation is coordinated Operationally, the series controller injects voltage in series with the line voltage and the shunt controller injects current into the system at the point of connection. The second type of this controller, where the shunt and series controllers are unified, is called a unified power flow controller (UPFC) [2].

3.3 FACTS Controllers based on Power Electronic Devices

3.3.1 Variable Source Converter (VSC)

1- Static Synchronous Series Compensator (SSSC)

The Static Synchronous Series Compensator (SSSC) is a series connected FACTS controller based on VSC and can be viewed as an advanced type of controlled series compensation, just as a STATCOM is an advanced SVC. A SSSC can be used to elimination of bulky passive components – capacitors and reactors, improved technical characteristics symmetric capability in both inductive and capacitive operating modes possibility of connecting an energy source on the DC side to exchange real power with the AC network [17].

2- Static Synchronous Compensator (STATCOM)

The static synchronous compensator (STATCOM) is another shunt connected FACTS devices it is a static synchronous generator operated as a static VAR compensator whose capacitive or inductive output currents are controlled to control the bus voltage with which it is connected [16].

STATCOM operation is based on the principle of voltage source or current source converter, Voltage-Source Inverter (VSI), which converts a DC, input voltage into AC output voltage in order to compensate the active and reactive power needed by the system [18].

3- Unified Power Flow Controller (UPFC)

A combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via a common dc link, to allow bidirectional flow of active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent active and reactive series line compensation without an external electric energy source.

The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and angle or, alternatively, the active and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation [19].

3.3.2 Variable impedance

3.3.2.1 Thyristor Controlled Series Compensator (TCSC)

TCSC A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance, when The thyristor valve is not triggered and the thyristors are kept in nonconducting state. The line current passes only through the capacitor bank. Thus, the boost factor is equal to one. In this mode the TCSC performs like a fixed series capacitor, when the thyristor valve is triggered continuously and therefore the valve stays conducting all the time. The TCSC behaves like a parallel connection of the series capacitor and the inductor [20].

3.3.2.2 Static VAR Compensator (SVC)

Static VAR Compensator is one of the most important shunt controller in FACTS technology. It is a shunt connected static VAR generator whose output is designed to draw capacitive or inductive current, so to maintain normal voltage at the bus with which the SVC is connected. SVC is based on thyristor without the gate turn-off capability. It includes thyristor controlled reactor (TCR) in parallel with fixed capacitor in it commonest form and is known as fixed capacitor thyristor controlled reactor type SVC for better control as shown in figure 3.1 [21].

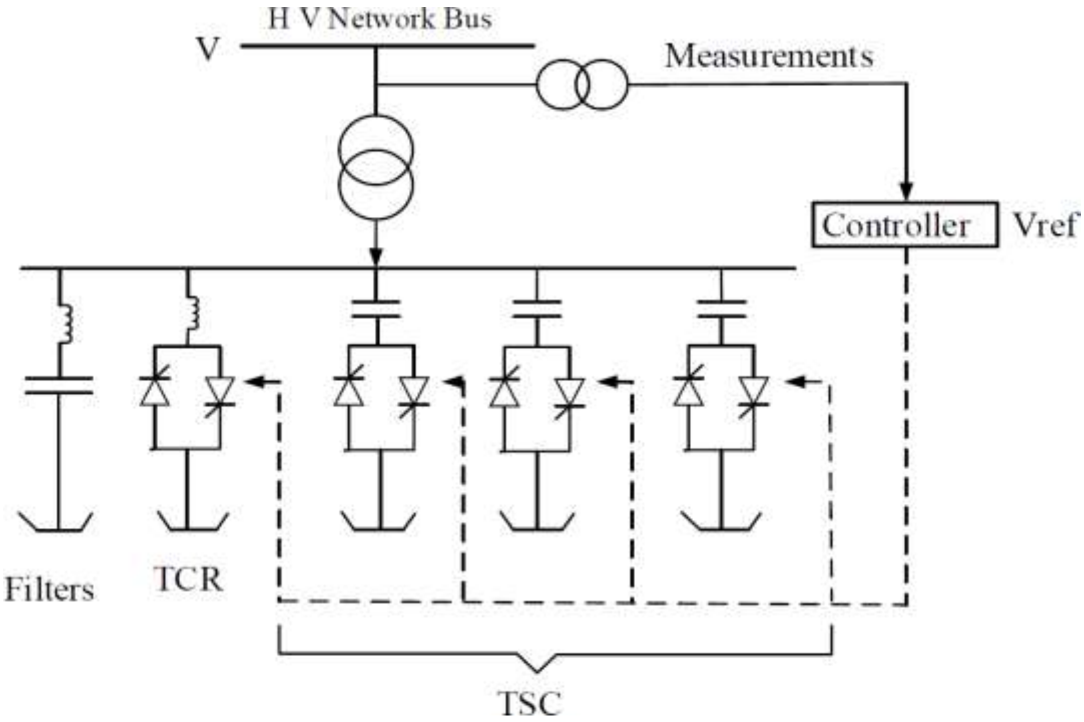

Figure 3.1: Configuration of Static VAR Compensator (SVC)

A simple and effective way to include the SVC in power flow techniques is to use this device as a variable susceptance. the shunt susceptance represents the total SVC susceptance necessary to maintain the voltage magnitude at the bus at specified value. The inclusion of SVC at any load node makes that node voltage controlled node, and at this node the voltage magnitude and the nodal active and reactive power are specified; the variable susceptance B_{SVC} is operated as a state variable.

The philosophy is that if B_{SVC} is within limits the specified voltage is attained and the bus operated as a PV bus. When B_{SVC} is above or lower than the limits, it becomes fixed at the violated limit, and the node becomes a PQ bus again if there is no other voltage regulating equipment present [16]. Then the current drawn by the SVC is:

$$I_{svc} = jB_{SVC} V_j \quad (3.1)$$

And the active and reactive power drawn by the SVC connected at node j given by:

$$P_j = 0;\ Q_j = -|V_j|^2 B_{SVC} \quad (3.2)$$

Also the mismatches are given as:

$$\begin{bmatrix} \Delta P_I \\ \Delta Q_J \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{\partial Q_J}{\partial B_{SVC}} \end{bmatrix} \begin{bmatrix} \Delta \delta_J \\ \Delta B_{SVC} \end{bmatrix} \quad (3.3)$$

At the end of iteration p, the variable shunt susceptance is corrected as:

$$B_{SVC}^{(P+1)} = B_{SVC}^{(P)} + \Delta B_{SVC}^{(P)} \quad (3.4)$$

Which may further be written as:

$$B_{SVC}^{(P+1)} = B_{SVC}^{(P)} + \left(\frac{\Delta B_{SVC}}{B_{SVC}}\right)^{(P+1)} B_{SVC}^{(P)} \quad (3.5)$$

Where, V_j =voltage at bus j

B_{SVC}= Susceptance of SVC

Q_{SVC}= reactive power drawn by SVC.

I_{SVC}= the current drawn by the SVC.

Q_j= reactive power at bus j.

P_j= active power at bus j.

The changing susceptance represents the total SVC susceptance necessary to maintain the nodal magnitude at specified value. SVC compensation may also be computed in terms of thyristor firing angle.

However, the additional requires an iterative solution as SVC susceptance and thyristor firing angle are non-linearly related [16].

The steady state susceptance of SVC can be obtained from the following relation:

$$B_{SVC} = B_C - B_{TCR} = \frac{1}{X_C X_L}\left[Xl - \frac{X_C}{\pi}(2(\pi-\alpha))+\sin(2\alpha)\right] \quad (3.6)$$

Where, $Xl = \omega L$ and $Xc = 1\omega C$ Since $QSVC = -Vj2BSVC$, we can write

$$Qj = \frac{-V_L^2 1}{X_C X_L}\left[Xl - \frac{X_C}{\pi}(2(\pi-\alpha))+\sin(2\alpha)\right] \quad (3.7)$$

Assuming Qj is the jth bus reactive power injection due to SVC installation at jth bus, the linearized SVC equation is given by:

$$\begin{bmatrix} P_J \\ Q_I \end{bmatrix}^{(P+1)} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{2V_I^2}{\pi X_I}[\cos(2\alpha)-1] \end{bmatrix} \begin{bmatrix} \Delta\delta_J \\ \Delta\alpha \end{bmatrix}^{(P+1)} \quad (3.8)$$

At the end of iteration (P), the variable firing angle α is updated by the following equation.

$$\alpha_{(P+1)} = \alpha_P + \Delta\alpha_P \quad (3.9)$$

$$V_j = V_{ref} + X_{SL} \,.\, I_{SVC} \quad (3.10)$$

1- Advantages of SVC

The main advantage of SVCs over simple mechanically switched compensation schemes is their near-instantaneous response to change in the system voltage. For this reason, they are often operated at close to their zero-point in order to maximize the reactive power correction.They are in general cheaper, higher-capacity, faster, and more reliable than dynamic compensation schemes such as synchronous compensators (condensers). In a word [22]:

1- Improved system steady-state stability.

2- Improved system transient stability

3- Better load division on parallel circuits.

4- Reduced voltage drops in load areas during severe disturbances.

5- Reduced transmission losses.

6- Better adjustment of line loadings

2- SVC V-I Characteristic

The typical steady-state control law of a SVC used here is depicted in figure 3.2, The steady-state operating domain of the SVC can be split into three sub-domains as showing in figure.

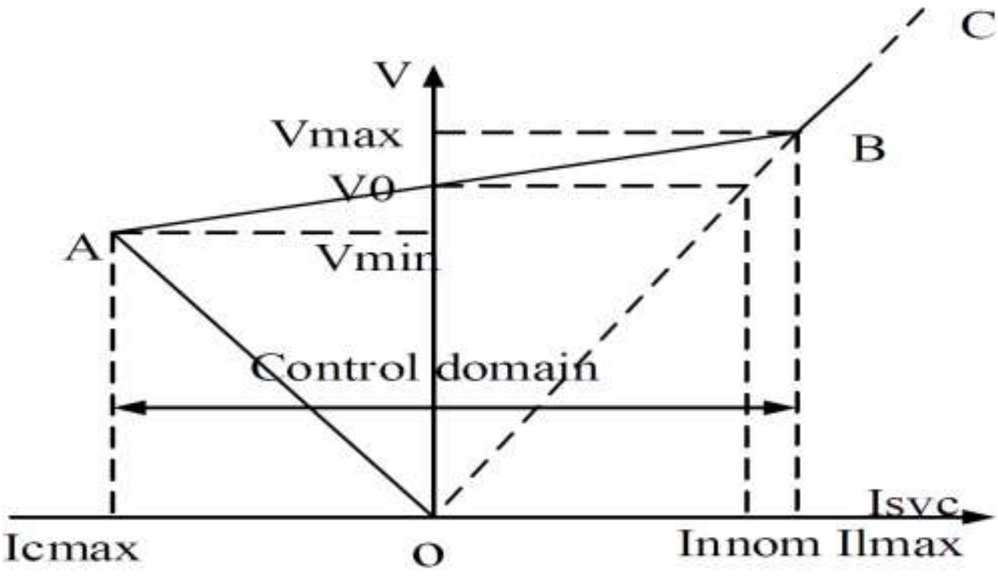

Figure 3.2: Steady State V-I characteristics of SVC

The linear control domain, in which the voltage control system is provided with appropriate reactive power resources, and the set-point can be defined anywhere on the AB characteristic. This domain is bounded by the reactive power $QC\ max$, supplied by the capacitors, and by the reactive power $QL\ max$ absorbed by the reactor, that is $Qc\ max \leq Q \leq QL\ max$ [23].

In practice, a SVC uses droop control of the voltage at the regulated bus, with a slope of about 5%. The droop control means that the voltage at the regulated bus is controlled within a certain interval [Vmin, Vmax], instead of a constant voltage value Vref. The high voltages domain (BC), resulted from the limitation in the inductive reactive power, i.e. Q > QLmax. The SVC, in this case is out of the control area and it behaves like a fixed inductive susceptance. The low voltages domain (OA), resulted from the limitation in the capacitive reactive power, i.e. Q < $QC\ max$. The SVC, in this case is out of the control area and it behaves like a fixed capacitive susceptance [24].

CHAPTER FOUR
SIMULATION AND RESULTS

4.1 Overview of Sudan National Grid

Electrification in Sudan began in 1908 with capacity of 100 KW, in 1925 the Sudanese government contracted with British companies to improve the capacity of generation to 3MW. In the year 1956 Burri power plant was added to old generation, with capacity of 30MW. The first hydro power plan was Sennar power station with capacity of 15MW. After many years, Khashim Elgirba station was added with small capacity. From 1971 to 1993, Rosseirs power station was phased with a total capacity of 280MW. In 1985 phase one of Khartoum North steam power plant with capacity of 60MW and after few years The total capacity was completed to 280MW [26].

With growing need of Sudan to electric power and with the increasing demand, the ministry has worked on the construction of new plants. At the end of year 2010 Marawi hydro power plant was constructed, which contain 10 units with designed capacity of 1250 MW to contribute 60% of the total loads of the national grid. In 2011 Garri thermal power station was added with designing reach to capacity of 200 MW. The ministry has worked to implement the A aley Atbara and Setit Dams, which are located in Kassala and Gadaref states with capacity of 320 MW, beside completion work in Um Dabakr thermal power plant with capacity of up to 500 MW from 4 units [26].

4.2 Case Study

The simplified transmission network of Sudan National Grid consists of four 500kV substation and thirty-five 220kV substations; the maximum power can be generated in the Sudanese National Electric Grid is a round 2086.276 MW, 472.999 MVAR which comes from eight power plants, Marawi, Garri, Roseires, Sennar, Jable Awlia, Rabak, Khashim Elgirba and Algadarif power plants. A single line diagram showing the Sudan National Electric Grid is attached in appendix C, this single line diagram is obtained after representing each power plant by one equivalent machine and all the transmission lines have been modeled with lumped parameter using the π equivalent and the double circuits transmission lines are reduced to equivalent lines. The corresponding line and bus data are given in appendix (A, B). All per unit values are referred to a power base of 1000 MVA. The NEPLAN Software Version 5.5.8 used to conduct study the static voltage stability analysis

4.3 Software Tool

The NEPLAN Software Version 5.5.8 used to conduct study the static voltage stability analysis, which is one of the most important planning, optimization and simulation tools [27].

4.4 System without SVC

The system is simulating in NEPLAN software environment using the operational data given in appendix (A, B). The network operated at normal condition. Newton-Raphson method was used to obtain the power-flow solution. Table 4.1 represents the voltage magnitude and voltage angle in the base case from load flow

Table 4.1 : Bus Voltage at base case

No.Bus	Bus name	Voltage(kv)	Voltage p.u	angle°
1	MAR	210.325	95.6	16.7
2	AROMA	221.304	100.59	37.7
3	ATB	223.683	101.67	-2.5
4	ATB 500	511.688	102.34	-1.3
5	DABA	230.9	104.95	-3.3
6	DON	231.808	105.37	-4.1
7	EDB	214.437	97.47	1.4
8	FRZ	219.915	99.96	2.4
9	GADAR	220	100	37.3
10	GAM	214.425	97.47	1
11	GARI	220	100	2.7
12	GIAD	215.451	97.93	4.4
13	GIRBA	220	100	38.3
14	HAW	220.28	100.13	33.4
15	JABAL	220	100	4.5
16	KAB	217.868	99.03	1.5
17	KAB 500	507.658	101.53	0.4
18	KASALA	221.222	100.56	37.8
19	KILOX	213.34	96.97	1.5
20	MAP	223.127	101.42	-0.7
21	MARW	500	100	0
22	MHD	211.38	96.08	-1.6
23	MRK	214.2	97.36	-0.6
24	MRK500	509.425	101.88	0.2
25	MRT	226.053	102.75	-1.8
26	MSH	215.471	97.94	18.3
27	N.HALFA	219.887	99.95	38.2
28	NEW	210.768	95.8	11.4
29	OBID	225.805	102.64	26.5
30	PORT	211.892	96.31	-14.8
31	RAB	220	100	29.5
32	RAN	222.287	101.04	34.5
33	ROSERES	220	100	39.2
34	SENAR	220	100	26.1
35	SENGA	219.998	100	30.4
36	SHEN	222.535	101.15	-0.3
37	SHOWAK	220.037	100.02	37.4
38	TANDA	224.277	101.94	28.1
39	UMR	226.063	102.76	27.3

It can be observed from the results presented in Table 4.1 that all nodal voltages are within accepted limits (0.95 – 1.05) pu, the five buses in the network are near to the lower limit. Figure 4.1 shows the voltage profile of the system buses

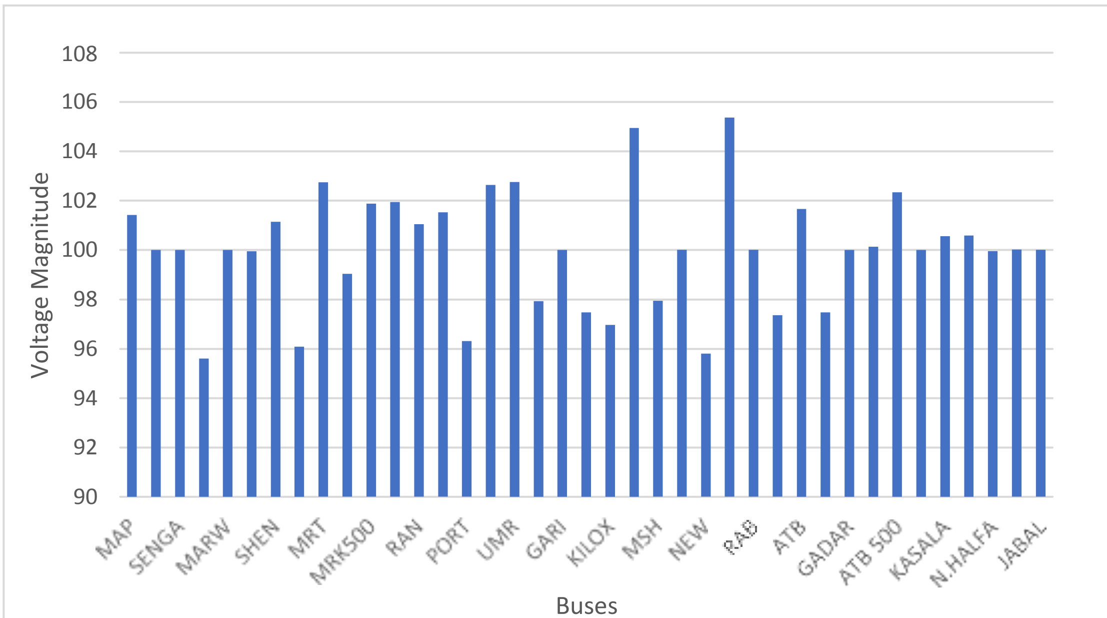

Figure 4.1: Voltage Profile of the System

Simulation of Network is carried out at the Base case and Critical Case. The table 4.2 provide the results of the V-Q Sensitivities, the 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 their sensitivities, it is observed that all buses have positive V-Q sensitivity this mean that the system is stable, the buses which have smaller V-Q Sensitivity are more stable buses. In this case the bus PORT , DON , OBID , DABA , UMR have small stability at base case. Figure 4.2 shows that the weakest buses are PORT , DON , OBID , DABA , UMR which have largest V-Q sensitivity, form Figure 4.3 it is observed that PORT , DON , OBID , DABA , UMR are the weakest buses in the system of Sudan National

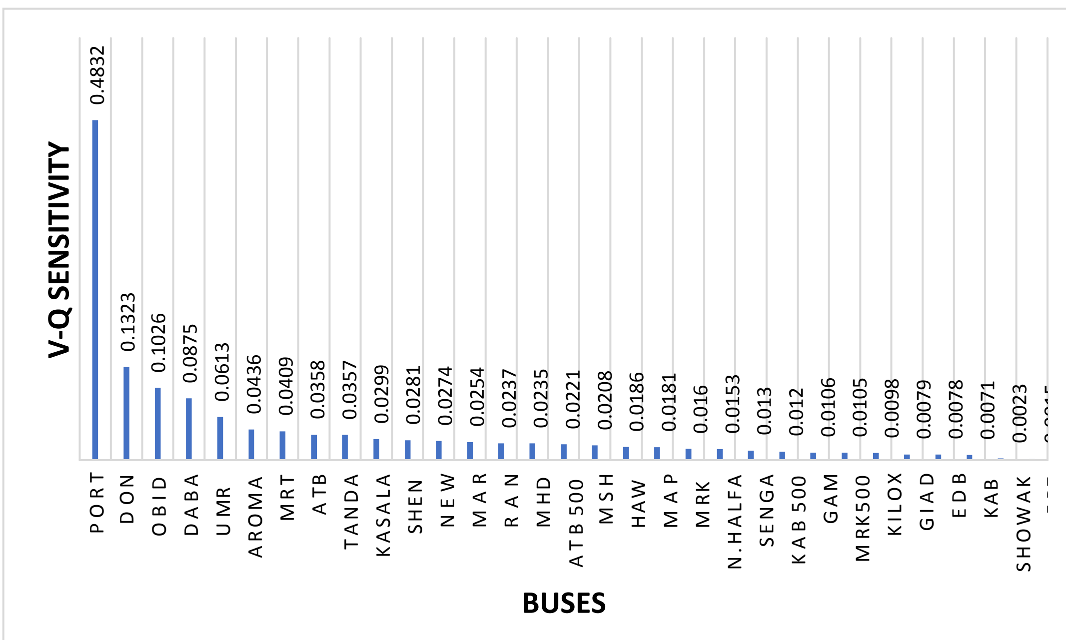

Figure 4.2: V-Q Sensitivity Analysis for Base Case

Table 4.2: V-Q Sensitivities at Base Case

No.Bus	**Bus name**	**voltage(kv)**
1	PORT	0.4832
2	DON	0.1323
3	OBID	0.1026
4	DABA	0.0875
5	UMR	0.0613
6	AROMA	0.0436
7	MRT	0.0409
8	ATB	0.0358
9	TANDA	0.0357
10	KASALA	0.0299
11	SHEN	0.0281
12	NEW	0.0274
13	MAR	0.0254
14	RAN	0.0237
15	MHD	0.0235
16	ATB 500	0.0221
17	MSH	0.0208
18	HAW	0.0186
19	MAP	0.0181
20	MRK	0.016
21	N.HALFA	0.0153
22	SENGA	0.013
23	KAB 500	0.012
24	GAM	0.0106
25	MRK500	0.0105
26	KILOX	0.0098
27	GIAD	0.0079
28	EDB	0.0078
29	KAB	0.0071
30	SHOWAK	0.0023
31	FRZ	0.0015

Table 4.3 shows the eigenvalues of the reduced Jacobian matrix of the system, it is observed that all eigenvalues are positive so the system is voltage stable, the critical mode is that corresponds to the smallest eigenvalue (2.0302).

Table 4.3: eigenvalues of the system at base case

No	Egenvalue
1	2.0302
2	4.4151
3	5.9604
4	14.8264
5	19.8889
6	21.4678
7	22.4390
8	32.5183
9	42.1265
10	43.0095

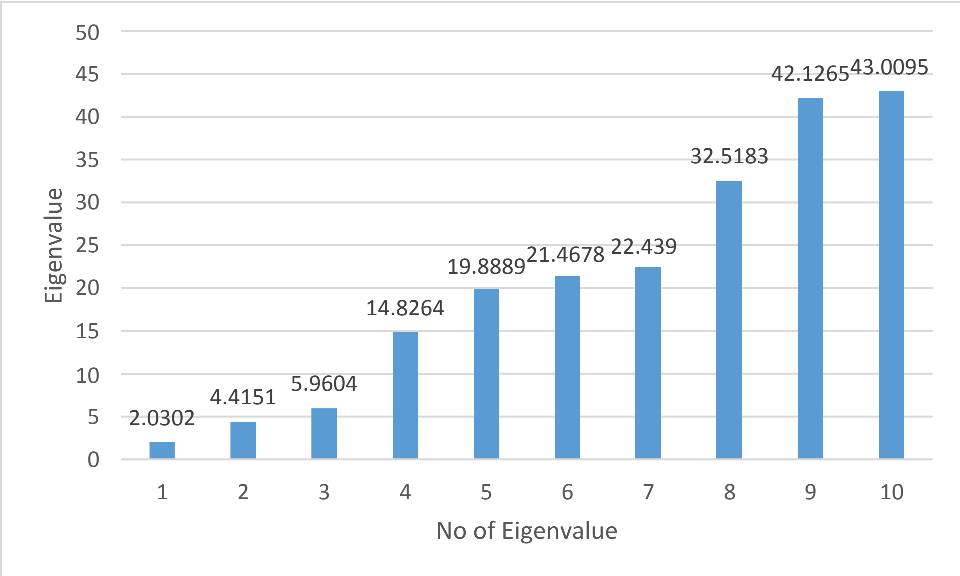

Figure 4.3: eigenvalues of the system at base case

To determine the weakest buses of the system, right eigenvector components and bus participation factors corresponding to that minimum critical eigenvalue can be calculated. Tables 4.4 illustrate the bus participation factors of the system buses at different eigenvector, 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. it is can be seen that the buses PORT , DON , DABA , OBID and UMR have highest participation factor that mean they are weakest buses in the system .

Table 4.3: Bus participation factors versus Bus P-F at Base case

No.Bus	**Eigenvalue**	**Bus name**	**Bus Participation Factor**
1	2.0302	PORT	0.9789
2	4.4151	DON	0.5326
3	-	DABA	0.3427
4	5.9604	OBID	0.5536
5	-	UMR	0.3145
6	14.8264	AROMA	0.6114
7	-	KASALA	0.3886
8	19.8889	ATB	0.4656
9	-	SHEN	0.2891
10	21.4678	MHD	0.3176
11	-	MRK	0.2230
12	22.4390	NEW	0.4000
13	-	MAR	0.3479
14	32.5183	MRT	0.4598
15	-	DON	0.2999
16	42.1265	RAN	0.9940
17	43.0095	HAW	0.6842

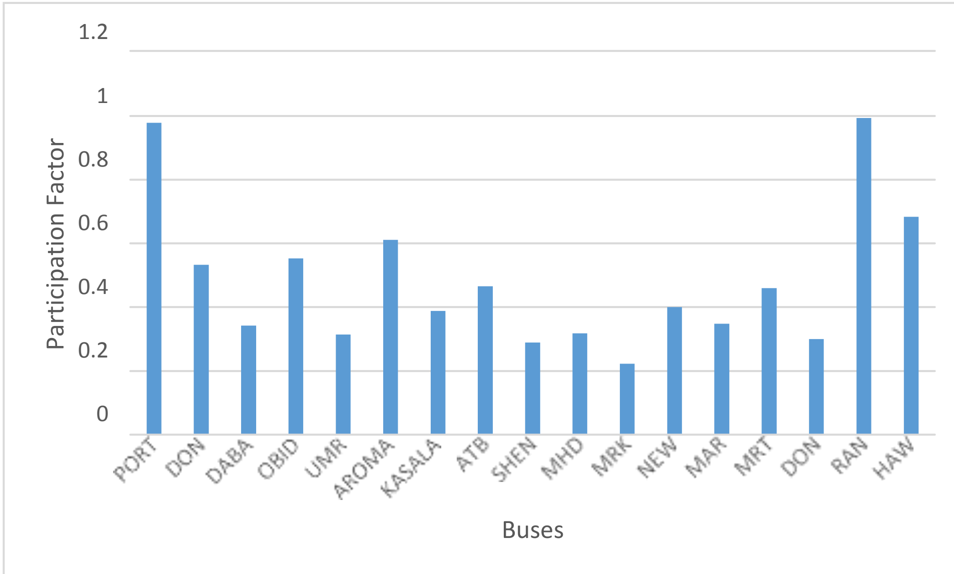

Figure 4.4: Participation factor for base case

In principle, PV curve is a representation of voltage change as a result of increased active power transfer between two systems. To show the weakest buses of the system the PV curve was drown at figure 4.5 for all buses.

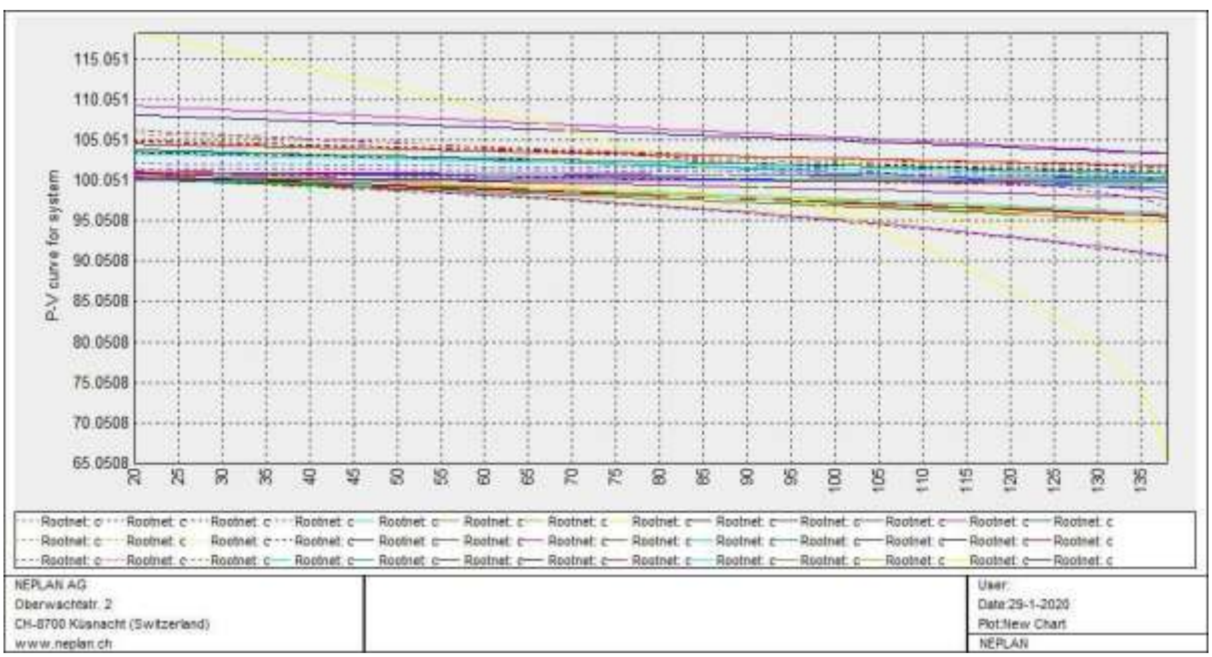

Figure 4.5 shown the weakest buses by drown the PV curve in NEPLAN 5.5.8 software.

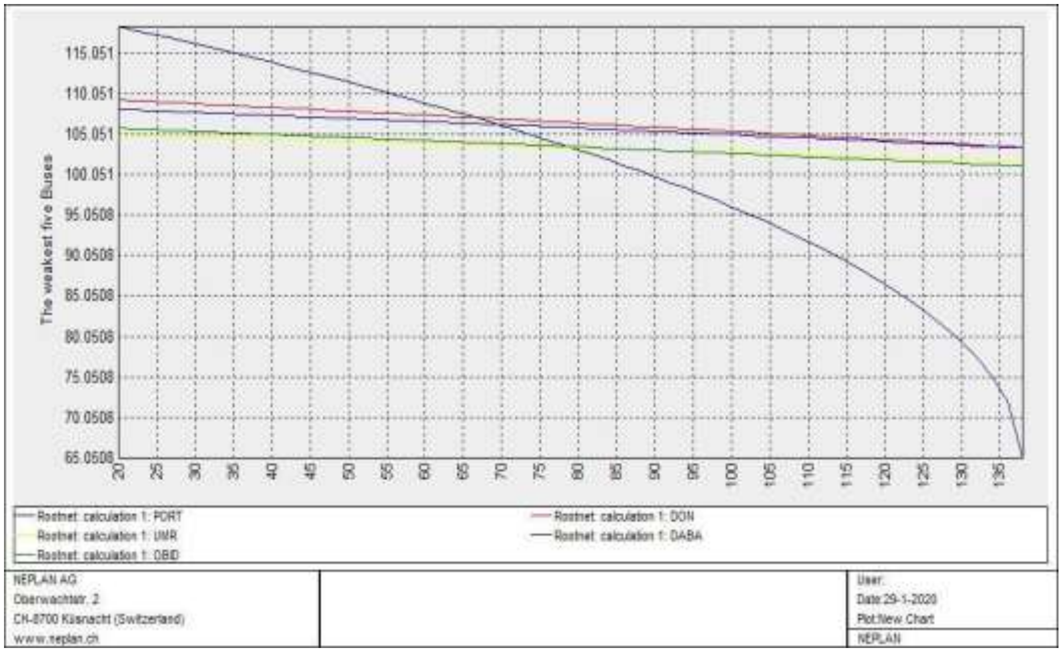

Figure 4.6: The PV curve in Neplan for the weakest five buses

From Figure 4.6 the weakest buses are obtained and drown througe PV curve as shown:
PORT-DON-DABA-OBID-UMR.

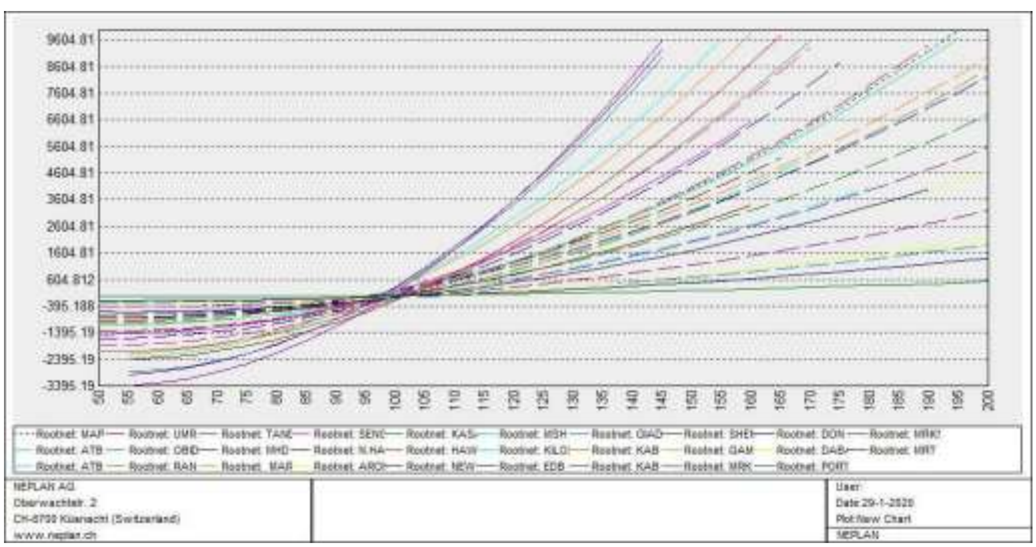

Figure 4.7 the QV curves drown on Neplan 5.5.8 software

By using Q-V curves, it is possible for the operators and the planners to know the maximum reactive power that can be achieved or added to the weakest bus before reaching minimum voltage limit or voltage instability, in figure 4.7 the QV curves drown on Neplan 5.5.8 software.

4.4 System with SVC

Table 4.4 : Bus Voltage after using SVC

No.Bus	Bus name	Voltage(kv)	Voltage p.u	angle°
1	MAR	210.332	95.61	16.7
2	SENGA	219.999	100	30.4
3	SENAR	220	100	26.1
4	MAP	220.778	100.35	-0.7
5	MARW	500	100	0
6	SHEN	222.938	101.34	-0.3
7	FRZ	219.931	99.97	2.4
8	MRT	220.845	100.38	-1.7
9	MHD	211.383	96.08	-1.6
10	MRK500	509.432	101.89	0.2
11	KAB	217.877	99.03	1.5
12	PORT	220	100	-14.7
13	KAB 500	507.667	101.53	0.4
14	RAN	222.289	101.04	34.5
15	TANDA	220.706	100.32	28.3
16	KILOX	213.345	96.98	1.5
17	EDB	214.443	97.47	1.4
18	GARI	220	100	2.7
19	GIAD	215.455	97.93	4.4
20	UMR	220	100	27.6

21	OBID	220	100	26.7
22	DABA	220	100	-2.9
23	DON	220	100	-3.7
24	NEW	210.776	95.81	11.4
25	ROSERES	220	100	39.2
26	MSH	215.47	97.94	18.3
27	RAB	220	100	29.5
28	MRK	214.203	97.36	-0.6
29	GAM	214.427	97.47	1
30	ATB	224.548	102.07	-2.5
31	HAW	220.282	100.13	33.3
32	GADAR	220	100	37.3
33	JABAL	220	100	4.5
34	SHOWAK	220.037	100.02	37.4
35	N.HALFA	219.887	99.95	38.1
36	AROMA	221.304	100.59	37.7
37	KASALA	221.222	100.56	37.8
38	GIRBA	220	100	38.3
39	ATB 500	512.674	102.53	-1.3

Figure 4.8 : Bus Voltage after and before using SVC

Table 4.9 illustrate voltage magnitude at base case and after installation SVC. The SVC injects VAR into selected weakest bus and keeps the nodal voltage magnitude at 1 p.u. The action of the SVC results in an overall improved voltage profile.

Table 4.5 : V-Q Sensitivities after using SVC

No.Bus	Bus Name	Sensitivity
1	AROMA	0.0436
2	ATB	0.0299
3	KASALA	0.0299
4	NEW	0.0274
5	SHEN	0.0268
6	MAR	0.0254
7	RAN	0.0237
8	MHD	0.0235
9	MSH	0.0208
10	MRT	0.0208
11	ATB 500	0.0206
12	HAW	0.0186
13	MRK	0.016
14	N.HALFA	0.0153
15	TANDA	0.0144
16	MAP	0.014
17	SENGA	0.013
18	KAB 500	0.012
19	GAM	0.0106
20	MRK500	0.0105
21	KILOX	0.0098
22	GIAD	0.0079
23	EDB	0.0078
24	KAB	0.0071
25	SHOWAK	0.0023
26	FRZ	0.0015
27	FRZ	0.0015

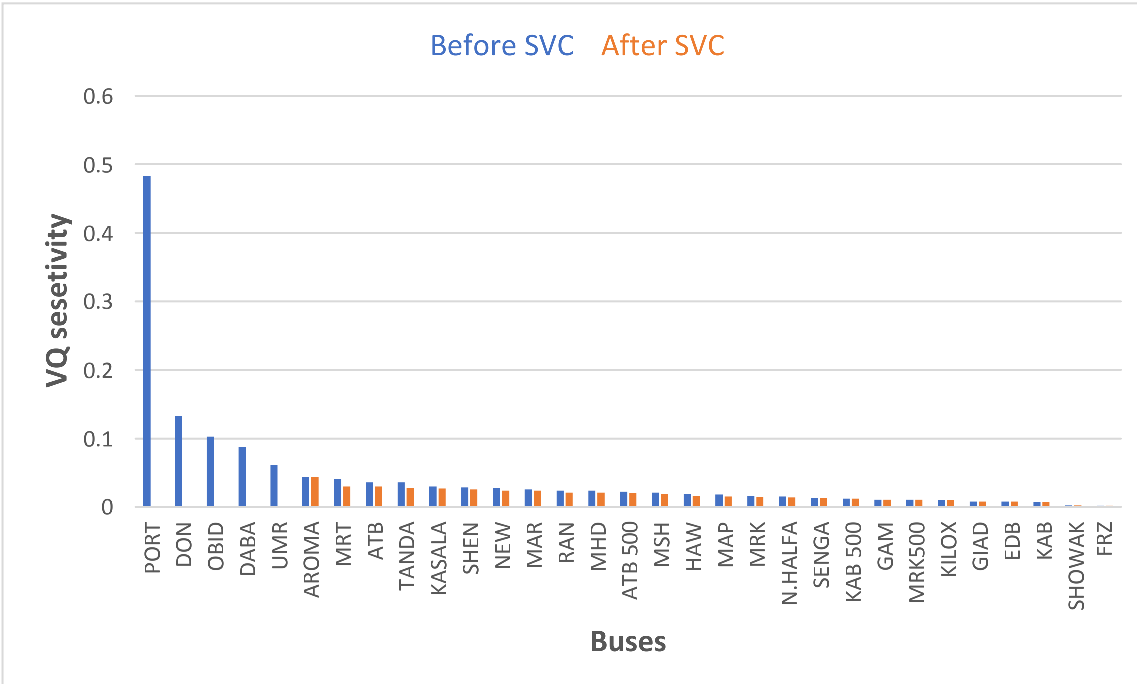

Figure 4.9 : V-Q Sensitivities after using SVC

Table 4.1 : Bus participatin factor after using SVC

No.Bus	Bus Name	Bus Participatin factor
1	AROMA	0.6114
2	KASALA	0.3886
3	ATB	0.4809
4	SHEN	0.2922
5	ATB 500	0.2184
6	MHD	0.3187
7	MRK	0.2238
8	NEW	0.108
9	MAR	0.0894
10	GAM	0.0818
11	MRK500	0.0662
12	KAB 500	0.0654
13	NEW	0.4002
14	MAR	0.3481
15	MHD	0.1008
16	MRT	0.6704
17	MAP	0.3296
18	RAN	0.994
19	AROMA	0.6114
20	KASALA	0.3886
21	ATB	0.4809
22	SHEN	0.2922
23	ATB 500	0.2184
24	MHD	0.3187
25	MRK	0.2238
26	NEW	0.108
27	MAR	0.0894

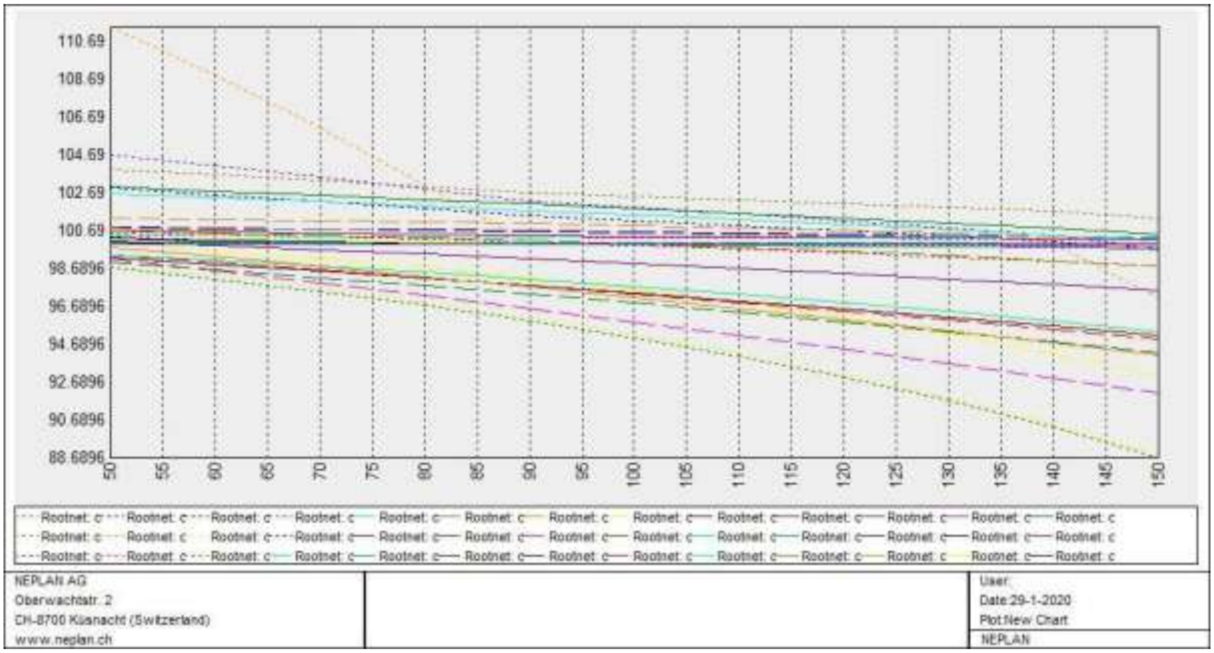

Figure 4.10 : PV curves for system after using SVC

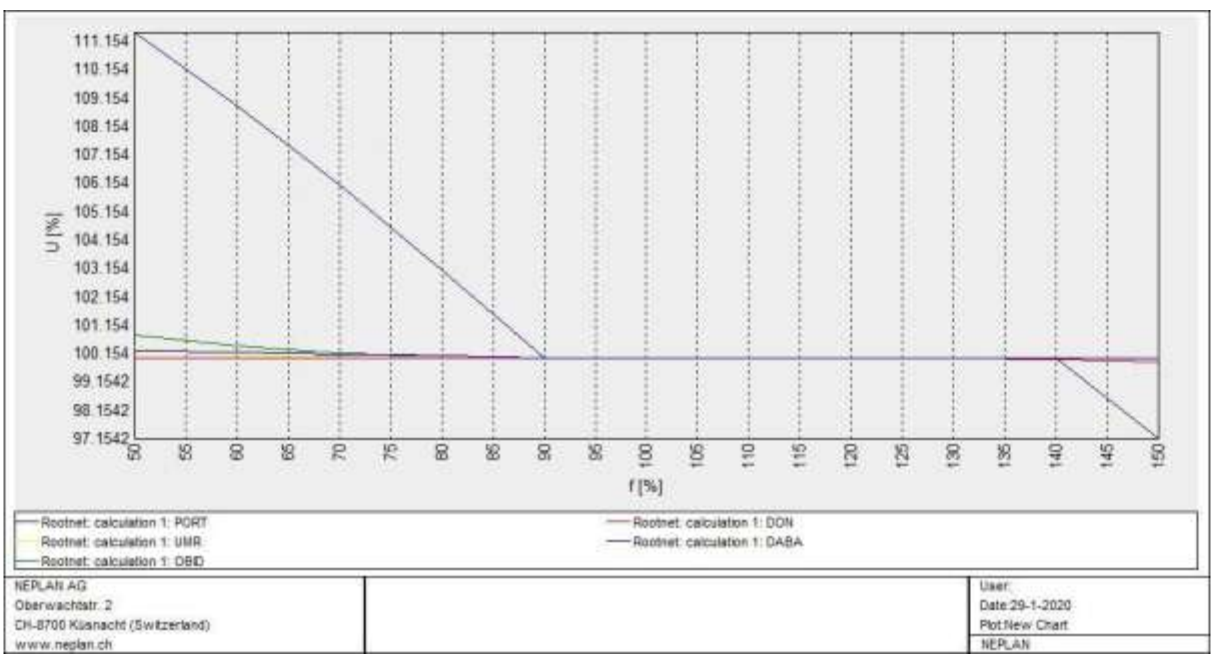

Figure 4.11 : PV curves for five weakest buses system after using SVC

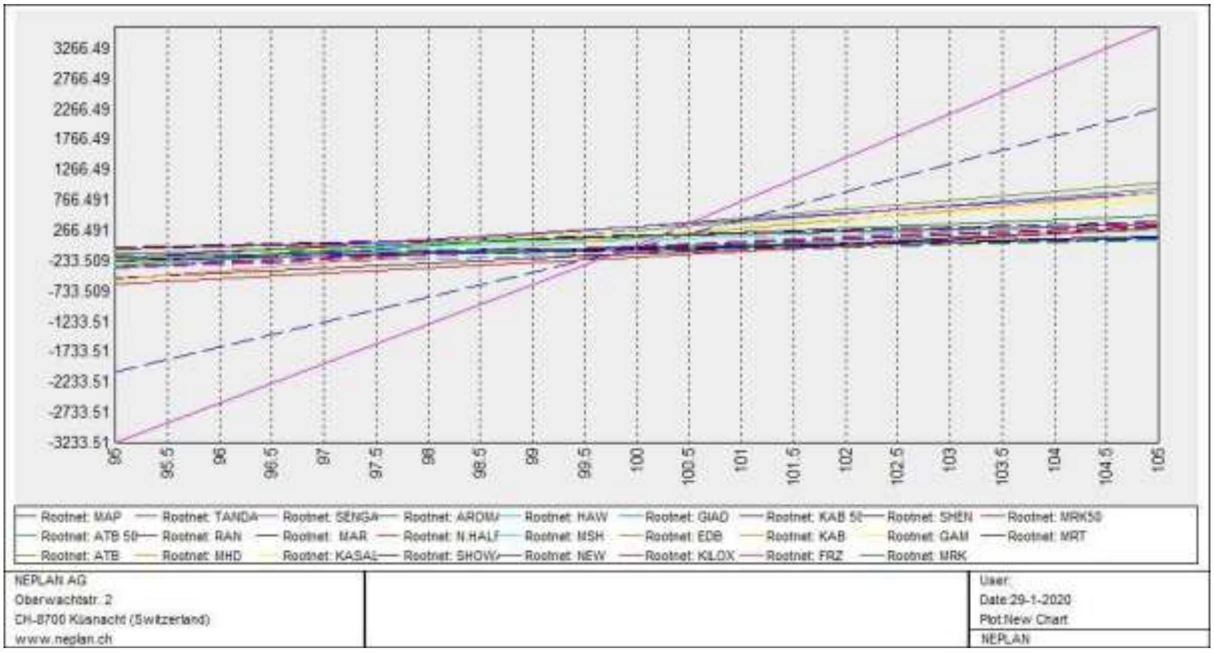

Figure 4.12 : Q-V curves for all buses system after using SVC

CHAPTER FIVE

COCLOUSION AND RECOMMENDATIONS

5.1 Conclusion

Static Var Compensators (SVC) are easier to insert in the network since they are connected to the grid through a power transformer. SVCs are the key solution when the transmission system is pushed to its limits and needs a continuous voltage control with a short time response in a contingency situation. More over with the new SVC, based on voltage source converters, it is possible to support the system during faults and transient period or to improve power quality. It has found that by load flow using Neplan program when SVCs 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.

5.2 Recommendations

- Use multiple types of FACTs (the combination of the series and shunt can provide better solution than shunt combination only).
- The algorithm required some improvement to study the effect of SVC for both steady state and transient conditions.
- To study the effect of SVC in economic operation and transmission lines loss reduction.

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Appendix (A)

Sudan National Grid Line DataData

From	To	Line length	No of	R(1)	X(1)	C(1)	V nominal
Bus	Bus	Km	Circuit	Ohm/Km	Ohm/Km	µF/Km	Kv
1	9	36.8	1	0.028	0.276	1.31E-05	500
11	15	38	2	0.067	0.302	0.01306	220
14	15	115	2	0.067	0.302	0.01306	220
3	14	140	2	0.067	0.302	0.01306	220
12	13	21	2	0.067	0.302	0.01306	220
19	20	39.88	2	0.067	0.302	0.01306	220
12	19	37	2	0.067	0.302	0.01306	220
15	16	5	2	0.067	0.302	0.01306	220
20	21	147.7	2	0.067	0.302	0.01306	220
21	22	107.2	2	0.067	0.302	0.01306	220
22	24	111	2	0.067	0.302	0.01306	220
25	26	126	2	0.067	0.302	0.01306	220
24	25	78.3	2	0.067	0.302	0.01306	220
16	17	60	2	0.067	0.302	0.01306	220
17	18	14	2	0.067	0.302	0.01306	220
18	39	43	2	0.076	0.403	0.00902	220
39	20	36	2	0.067	0.302	0.01306	220
39	37	86	2	0.076	0.403	0.00902	220
22	23	163.3	2	0.067	0.302	0.01306	220
27	23	140	2	0.067	0.302	0.01306	220
27	29	178	2	0.076	0.403	0.00902	220
29	28	50	2	0.076	0.403	0.00902	220
28	38	84	2	0.076	0.403	0.00902	220
37	38	55	2	0.076	0.403	0.00902	220
30	31	100	2	0.067	0.302	0.01306	220
31	32	8.245	2	0.067	0.302	0.01306	220
32	35	70	2	0.067	0.302	0.01306	220
35	33	48.87	2	0.067	0.302	0.01306	220
35	34	95	2	0.067	0.302	0.01306	220
34	36	43.76	2	0.067	0.302	0.01306	220
11	17	30	2	0.067	0.302	0.01306	220
7	8	139.38	2	0.067	0.302	0.01306	220
4	3	448.92	1	0.067	0.302	0.01306	220
2	1	236.7	1	0.028	0.276	0.01308	500
1	9	345	2	0.028	0.276	0.01308	500
5	6	34.55	1	0.067	0.302	0.01306	220
6	7	139.3	2	0.067	0.302	0.01306	220
29	30	90	2	0.067	0.302	0.01306	220

Appendix (B)

Sudan National Grid Bus and Generator Data

Bus.NO	Type	P-load MW	Q- load Mvar	P-Gen MW	Q-Gen Mvar	Base KV	Bus.NO
1	Slack	0	0	……	…….	500	1
2	PQ	0	0	0	0	500	2
3	PQ	90.112	55.849	0	0	220	3
4	PQ	73	35.6	0	0	220	4
5	PQ	0	0	0	0	220	5
6	PQ	24.3	14.5	0	0	220	6
7	PQ	16.55	13	0	0	220	7
8	PQ	31.5	13.5	0	0	220	8
9	PQ	0	0	0	0	500	9
10	PQ	0	0	0	0	500	10
11	PQ	0	0	0	0	220	11
12	PQ	0	0	0	0	220	12
13	PQ	266.6	130.7	0	0	220	13
14	PQ	30.962	18.565	0	0	220	14
15	PQ	13.2	3.2	0	0	220	15
16	PV	0	0	280	63.462	220	16
17	PQ	222.8	151.6	0	0	220	17
18	PQ	241.2	119.4	0	0	220	18
19	PQ	282.8	123.5	0	0	220	19
20	PV	69.2	28.4	30	266.473	220	20
21	PQ	57.6	22.6	0	0	220	21
22	PV	120.3	227.193	450	0	220	22
23	PQ	2.5	0.9	0	0	220	23
24	PQ	13.2	11.5	0	0	220	24
25	PQ	5.2	3.8	0	0	220	25
26	PQ	39.7	20.3	0	0	220	26
27	PV	28.7	107.348	280	0	220	27
28	PV	26.9	10.5	15	130.082	220	28
29	PQ	25.1	8.8	0	0	220	29
30	PQ	30	10	0	0	220	30
31	PV	34.2	46.443	58	0	220	31
32	PQ	9.1	5.6	0	0	220	32
33	PQ	15.5	9.6	0	0	220	33
34	PQ	13.8	8.6	0	0	220	34
35	PV	26.14	101.378	5	0	220	35
36	PQ	10.4	3.7	0	0	220	36
37	PQ	50.544	20.326	0	0	220	37
38	PQ	90	75.2	0	0	220	38
39	PQ	77.2	50.9	0	0	220	39

Appendix (C)

Transformers Data

Name	Vector group	S (MVA)	Kr1 (Kv)	Kr2(Kv)	Vkr (%)
Marwi	YNd11	900	500	220	16
Atbara	YNd11	600	500	220	16
Markiyat	YNd11	600	500	220	16
Kabashi	YNd11	600	500	220	16

Appendix (D)

Sudan National Grid Single Line Diagram