PERFORMANCE EVALUATION OF POWER SYSTEM STABILIZER AND STATIC SYNCHRONOUS COMPENSATOR ON OSCILLATION DAMPING OF NORTH-CENTRAL NIGERIA GRID SYSTEM

BY

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DECLARATION

I hereby declare that this thesis "Performance Evaluation of Power System Stabilizer and Static Synchronous Compensator on Oscillation Damping of North-Central Nigeria Grid System" is a collection of my original research work and it has not been presented for any other qualification anywhere. Information from other sources (published and unpublished) has been duly acknowledged.

3/5/2012
Signature and Date

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DEDICATION

This work is dedicated to Almighty God and to my family for being resourceful in the completion of this research work.

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ABSTRACT

This research aims at discussing the effective performances of Power System Stabilizer (PSS) and Static Synchronous Compensator (STATCOM) that are considered separately in damping oscillations on the 330KV North-Central network of Nigeria Grid System. The result of this study reveals effective damping of the controllers, the PSS and STATCOM suitably located in the power system. Placement of the STATCOM requires the use of optimization technique; hence Genetic Algorithm (GA) was adopted. Also, the location of the PSS in requisite generator is determined by eigenvalues analysis and damping coefficient. Simulations were carried out in Power System Analysis Toolbox (PSAT) environment to evaluate the performance of the PSS and STATCOM in damping oscillations on North-Central network of Nigeria 330KV Grid System. By simulation, it was observed that the damping effect of PSS is limited to the local modes (generator) where it is placed; while STATCOM is very effective in both local and inter-area modes of oscillation damping.

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ABBREVIATIONS AND SYMBOLS

AC	Alternating Current
AVR	Automatic voltage regulator
DC	Direct current
FACTS	Flexible alternating current transmission system
PHCN	Power holding company of Nigeria
PSAT	Power system analysis toolbox
PWM	Pulse width modulation
SSSC	Static synchronous series compensator
STATCOM	Static synchronous compensator
SVC	Static Var Compensator
TCR	Thyristor controlled reactor
TS	Transient stability
TCSC	Thyristor controlled series compensator
UPFC	Unified power flow controller
VSC	Voltage source converter
VSI	Voltage Source Inverter
α	Firing angle
V_i	Controlled bus voltage magnitude
V_k	Thyristor controlled reactor and fixed capacitor voltage magnitude
V_{ref}	Controller set point
X_{sl}	Droop
P	active power
Q	Reactive power

B	Susceptance
X_L	Fundamental frequency reactance of L
X_C	Fundamental frequency reactance of C
I*	Complex current
I_{max}	Maximum converter current
I_{min}	Minimum converter current
$\bar{I}_d$	Direct current in line
$\bar{I}_q$	Quadrature current with $\overline{V_i}$
k	Converter ratio
V_{dc}	dc voltage across the capacitor C_{dc}
$\bar{I}_p$	Line current
K_{ac}	Transfer functions of STATCOM ac voltage
K_{dc}	Transfer functions of STATCOM dc voltage
m	Pulse Width Modulation index

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Introduction

Commercial electricity was first generated by Thomas Alva, Edison in 1882, which produced direct current (dc) electrical power. Later on, a Serbian American electrical engineer Nikola Tesla in 1888 designed the first practical system of generating and transmitting of electrical power (Sadaat, 2004). The generator output is usually decided by the turbine mechanical torque, which could be altered by excitation value transiently. This alteration is associated with some disturbances in the form of power swings/ oscillations that are usually unwanted. There is need to damp the unwanted power swing by changing output power, controlling the excitation value and reducing the power oscillation in order to have a stable system. The stability of electrical power can most simply be defined as its ability to continue in a stable operation after some disturbances. The synchronous operation of a generator is endangered by close and remote short-circuits in the network, by line and load interruptions, variation in generators speed and turbine systems. In that case the system stability maintenance depends on the drive operation conditions prior to disturbance (load, generator, network configuration) as well as on nature of disturbance (category of defect, location of occurrence, clearing time, and so on). In a case of a power plant connected to an insufficiently strong high-voltage grid (highly loaded grid), a major close disturbance in the network and disconnection of defective line can lead to long lasting and poorly damped oscillations of generator's rotor, and can result in its instability after the transient period. All these result into power swing mode (Electromechanical) oscillation.

The emergence of Power System Stabilizer (PSS) brought some relief in power swing problems. The PSS is used to damp power system swing mode (Electromechanical) oscillation, by basically detecting change of generator output power, control of excitation value and reduce the power swing rapidly. PSS, initially called Supplementary Control System, were developed in the mid 1960's in response to power system oscillations on the pacific inter tie. These oscillations occur at very lightly damped, and became known as inter-area modes of oscillation. The term inter-area is used because the real power oscillations were observed between the Pacific North and Southwest of U.S.A. The oscillations are composed of combinations of many machines on one part of a system (Northwest) swinging against machines on another part of the system (Southwest). This situation developed slowly as the stability margins were reduced when electrical systems were interconnected together and power was transmitted from one region to another. It was further exacerbated with the utilization of high gain excitation systems required for transient stability. PSS enhance system stability by providing additional damping to a power system by utilizing the rotating inertia of the generating unit to dampen power system oscillations (Nettleton and Padilla, 1999).

The advent of power electronics gave rise to the development of new and advanced devices such as Flexible Alternating Current Transmission Systems (FACTS) devices that effectively damp oscillations by circuits combined with the control mechanism prominent in the modern control systems. FACTS devices have been produced to make impact on the improvement of overall power systems performance. Shunt FACTS controllers, such as Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM), are capable of effectively damping power swing mode oscillation (electromechanical oscillation) (Mitsubishi Electric, 2001).

An appropriate model of PSS and STATCOM will be used to capture the influence of the devices on power flows. The case study will be a regional network (North-Central region) of the Nigerian Grid system under different generating capacities. Also, loaded and perturbed system scenarios will be presented and discussed to justify the effectiveness of PSS and STATCOM in this research work. The case study will be mathematically modelled in details using system parameters in Power System Analysis Toolbox (PSAT) environment where most of the simulations will be carried out.

Finally, a multi-machine system with PSS and STATCOM devices installed will be simulated using PSAT to evaluate the applicability and performance of these installations.

1.2 Aims and Objectives

The proposed research work aims at evaluating the use of PSS and STATCOM separately in enhancing the steady state dynamic and transient power stability in a network of three generating stations namely: Kainji, Jebba and Shiroro hydroelectric power stations located at the North-Central region (area of interest) of the electrical power network of the Nigerian grid system. This research work, subsequently, aims at achieving the following objectives:

- To come up with optimization technique that will best define a suitable location for optimal placement of STATCOM for damping of electromechanical oscillations in the areas of interest.

- To come up with techniques that will best define a suitable generator for placing PSS for damping of electromechanical oscillations in the area of interest.
- To minimize the incessant power mode swing that occur usually at low frequencies.
- To establish the effectiveness of both PSS and STATCOM in damping of electromechanical oscillations in the network.
- To improve the damping of power oscillations present in North-Central region of the Nigerian grid network by using PSS and FACTS one at a time in order to enhance the stability limits of the system.

1.3 Problem Statement/Motivation

A stable continuous supply of electric energy is essential for the functioning of our industries and comfort of electricity users. Emanation of electromechanical oscillations have constituted nuisance to the stability of power systems worldwide (Rogers, 2000). In interconnected large electric power systems, there have been always spontaneous system oscillations at very low frequencies in order of 0.2-2.0Hz (electromechanical oscillations). Once started, they would continue for a long period of time. In some cases, they continue to grow causing system separation due to lack of damping the modes (Abido, 2009).

In the past three decades, PSS have been extensively used to increase the system damping for low frequency oscillations. Power utilities worldwide have been using PSS as effective excitation controllers to enhance the system stability (Abido, 2009). North-Central region of the Nigerian power grid uses PSS in damping of electromechanical oscillations. However, there have been problems experienced with PSS over the years of operation worldwide. Some of these were due to the limited capability of PSS in damping only local and not inter-area modes of electromechanical oscillations. Furthermore, PSS can cause great variations in the voltage profile under severe disturbances and they may even result in leading power factor operation and losing stability (Eriksson, 2008).

The emergence of FACTS devices was a welcome idea. FACTS is being increasingly used to better utilize the capacity of existing transmission systems. FACTS is a technology based solution to help the utility industry deal with changes in the power delivery business. A major thrust of FACTS technology is the development of power electronics based systems that provide dynamic control of the power transfer parameters such as transmission voltage, line impedance and phase angle. The availability of FACTS controllers such as Static Var Compensators (SVC), Thyristor Control Series Compensators (TCSC), Static Synchronous Compensators (STATCOM), and Unified Power Flow Controller (UPFC), has led to their uses in damping inter-area oscillations (Hingorani N. G. and Gyugyi L., 2000). They are efficient where PSS are limited.

The installations of PSS and STATCOM lead to the improvement of stability margin, greater flexibility, and better utilization of existing power systems in the North-Central region of the Nigerian grid. The services of PSS and STATCOM will be independently employed to eliminate the oscillations. Finally, the study shall reveal how effective are the PSS and STATCOM considered separately in improving electromechanical oscillations on the network.

1.4 Organization of Thesis

This thesis is to be outlined as follows: Chapter one includes introduction of the concepts adopted, aims and objectives and problem statement/motivation. In chapter two, literature review of publications supportive of this research are discussed and the benefits of using the controllers (PSS and FACTS). Chapter three discusses the optimal location of STATCOM and PSS in the North-Central region of the Nigerian Grid System and the mathematical models of STATCOM and PSS. Chapter four presents the computer simulation of the network(s) considered with results. Chapter five gives the discussions of results obtained after simulation, conclusions and suggestions for further investigations.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

Many researchers have meaningfully contributed on this issue of mitigating power swing in some network worldwide, using different approaches. These contributions are discussed below:

Mithulananthan, *et al* (2001), researched on the direct correlation between typical electromechanical oscillations in power systems and Hopf bifurcations, so that Hopf bifurcation theory can be used to design remedial measures to resolve oscillation problems. A placement technique was proposed to identify and rank suitable locations for placing shunt FACTS controllers, for the purpose of oscillation control. In the case of Robak, *et al* (2003), they did a comparative study on the power system stability enhancement using PSS and UPFC with Lyapunov-based controllers. The PSS constitutes a supplementary loop to the Automatic Voltage Regulator (AVR) and UPFC controller. The robustness of both proposed controllers was proved. It was also shown that the proposed controllers used local available measurements to execute the derived control strategy and could be easily applied to power system. Both PSS and UPFC controllers provided post-fault additive damping while PSS action is better than UPFC when performing control during disturbance. Bamasak and Abido (2005) researched on the power system stability enhancement via PSS and STATCOM-based stabilizer when applied independently. They also investigated coordinated application and added a supplementary damping controller to the STATCOM AC voltage control loop to improve STATCOM power oscillation damping. The coordination between STATCOM damping stabilizer and internal PI voltage controllers is taken into consideration in their design stage. Cañizares (2000) used STATCOM controllers to address some voltage and angle stability and control problems, especially in distribution systems of grids. They discussed the validity of a typical transient stability (TS) model of a STATCOM widely used in small-disturbance stability studies of large, interconnected power grids as well as micro grids. Kanojia and Chandrakar, (2009) designed a power system installed with a STATCOM and demonstrated the application of linearized Phillips-heffron model in analysing the damping effect of the STATCOM to improve power system oscillation stability. Abido (2009), made a review of the current status of power system stability enhancement using FACTS controllers. The essential features of FACTS controllers and their potential to enhance system stability was addressed. The location and feedback signals used for design of FACTS-based damping controllers were discussed. The coordination problem among different control schemes was also considered. Performance comparison of different FACTS controllers was reviewed. The likely future direction of FACTS technology, especially in restructured power systems, was discussed as well. In addition, utility experience and major real-world installations and semiconductor technology development were summarized. A brief review of FACTS applications to optimal power flow and deregulated electricity market was presented. Kanojia and Chandrakar, (2009) did a comparative study on enhancement of damping of power system oscillation using STATCOM and Static Synchronous Series Compensator (SSSC). They equipped the generators used with a PSS. It was done in order to enhance both rotor angle and power system stability. On the other hand, Prabhakar *et al* (2010), studied damping power system oscillations by using STATCOM on the basis of locally measured variables with an objective that made it necessary to improve the STATCOM control strategy by introducing locally measurable signals obtained from constant resistive load located near the STATCOM, which reflect power system oscillations at any point in the power system.

2.2 Power System Modelling

In general, power systems are modelled by a set of differential and algebraic equations (DAE),

$$\dot{X} = f(x, y, \lambda, \rho) \qquad (2.1)$$
$$0 = g(x, y, \lambda, \rho)$$

Where $x \in \Re^n$ is a vector of state variables associated with the dynamic states of generators, loads, and other system controllers; $y \in \Re^j$ is a vector of algebraic variables associated with steady-state variables resulting from neglecting fast dynamics (e.g. some generating sources, most load voltage phasor magnitudes and angles); $\lambda \in \Re^l$ is a set of uncontrollable parameters, such as variations in active and reactive power of loads (parameters that drive the system to collapse); and $\rho \in \Re^k$ is a set of controllable parameters such as tap and AVR settings, or controller reference voltages.

Based on equation (2.1), we may define the collapse point under the influence of some certain assumptions, as the equilibrium point where the related system Jacobian is singular, i.e., the point $(x_o, y_o, \lambda_o, \rho_o)$ where:

$$\begin{bmatrix} f(x_*, y_*, \lambda_*, \rho_*) \\ g(x_*, y_*, \lambda_*, \rho_*) \end{bmatrix} = F(z_*, \lambda_*, \rho_*) = 0 \qquad (2.2)$$

And its Jacobian has a zero eigenvalue (or zero singular value). Power system models are typically detected by monitoring the eigenvalues of matrix say A as the system parameters (λ, ρ) change (Nwohu, 2009).

2.3 Brief Overview of North-Central Nigerian Grid System

The rising demand of electricity in this country has resulted into building many power stations in different locations around the country. The power generated would have to be transmitted to different load centres in the country through the national grid. The bulk of electric energy is transmitted either by the 330kV transmission lines or 132kV transmission lines across the country. But the description and analysis of the North-Central Nigerian grid system will be limited to the 330kV transmission lines in this research work. The 330 kV lines are constructed to have double circuits though on separate towers for reliability and larger power evacuation. It is only the extension of the 330kV Shiroro substation to Abuja that has a single tower with double circuits.

North central network is a subsection of the Nigeria national 330KV lines power grid composed of Niger, Kebbi, Kaduna and Abuja (FCT). This network has three generating stations located at Shiroro, Jebba and Kainji all in Niger state. Also the network has five load centres. Figure 2.1 depicts one line diagram of the 330KV North-Central Nigeria network.

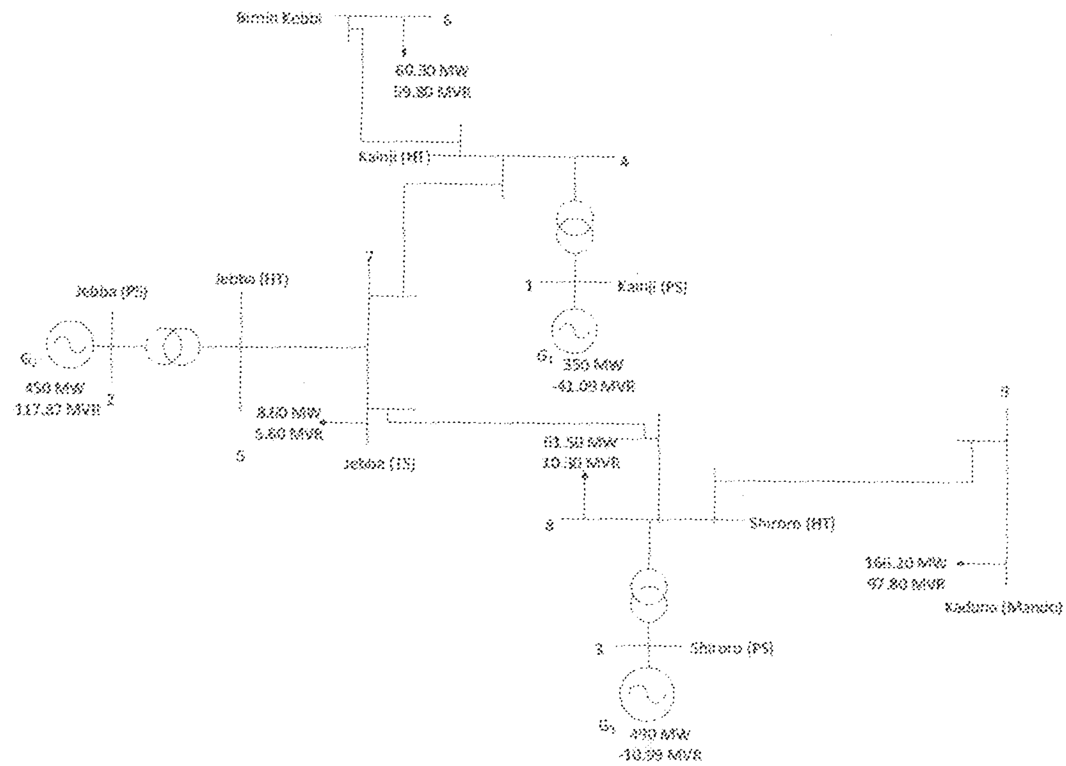


Figure 2.1: One line diagram representation of 330KV North-Central Nigeria power grid.

Table 2.1 depicts the capacities of the Three generation stations in the case study network.

Table 2.1: The Electricity Power Stations in North-Central of Nigeria Grid (PHCN)

S/n	Power Stations	Year Commissioned	Type/Fuel used	Installed Capacity (MW)	No. of Turbines	% in National Grid	Available capacity as at 30/12/2003 (MW)
1	Kainji	1968	Hydro	760	8	12	410
2	Jebba	1986	Hydro	578	6	9	540
3	Shiroro	1990	Hydro	600	4	10	600

Source: PHCN [formerly called, NEPA] NEWS bulletin (2004).

The choice of location of some of these generating stations was obviously due to the existence of natural falls at their various locations, like Kainji, Jebba and Shiroro. With the existence of all these generating stations, all the "electricity" produced are interconnected together and transmitted to various load centres.

The North-Central Nigerian network is presently modelled as 9 buses fed by 3 hydro generating stations. Table 2.1 gives the capacity of the three stations as at 2004. In this work, PSAT 1.3.4 is used in running the load flow of the North-Central Nigerian Grid network. The transmission line parameters of the case study are given in Table 2.2 below:

Table 2.2: Transmission Line Data in p.u. on 100 MVA base of North-Central Nigerian Grid System (330kV)

LINE NO.	FROM BUS (i)	TO BUS (j)	LINE PARAMETERS (P.U.) R	X	B	TAP	PHASE
1	4	6	0.01218	0.09163	1.0269		
2	7	4	0.00159	0.01197	0.5366		
3	7	8	0.0048	0.03606	1.6165		
4	8	9	0.00189	0.01419	0.636		
5	5	7	0.00016	0.00118	0.053		
6	1	4	0	0.01351	0	1	0
7	2	5	0	0.01932	0	1	0
8	3	8	0	0.01638	0	1	0

Source: PHCN [NEPA] (Shiroro Transmission Station).

2.4 FACTS devices

The Flexible AC Transmission System (FACTS) is a concept that involves the application of high power electronic controllers in AC transmission networks which enable fast and reliable control of power flows and voltages. FACTS do not indicate a particular controller but a host of controllers which a system planner can choose, based on cost benefit analysis. The main objectives of FACTS controllers are as follows:

- Regulation of power flows in prescribed transmission routes.
- Secure loading of lines near their thermal limits.
- Prevention of cascading outages by contributing to emergency control.

- Damping of oscillations which can threaten security or limit the usable line capacity.
- Prevention of voltage collapse by providing reactive power support.

The active and reactive power flows in a transmission line can be precisely controlled by injecting a series voltage phasor with desirable magnitude and phase angle, leading to an improvement in system stability and reliability. Also, reduction in operating cost and new transmission line investment cost is an added advantage. It is also possible to force power flow through a specific line and regulate the unwanted loop and parallel power flows by varying the impedance of the line. FACTS controllers have a significant impact on damping power system oscillations and compensating dynamic reactive power.

2.5 Classification of FACTS devices

FACTS can be divided into four categories based on their connection in the network.

i. **Shunt Controllers**: These types of controllers are connected in shunt with the transmission line. They can be of variable impedance, variable source or a combination of both. SVC and STATCOM are two commonly used shunt FACTS controllers. The basic principle of all shunt FACTS controllers is that they inject current into the system at the point of connection. The fundamental difference in operation principle between a SVC and a STATCOM is that STATCOM is with a converter based Var generation. It functions as a shunt connected synchronous voltage source whereas SVC is with thyristor controlled reactors and thyristor switched capacitors. It also functions as a shunt connected controlled reactive admittance. The shunt controller injects or absorbs reactive power into or from the bus as long as the current injected by the controller remains in quadrature and in phase with the bus voltage. Any other phase relation will involve the handling of real power as well. STATCOM has the ability to exchange real power from the system if it is equipped with the energy storage element at its DC terminal (Griffo, 2006).

ii. **Series Controllers**: These types of controllers are connected in series with the transmission line. They can be of switched impedance or power electronics based variable source. TCSC, TCPAR and SSSC are among the series FACTS controllers. The basic principle of all series FACTS controllers is that they inject voltage in series with the line. In switched impedance controller, the variable impedance when multiplied with the current flow through the line represents an injected voltage in the line. The series controller injects or absorbs reactive power as long as the current injected by the controller remains in phase and in quadrature with the bus voltage. Any other phase relation will involve the handling of real power as well (Hingorani, 2000).

iii. **Combined Series-Series Controller**: This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. Or it could be a unified controller, in which series controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. The real power transfer capability of the unified series-series controller, referred to as Interline Power Flow Controller (IPFC), makes it possible to balance both the real and reactive power flow in the lines thereby maximize the utilization of the transmission system. Also, the term 'unified' used here means that the dc terminals of all controller converters are all connected together for real power transfer (Hingorani, 2000).

iv. **Combined Series-Shunt Controllers:** They usually are controlled in a unified manner. The Unified Power Flow Controller (UPFC) is one such controller. It is the most versatile and powerful device among the FACTS device family. It can operate as a shunt and/or series compensator, a power flow controller, a voltage regulator or a phase shifter depending on its main control strategy. In this way simultaneous control on bus voltage and transmission line power flow can be realized. It can also exchange real power between a bus and a transmission line through the common DC link, provided that the shunt and series parts of the UPFC are unified (Hingorani, 2000).

2.6 STATCOM

A STATCOM is built based on voltage source converter (VSC) technology, meaning that the FACTS device is built up with power electronics having turn-off capabilities. In the other words, it is a gate turn-off type thyristor (GTO) based Static Var Compensator (Klaus and O'leary, 2000). There are many possible configurations of voltage source converters and consequently many different configurations of STATCOMs and distribution STATCOMs. The term often applied to voltage source converter configurations are (Woodford, 2004):

- Two level
- Multi-level
- Six and twelve pulse
- Pulse width modulation (PWM)

In order to have full understanding of how to simulate, control and apply STATCOMs, a simpler configuration of voltage sourced converter will be studied. Any voltage sourced converter such as STATCOM with PWM has two independent parameters it can control. These are:

I. The magnitude of the fundamental frequency component of the ac voltage on the converter side of the converter transformer or reactor.

II. The phase angle of the fundamental frequency component of the ac voltage on the converter side of the converter transformer or reactor.

The basic structure of a STATCOM with PWM-based voltage controls is depicted in Figure 2.1 (Cañizares, 2000). Eliminating the dc voltage control loop on this Figure would yield the basic block diagram of a controller with typical phase angle controls. Assuming balanced fundamental frequency voltages, the controller can be accurately represented in transient stability studies using the basic model shown in Figure 2.2 (Nwohu, 2009). The per-unit differential-algebraic equations corresponding to this model are:

$$\begin{bmatrix} \dot{X}_c \\ \dot{\alpha} \\ \dot{m} \end{bmatrix} = f(x_c, \alpha, m, V, V_{dc}, V_{ref}, V_{dcref}) \qquad (2.3)$$

$$\dot{V}_{dc} = \frac{VI}{CV_{dc}}\cos(\delta-\theta) - \frac{1}{R_c C}V_{dc} - \frac{RI^2}{CV_{dc}} \qquad (2.4)$$

$$0 = \begin{bmatrix} P - VI\cos(\delta-\theta) \\ Q - VI\cos(\delta-\theta) \\ P - V^2G + KV_{dc}VG\cos(\delta-\alpha) + KV_{dc}VB\sin(\delta-\alpha) \\ Q + V^2B + KV_{dc}VB\cos(\delta-\alpha) + KV_{dc}VG\sin(\delta-\alpha) \end{bmatrix} = g(\alpha, K, V, V_{dc}, \delta, I, \theta, P, Q) \qquad (2.5)$$

Were the admittance $G+jB=(R+jX)^{-1}$ is used to represent the transformer impedance, any ac series filters, and the 'switching inertia' of the inverter due to its high frequency switching. The constant $K=\sqrt{\frac{3}{8}}m$, is directly proportional to the pulse width modulation index m and x_c represents internal control system variables.

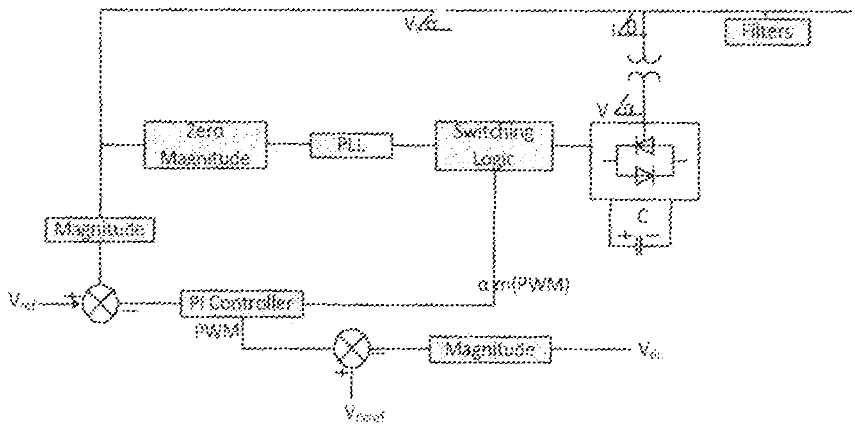


Figure 2.2: Block diagram of a STATCOM with PWM voltage control (Canizares, *et al*, 1998)

The ac bus voltage magnitude is controlled through the modulation index m, since this has a direct effect on the side ac side voltage source inverter (VSI) voltage magnitude. But the phase angle, α which basically determines the active power P flowing into the controller charges and discharges the capacitor. The controller limits are defined in terms of the controller current limits which are directly related to the switching device current limits, as these are basic limiting factor in VSI-based controllers. In simulations, these limits can be directly defined in terms of the maximum and minimum converter currents, $I_{max}(I_{Lmax})$ and $I_{min}(I_{Cmax})$ respectively. A graphical representation of the controller droop is shown in the V-I characteristic curve of the STATCOM with the controller limits being defined by its ac current limits, see fig 2.4 (Technical report, IEEE 1996).

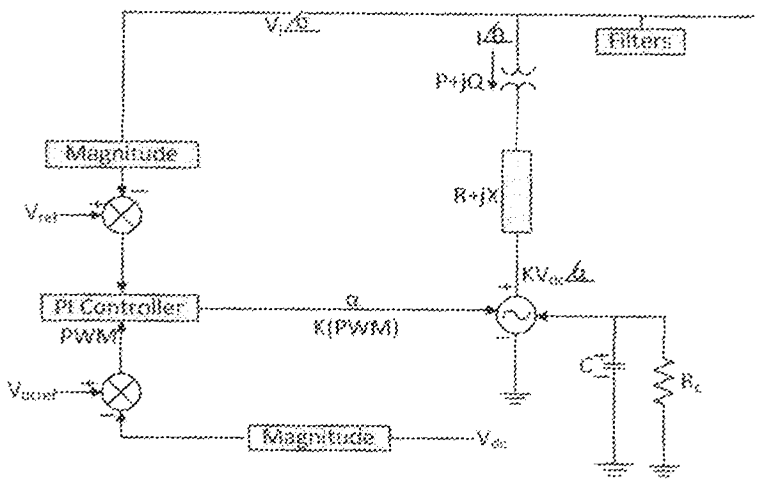


Figure 2.3: Transient stability model of a STATCOM with PWM voltage control

However, the steady state model can be obtained from equation (2.3) by replacing the differential equations with the steady state equations of the dc voltage and the voltage control characteristics of the STATCOM, thus,

$$0 = \begin{bmatrix} V - V_{ref} + X_{SL} I \\ V_{dc} - V_{dcref} \\ P - \dfrac{V_{dc}^2}{R_c} - RI^2 \\ g(\alpha, K, V, V_{dc}, \delta, I, \theta, P, Q) \end{bmatrix} \tag{2.6}$$

So, a phase control technique can be readily modelled by simply replacing the dc voltage control equation in (2.6) with an equation for k i.e. $0 = [K - 0.9]$. In this case the dc voltage change as α change, hence charging and discharging the capacitor to control the inverter voltage magnitude.

The voltage sourced converter technology using power transistor (IGBTs) operates at a frequency in the KHz range, giving possibilities to implement advanced algorithms in the control system. A comparison with Static Var compensator yields that the capacitors and reactors are replaced with intelligent switching of semiconductors and can generate full capacitive output at low voltage (Allen, *et al*, 2003). By connecting DC capacitors on one side of the converter, the STATCOM is able to vary its output with respect to magnitude, frequency and phase angle, thus providing voltage and transient stability.

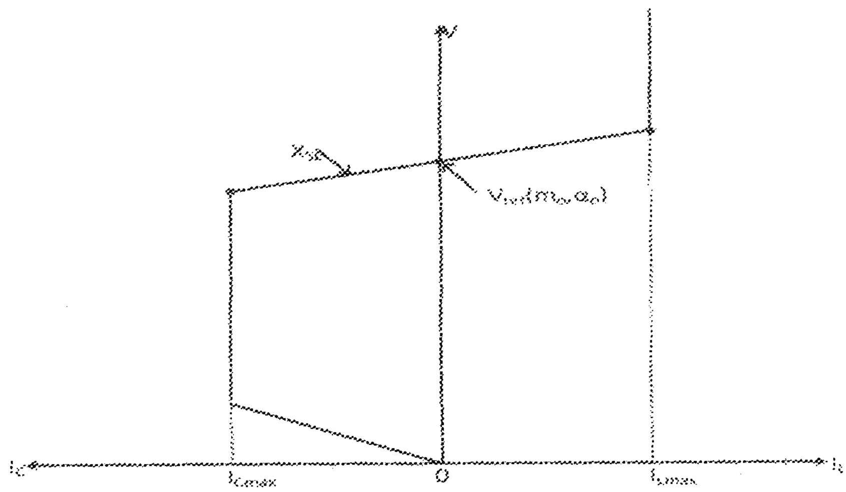


Figure 2.4: Typical Steady state V-I characteristics of a STATCOM

2.6.1 STATCOM V-I Characteristic

Modes of the STATCOM operation:

1) Voltage regulation mode

2) VAR control mode

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Introduction

This project as part of the Nigerian Grid System will be implemented using the Power flow analysis within the environment of PSAT version 1.3.4 software. The North-Central region of the Nigeria 330KV grid was modelled and simulated. The optimal placement of STATCOM was realized by use of GA, and the best location for PSS was determined using damping coefficient and eigenvalues analysis. Finally, the modified IEEE 9-bus and 14-bus were used as yardstick in establishing the optimal placement of STATCOM in this section.

3.2 Optimal Placement of STATCOM using Genetic Algorithm

The objective function considered is maximization of losses.

Losses in electric power is defined as: $LOSSES = |I^*|^2 R$

$$LOSSES = |I^*|^2 R \quad (3.1)$$

$$\left.\begin{aligned} |I^*| &= \frac{S}{|V|} \\ LOSSES &= R\left(\frac{S}{|V|}\right)^2 \\ |S| &= |P| + |Q| \\ S &= \sqrt{P^2 + Q^2} \\ LOSSES &= R\frac{\left(P^2 + Q^2\right)}{|V|^2} \end{aligned}\right\} \quad (3.2)$$

Generalizing, $$LOSSES = R_i \frac{(P_i^2 + Q_i^2)}{|V_i|^2} \quad (3.3)$$

Where R_i = sum of the resistances of all lines associated to bus i.

P_i = active power of bus i.

Q_i = reactive power of bus i.

V_i = voltage profile of bus i.

The idea is to locate the bus that has the highest amount of losses which could be considered as the optimal point for placing the device STATCOM.

3.2.1 Genetic Algorithm (GA)

No. of Generation= the total number of buses.

$$\max f(V_i) = R_i \frac{(P_i^2 + Q_i^2)}{|V_i|^2} \quad (3.4)$$

$$0.98 \le V_i \le 1.00$$

- **Encoding**

We need to encode decision variables into binary strings known as chromosomes or genotype. Let the domain of variable x_j be $[a_j, b_j]$ and the required precision is four decimal points. The required bits m_j is calculated as

$$2^{m_j - 1} < (b_j - a_j) \times 10^4 \le 2^{m_j} - 1 \quad (3.5)$$

The required bits for x_1 is

$$\left(1.0-\left(0.98\right)\right)\times 10000 = 200$$

From the result obtained above for the required bits, we can now have a range of bits,

$2^7 < 200 \leq 2^8$

Therefore, we assume *taking the lower limit,* m= 7 *bits*

- **Decoding**

The corresponding values for variables x_1 (phenotype) are as follows:

The *mapping from binary string* to a real number **(decoding)** for variable x_j is

$$x_j = a_j + decimal(binary \text{ string})_j \times \frac{b_j - a_j}{2^{m_j} - 1} \qquad (3.6)$$

- **Initial Population**

Initial population is randomly generated and let say

$$r = a + (b - a).* rand(Gen, n) \qquad (3.7)$$

- **Evaluation**

The process of evaluating the fitness of a chromosome is stated below:

- **Procedure**

1. Convert the chromosome's genotype to its phenotype, i.e. converting binary string into relative real values, $x^k = (x_1^k, x_2^k)$, k=1, ... , pop size.
2. Evaluate the objective function $f\left(x^k\right)$.
3. Convert the value of objective function into fitness. For maximization problem, the fitness is simply equal to the objective function $eval(v_k)$, k = 1... pop size.

Thus the fitness function values of the chromosomes.

➢ **Selection**

A roulette wheel approach is adopted as the selection procedure. A new population is selected with respect to probability distribution based on fitness values. The roulette wheel is constructed as follows:

1. Calculate the fitness value $eval(v_k)$ for each chromosome v_k:

   $eval(v_k) = f(k)$, $k = 1, \ldots, pop\_size$

2. Calculate the total fitness for the population:

$$F = \sum_{k=1}^{pop\_size} eval(v_k) \tag{3.9}$$

3. Calculate selection probability p_k for each chromosome v_k:

$$p_k = \frac{eval(v_k)}{F} \tag{3.10}$$

4. Calculate cumulative probability q_k for each chromosome v_k:

$$q_k = \sum_{j=1}^{k} p_j \tag{3.11}$$

- **Procedure**

1. Generate a random number r from the range [0, 1].
2. If $r \le q_1$, then select the first chromosome v_1; otherwise, select the kth chromosome v_k such that $q_{k-1} < r < q_k$.

   The total fitness F of the population is

$$F = \sum_{k=1}^{pop\_size} eval(v_k)$$

   The probability of a selection p_k for each chromosome v_k is calculated using

$$p_k = \frac{eval(v_k)}{F}$$

The cumulative probability q_k for each chromosome v_k is also obtained using

$$q_k = \sum_{j=1}^{k} p_j$$

Now we spin the roulette wheel n times, and each time we select a single chromosome for a new population.

- **Crossover**

One-cut-point method is used which randomly select one cut-point and exchanges the right parts of two parents to generate offspring. Not all chromosomes undergo crossover. Example the probability of crossover set as pc = 0.25, means only 25% of chromosomes in the population undergo crossover. Generate n (population size) random number [0, 1]

- **Mutation**

Mutation alters one or more genes with a probability equal to the mutation rate. Let say the mutation rate pm = 0.01, so we expect 1% of the genes in the population will mutate. In this case we have 72 genes; therefore we expect 0.72 mutations per generation. Every gene (bit) has an equal chance to be mutated. Therefore generate 72 random numbers in the range [0, 1] (Jamaluddin, 2009).

$$genes = gen. \times bits. \qquad (3.12)$$

3.3 Mathematical Model of a STATCOM on a single machine Infinite Bus network.

A single-machine infinite-bus power system is shown by Figure 3.1, where a shunt-connected device STATCOM is installed at bus bars. $\bar{V}_c$, at the ac terminal of the device is controlled by the modulation ratio m and the phase ψ respectively so as to regulate the exchange of active and reactive power between the device and the rest of the power system.

The installed device can have a fuel cell or photovoltaic power generation or energy storage unit integrated into the power grid, which will be connected to the device through the dc capacitor by a dc-dc converter (Sedghisigarchi and Feliachi, 2004; Tan *et al.*, 2004; Arabi and Kundur, 2001). Hence the connection of the devices into the power system could have different impacts on power system oscillation stability.

The commonly-used dynamic equations of the generator for the study of power system oscillation stability are (Yu, 1983).

$$\left.\begin{aligned} \dot{\delta} &= \omega_s(\omega - 1) \\ \dot{\omega} &= \frac{1}{M}\left[P_m - P_t - D(\omega - 1)\right] \\ \dot{E}_q' &= \frac{1}{T_{d0}'}\left(-E_q + E_{fd}\right) \\ E_{fd} &= TE(s)\left(V_{ref} - V_t\right) \end{aligned}\right\} \quad (3.13)$$

$$\begin{aligned} &where: \\ &V_t = V_1 \\ &P_t = v_{1d} i_{pd} + v_{1q} i_{pq} = x_q i_{pq} i_{pd} + (E_q' - x_d' i_{1d}) i_{sq} \\ &= E_q' i_{1q} + (x_q - x_d') i_{1d} i_{1q} \\ &E_q = E_q' - (x_d - x_d') i_{1d} \\ &V_t = \sqrt{v_{td}^2 + v_{tq}^2} = \sqrt{(x_q i_{1sq})^2 + (E_q' - x_d' i_{1d})^2} \end{aligned}$$

$\dot{\delta}, \dot{\omega}, \dot{E}_q'$, are differential terms.

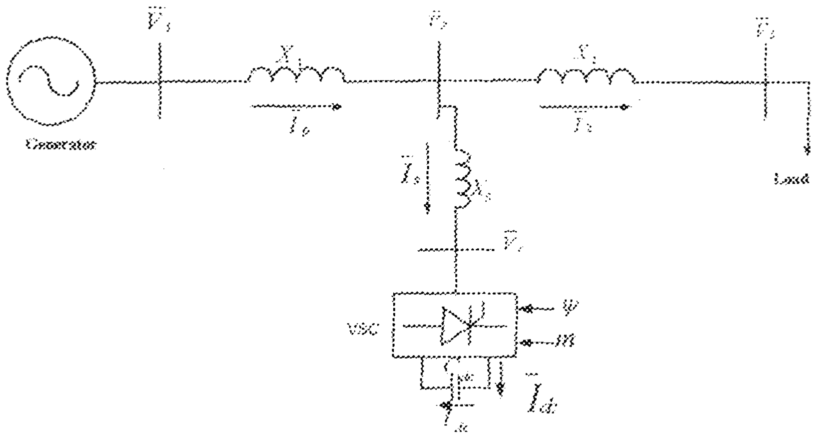


Figure 3.1: A power system embedded with a shunt-connected STATCOM device

From Figure 3.1 the following equations are deduced:

$$\left.\begin{aligned} \bar{V}_1 &= jx_1\bar{I}_p + \bar{V}_s \\ \bar{V}_s &= jx_s\bar{I}_s + \bar{V}_c \\ \bar{V}_s - \bar{V}_2 &= jx_2\left(\bar{I}_p - \bar{I}_s\right) \end{aligned}\right\} \qquad (3.14)$$

Equations (3.14) now give

$$\left.\begin{aligned} jx_s\bar{I}_s + \bar{V}_c - \bar{V}_2 &= jx_2\left(\bar{I}_p - \bar{I}_s\right) \\ \bar{V}_1 &= jx_1\bar{I}_p + jx_2\left(\bar{I}_p - \bar{I}_s\right) + \bar{V}_2 \end{aligned}\right\} \qquad (3.15)$$

In d-q coordinate of the generator, as shown by Figure 3.2, from Equation (3.15) it can be obtained that

$$\left.\begin{aligned} \begin{bmatrix} x_2 & -x_s - x_2 \\ x_q^{'} + x_1 + x_2 & -x_2 \end{bmatrix}\begin{bmatrix} i_{pq} \\ i_{sq} \end{bmatrix} &= \begin{bmatrix} -V_c\cos\psi + V_2\sin\delta \\ V_2\sin\delta \end{bmatrix} \\ \begin{bmatrix} x_2 & -x_s - x_2 \\ x_d^{'} + x_1 + x_2 & -x_2 \end{bmatrix}\begin{bmatrix} i_{pd} \\ i_{sd} \end{bmatrix} &= \begin{bmatrix} V_c\sin\psi - V_2\cos\delta \\ E_q^{'} - V_2\cos\delta \end{bmatrix} \end{aligned}\right\} \qquad (3.16)$$

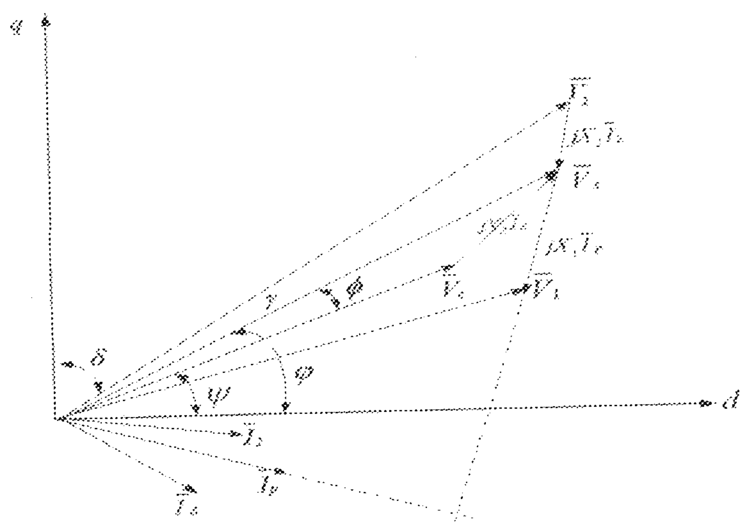


Figure 3.2: Phasor diagram of power system of Figure 3.1

From phasor diagram of Figure 3.2, in the *d-q* coordinate of the generator the ac voltage at the VSC terminal is

$$\overline{V}_s = mkV_{dc}\left(\cos\psi - j\sin\psi\right) = mkV_{dc}\angle\psi \qquad (3.17)$$

where *k* is the converter ratio dependent of VSC structure and V_{dc} is the dc voltage across the capacitor C_{dc} in Figure 3.1. Active power received by the STATCOM from the power system is

$$V_{dc}I_{dc} = i_{sd}v_{cd} + i_{sq}v_{cq} = i_{sd}mkV_{dc}\cos\psi + i_{sq}mkV_{dc}\sin\psi \qquad (3.18)$$

Hence

$$I_{dc} = i_{sd}mk\cos\psi + i_{sq}mk\sin\psi \qquad (3.19)$$

STATCOM dynamic equation is

$$\left.\begin{aligned} \dot{V}_{dc} &= \frac{1}{C_{dc}}I_{dc} = \frac{1}{C_{dc}}I_{dc} \\ \dot{V}_{dc} &= \frac{1}{C_{dc}}\left(i_{sd}mk\cos\psi + i_{sq}mk\sin\psi\right) \end{aligned}\right\} \qquad (3.20)$$

STATCOM ac and dc voltage control functions are

$$m = m_{*} + K_{ac}(s)\left(V_s - V_{sref}\right) \tag{3.21}$$

$$\begin{aligned} \phi &= \phi_{*} + K_{dc}(s)\left(V_{dc} - V_{dcref}\right) \\ \psi &= \psi_{*} + \phi \end{aligned} \tag{3.22}$$

where $K_{ac}(s)$ and $K_{dc}(s)$ are the transfer functions of STATCOM ac and dc voltage controller respectively. Eq.(3.13), (3.16) and (3.20)-(3.22) give the mathematical model of the power system with the embedded STATCOM, including the mathematical description of its dynamic and control function by Eq.(3.21) and (3.22).

For the analysis in the following section, an explicit mathematical description of active power delivered along the transmission line from the generator in Figure 3.1 needs to be established. This is presented as follows

$$\overline{V}_s = \frac{jx_2}{1+\frac{x_2}{x_s}}\overline{I}_p + \frac{x_2}{x_s\left(1+\frac{x_2}{x_s}\right)}\overline{V}_c + \frac{\overline{V}_2}{1+\frac{x_2}{x_s}} \tag{3.23}$$

That gives

$$\overline{V}_1 = jx_1\overline{I}_p + \overline{V}_s = j\left(x_1 + \frac{x_s x_2}{x_s + x_2}\right)\overline{I}_p + \frac{x_2}{x_s + x_2}\overline{V}_c + \frac{x_s}{x_s + x_2}\overline{V}_2 = jx\overline{I}_p + \overline{V}_a \tag{3.24}$$

where

$$x = \left(x_1 + \frac{x_s x_2}{x_s + x_2}\right)$$

$$\overline{V}_a = \frac{x_2}{x_s + x_2}\overline{V}_c + \frac{x_s}{x_s + x_2}\overline{V}_2 = a\overline{V}_c + b\overline{V}_2$$

For a single-machine infinite-bus power system without the STATCOM the following voltage equation holds

$$\overline{V}_1 = jx_l\overline{I}_P + \overline{V} \tag{3.25}$$

Where, x_l is the equivalent reactance of the transmission line, $\overline{I}_P$ is the line current and $\overline{V}$ is the voltage at the infinite bus bar. Thus the active power delivered along the transmission line is

$$P_1 = \frac{E_q^{'}V}{x_{d\Sigma}^{'}}\sin\delta - \frac{V^2\left(x_q - x_d^{'}\right)}{2x_{d\Sigma}^{'}x_{q\Sigma}}\sin 2\delta \tag{3.26a}$$

where, δ is the angle (load angle) between $E_q^{'}$ (q axis of the generator) and $\overline{V}$ and

$$\begin{aligned} x_{d\Sigma}^{'} &= x_l + x_d^{'} \\ x_{q\Sigma} &= x_l + x_q \end{aligned} \tag{3.26b}$$

Comparing Eq.(3.24) and (3.25) it can be seen that the power system with the STATCOM of Figure 3.1 is electrically equivalent to a power system without the STATCOM with an equivalent line reactance to be x and voltage at the infinite bus bar to be $\overline{V}_a$. Hence by replacing x_l and V in Equation (3.26) by x and V_a respectively, and therefore the active power delivered along the transmission line in the power system of Figure 3.1 can be deduced, thus

$$P_1 = \frac{E_q^{'}V_a}{x_{d\Sigma}^{'}}\sin\delta^{'} - \frac{V^2\left(x_q - x_d^{'}\right)}{2x_{d\Sigma}^{'}x_{q\Sigma}}\sin 2\delta^{'} \tag{3.27a}$$

where, $\delta^{'}$ is the angle between $E_q^{'}$ and $\overline{V}_a$ and

$$\left.\begin{aligned} x_{d\Sigma}^{'} &= x + x_d^{'} \\ x_{q\Sigma} &= x + x_q \end{aligned}\right\} \tag{3.27a}$$

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Introduction

The results obtained on the performance of power system with the placement of STATCOM and PSS in the North-Central zone of the 330KV Nigeria grid system are shown in the tables below. The installation of STATCOM and PSS, have been studied for the optimal location decided by G.A. and eigenvalues analysis respectively. Also, modified IEEE 9-bus and 14-bus systems were simulated and shown in the tables to confirm the G.A.'s decision for the optimal placement of the STATCOM on any other system. The performances of the network studied with and without STATCOM/PSS are also presented graphically in this chapter. The results obtained were later discussed here.

4.2 Results

The following results were obtained after optimization and simulations:

Table 4.1 shows the results obtained after the optimization of the 330KV North-Central network using G.A.

Table 4.1: Optimization result with GA Based generated voltages

BUS no.(i)	R(t)	P(i)	Q(i)	V(i)	$P_{loss}(i)$
1	0	-6.313	0.1036	0.9951	0
2	0	4.5	-0.5172	0.9951	0
3	0	4.9	0.36975	0.9876	0
4	0.01377	0	0	0.9913	0
5	0.00016	0	0	0.9913	0
6	0.01218	0.603	0.598	0.9951	0.0089
7	0.00655	0.086	0.056	0.9876	0.0001
8	0.00669	0.615	0.103	0.9951	0.0026
9	0.00189	1.662	0.978	0.9951	0.0071

Table 4.2 shows the results obtained after the optimization of modified IEEE 9-bus using G.A.

Table 4.2. Optimization results of modified IEEE 9-bus

BUS no.(i)	R(t)	P(i)	Q(i)	V(i)	$P_{loss}(i)$
1	0	0.71641	0.27046	1.04	0
2	0	1.63	0.06654	1.025	0
3	0	0.85	-0.1086	1.025	0
4	0.027	0	0	1.0264	0
5	0.042	1.25	0.5	0.99605	0.07673
6	0.056	0.9	0.3	1.0093	0.049475
7	0.0405	0	0	1.0257	0
8	0.0204	1	0.35	1.0156	0.022201
9	0.0289	0	0	1.0317	0
10	0.034	0	0	1.0197	0

Table 4.3 shows the results obtained after the optimization of modified IEEE 14-bus using G.A.

Table 4.3: Optimization result of modified IEEE 14-bus.

BUS no.(i).	R(t)	P(i)	Q(i)	V(i)	$P_{loss}(i)$
1	0.07341	3.5203	-0.282	1.06	0.814855
2	0.18143	0.7038	1.1264	1.0472	0.291861
3	0.114	1.3188	0.86336	1.0048	0.280547
4	0.13847	0.6692	0.056	0.97662	0.065471
5	0.12549	0.1064	0.0224	0.98588	0.001526
6	0.18906	0.1568	0.54933	1.0606	0.05485
7	0	0	0	1.0218	0
8	0	0	0.33402	1.0822	0
9	0.15892	0.413	0.2324	0.99845	0.035801
10	0.11386	0.126	0.0812	0.99865	0.002565
11	0.17703	0.049	0.0252	1.0241	0.000512
12	0.34383	0.0854	0.0224	1.0366	0.002494
13	0.458	0.189	0.0812	1.0266	0.018389
14	0.29804	0.2086	0.07	0.98474	0.01488

Table 4.4 shows the Voltage magnitudes of the 330KV of the North-Central network, with and without STATCOM/PSS installed.

Table 4.4: Voltage magnitudes of the 330KV North-Central network

Bus no.(i)	Voltage without controller	Voltage with STATCOM	Voltage with PSS
1	1	1	1
2	1	1	1
3	1.04	1.04	1.04
4	1.0022	1.0028	1.0022
5	1.0137	1.014	1.0137
6	0.98386	0.98965	0.9839
7	1.0141	1.0144	1.0141
8	1.0371	1.0372	1.0371
9	1.0248	1.0249	1.0248

Table 4.5 shows the active and reactive power magnitudes of the 330KV North-Central network, with and without STATCOM/PSS installed.

Table 4.5: active and reactive power magnitude of the 330KV North-Central network

Bus no.(i)	Active Power Without controller	Active Power With STATCOM	Active Power With PSS	Reactive Power Without controller	Reactive Power With STATCOM	Reactive Power With PSS
1	-6.313	-6.3122	-6.313	0.1036	0.06433	0.1036
2	4.5	4.5	4.5	-0.5172	-0.5316	-0.5172
3	4.9	4.9	4.9	0.36975	0.36372	0.36975
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0.603	0.60408	0.603	0.598	0.5477	0.598
7	0.086	0.086	0.086	0.056	0.056	0.056
8	0.615	0.615	0.615	0.103	0.103	0.103
9	1.662	1.662	1.662	0.978	0.978	0.978

Table 4.6 shows the line flows and losses of the 330KV North-Central network of the Nigeria grid system without any controller installed.

Table 4.6: Line Flows and line losses of the 330KV North-Central network

			Without controller			
			Power		Losses	
Line no.(i)	From	To	P	Q	P	Q
1	4	6	0.6077	-0.3794	0.0047	-0.9774
2	7	4	6.9966	0.08152	0.07589	0.02591
3	7	8	-2.5859	-1.0208	0.03138	-1.4647
4	8	9	1.6677	0.34493	0.00572	-0.6331
5	5	7	4.5	-0.9136	0.00328	-0.0303
6	1	4	-6.313	0.1036	0	0.53858
7	2	5	4.5	-0.5172	0	0.3964
8	3	8	4.9	0.36975	0	0.36568

Table 4.7 shows the line flows and losses of the 330KV North-Central network of the Nigeria grid system with STATCOM installed.

Table 4.7: Line Flows and line losses of the case study network with STATCOM

			With STATCOM			
Line			Power		Losses	
No.(i)	Bus From	Bus To	P	Q	P	Q
1	4	6	0.60865	-0.4371	0.00456	-0.9848
2	7	4	6.9967	0.06186	0.07582	0.02498
3	7	8	-2.5859	-1.0158	0.03135	-1.4655
4	8	9	1.6677	0.34479	0.00572	-0.6332
5	5	7	4.5	-0.9283	0.00328	-0.0303
6	1	4	-6.3122	0.06433	0	0.53834
7	2	5	4.5	-0.5316	0	0.39669
8	3	8	4.9	0.36372	0	0.36562

Table 4.8 shows the eigenvalues parameters of the 330KV North-Central network of the Nigeria grid system without any controller installed.

Table 4.8: Eigenvalues analysis of the case study network without compensation

Most Associated States	Dominant Values	Frequency	Damping ratio
vm_Exc_1, vr1_Exc_1	-24.5645±12.523	1.9931	0.890907
omega_Syn_3, delta_Syn_3	-1.5741±11.0661	1.7612	0.140828
e1q_Syn_3, vr3_Exc_3	0.10235±9.2054	1.4651	-0.011118
e1q_Syn_1, vr3_Exc_2	-1.0636±7.2552	1.1547	0.145048
e1q_Syn_2, vf_Exc_1	1.0292±4.4907	0.71472	0.223393

Table 4.9 shows the eigenvalues parameters of the 330KV North-Central network of the Nigeria grid system with STATCOM installed.

Table 4.9: Eigenvalues analysis of the case study network with STATCOM

Most Associated States	Dominant Values	Frequency	Damping ratio
vm_Exc_1, vr1_Exc_1	-24.6081±12.4858	1.9872	0.891777
delta_Syn_3, omega_Syn_3	-1.4207±11.0422	1.7574	0.127609
e1q_Syn_3, vr3_Exc_3	-0.17106±8.9768	1.4287	0.019052
e1q_Syn_1, vr3_Exc_2	-1.1512±6.936	1.1039	0.163735
e1q_Syn_2, vf_Exc_1	-1.0267±4.4896	0.71455	0.222929

Table 4.10 shows the eigenvalues parameters of the 330KV North-Central network of the Nigeria grid system with PSS installed.

Table 4.10: Eigenvalues analysis of the case study network with PSS

Most Associated States	Dominant Values	Frequency	Damping ratio
vm_Exc_1, vr1_Exc_1	-24.5638±12.5229	1.9931	0.890904
omega_Syn_3, delta_Syn_3	-0.15279±12.2268	1.946	0.012495
e1q_Syn_1, e1q_Syn_3	-0.95944±8.4542	1.3455	0.112763
e1q_Syn_1, vr3_Exc_2	-0.93578±7.3188	1.1648	0.126827
e1q_Syn_2, vf_Exc_1	-1.0594±4.4797	0.71296	0.230141

Figure 4.1 represents the simulink model of the 330KV North-Central network of the Nigeria grid system without any controller installed.

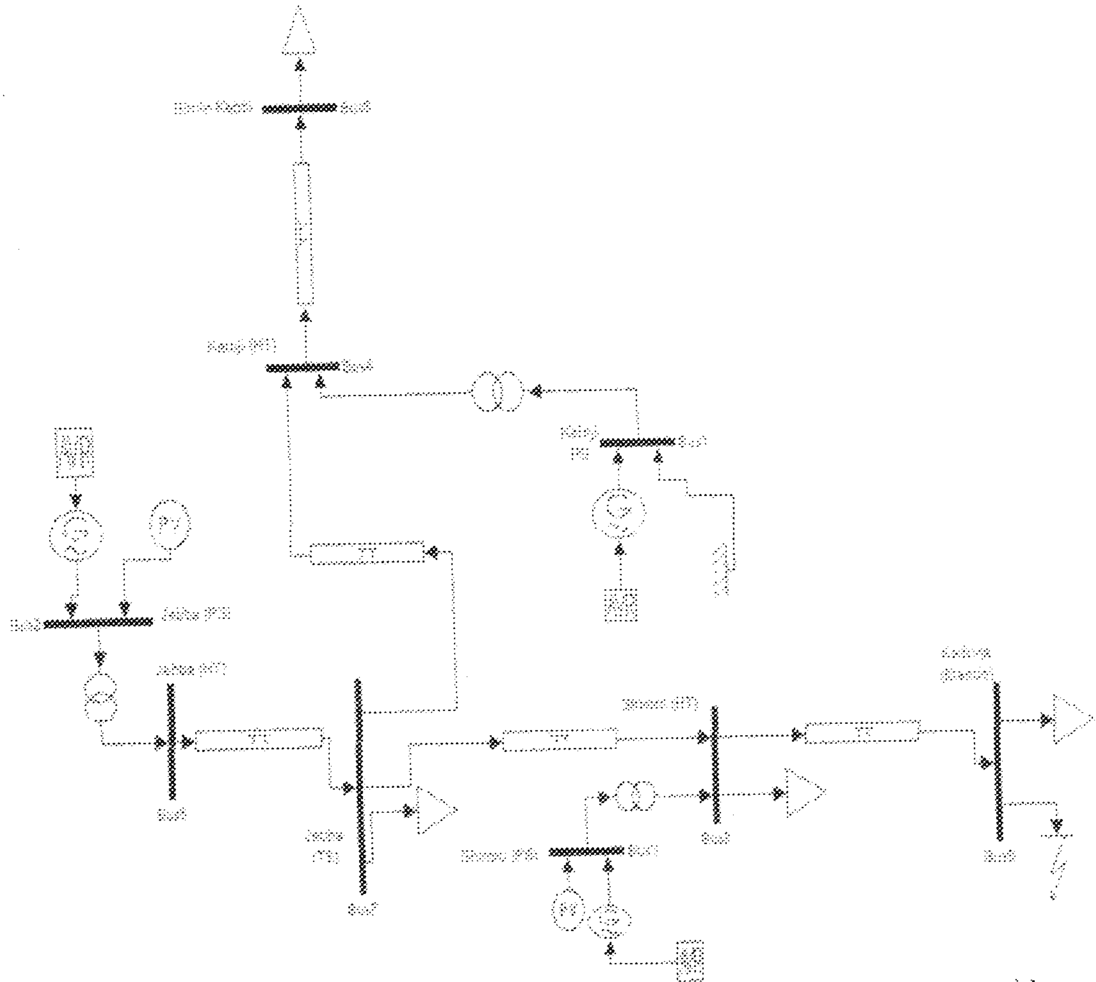


Figure 4.1: PSAT representation of 330KV North-Central Nigeria power grid.

Figure 4.2 represents the simulink model of the 330KV North-Central network of the Nigeria grid system with STATCOM installed.

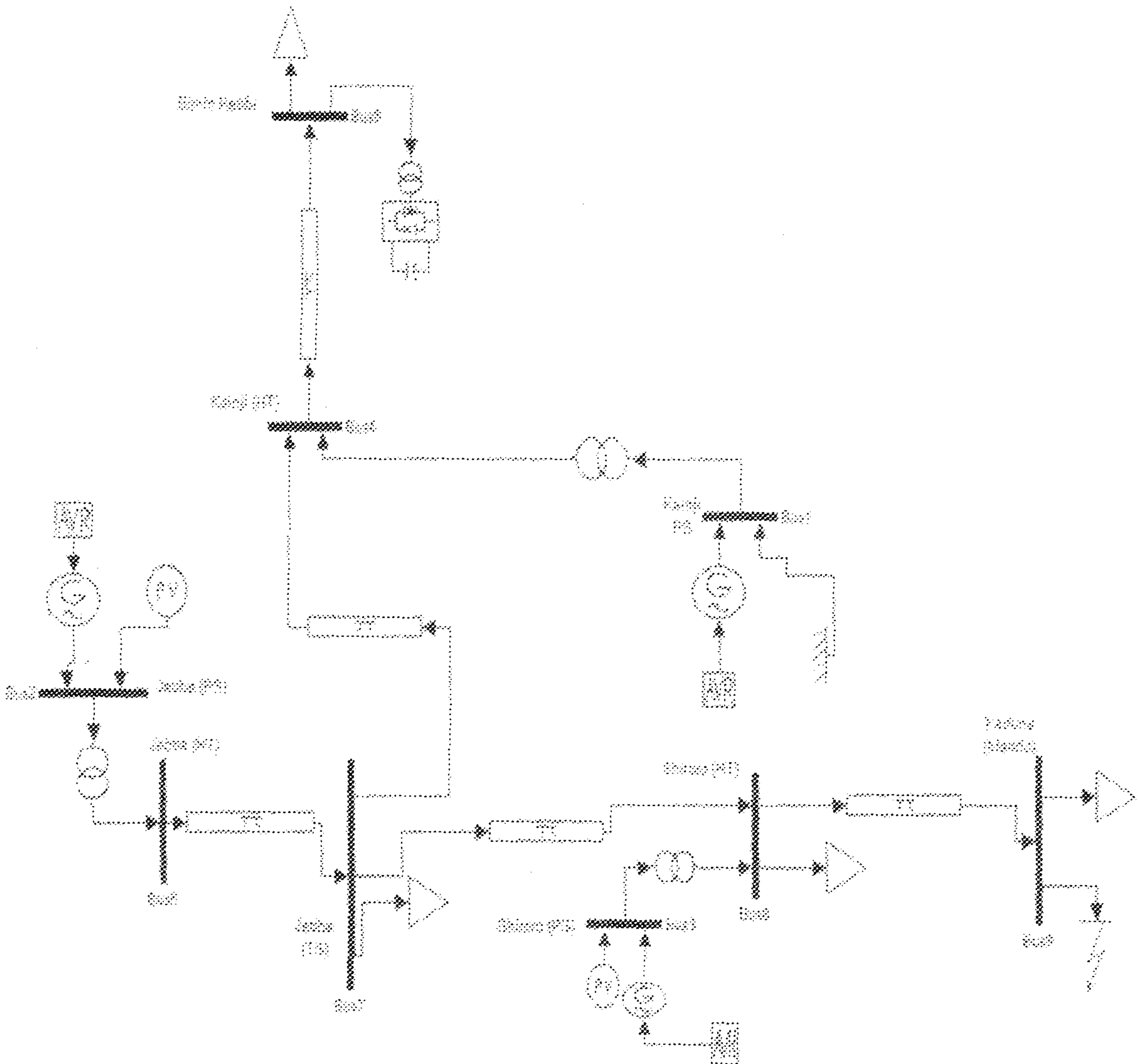


Figure 4.2: North-Central zone of the 330KV Nigeria grid system with STATCOM.

Figure 4.3 represents the simulink model of the 330KV North-Central network of the Nigeria grid system with PSS installed.

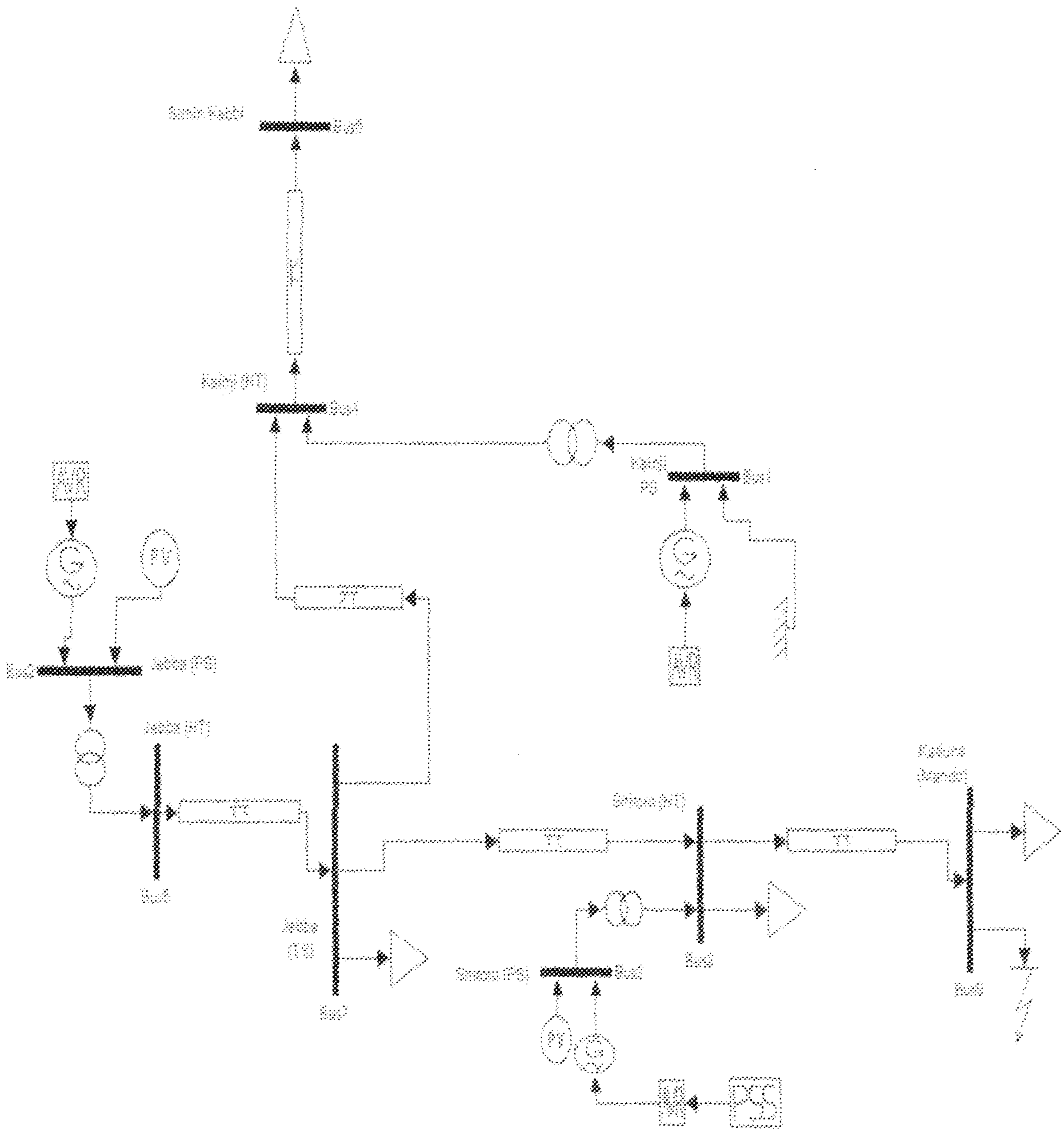


Figure 4.3: North-Central zone of the 330KV Nigeria grid system with PSS.

Figure 4.4 represents the simulink model of the modified IEEE 9-bus with STATCOM installed.

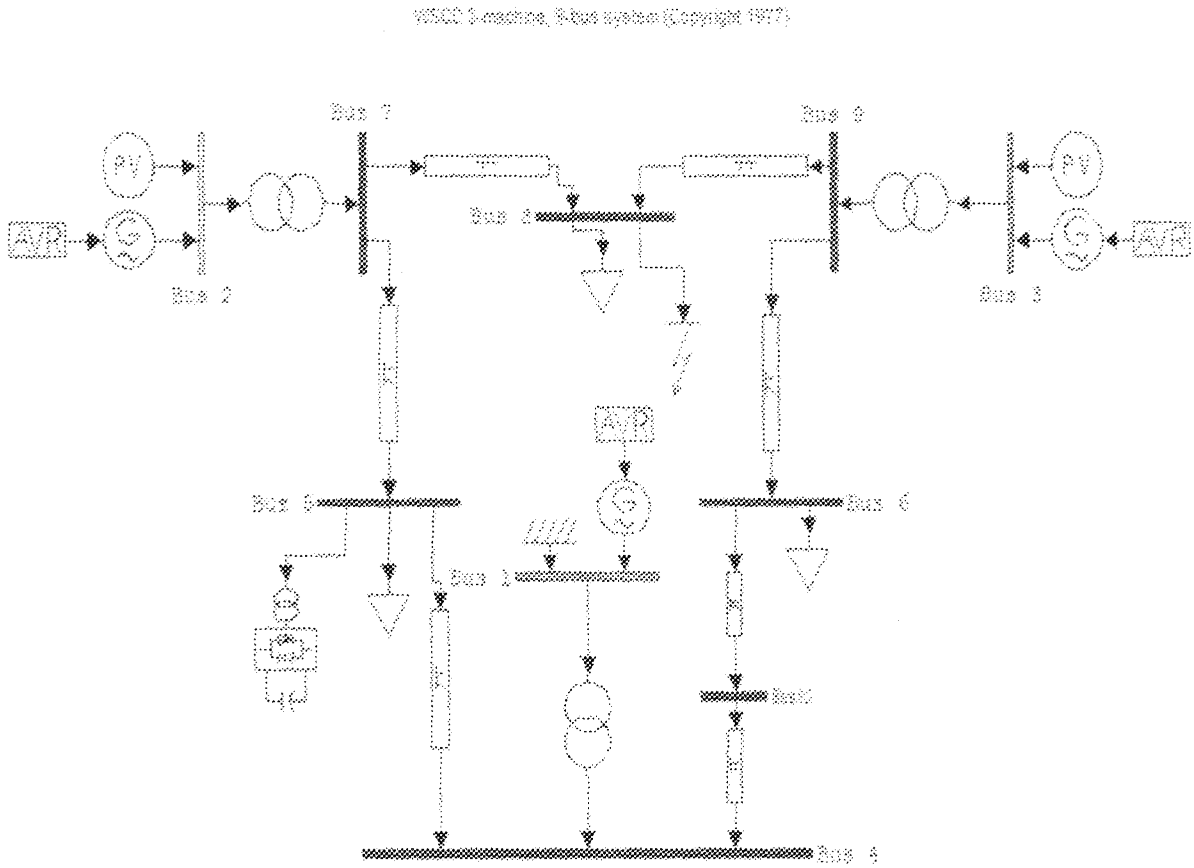


Figure 4.4: Modified IEEE 9-bus model with fault at bus 8 and STATCOM at bus 5.

Figure 4.5 represents the simulink model of the modified IEEE 14-bus with STATCOM installed.

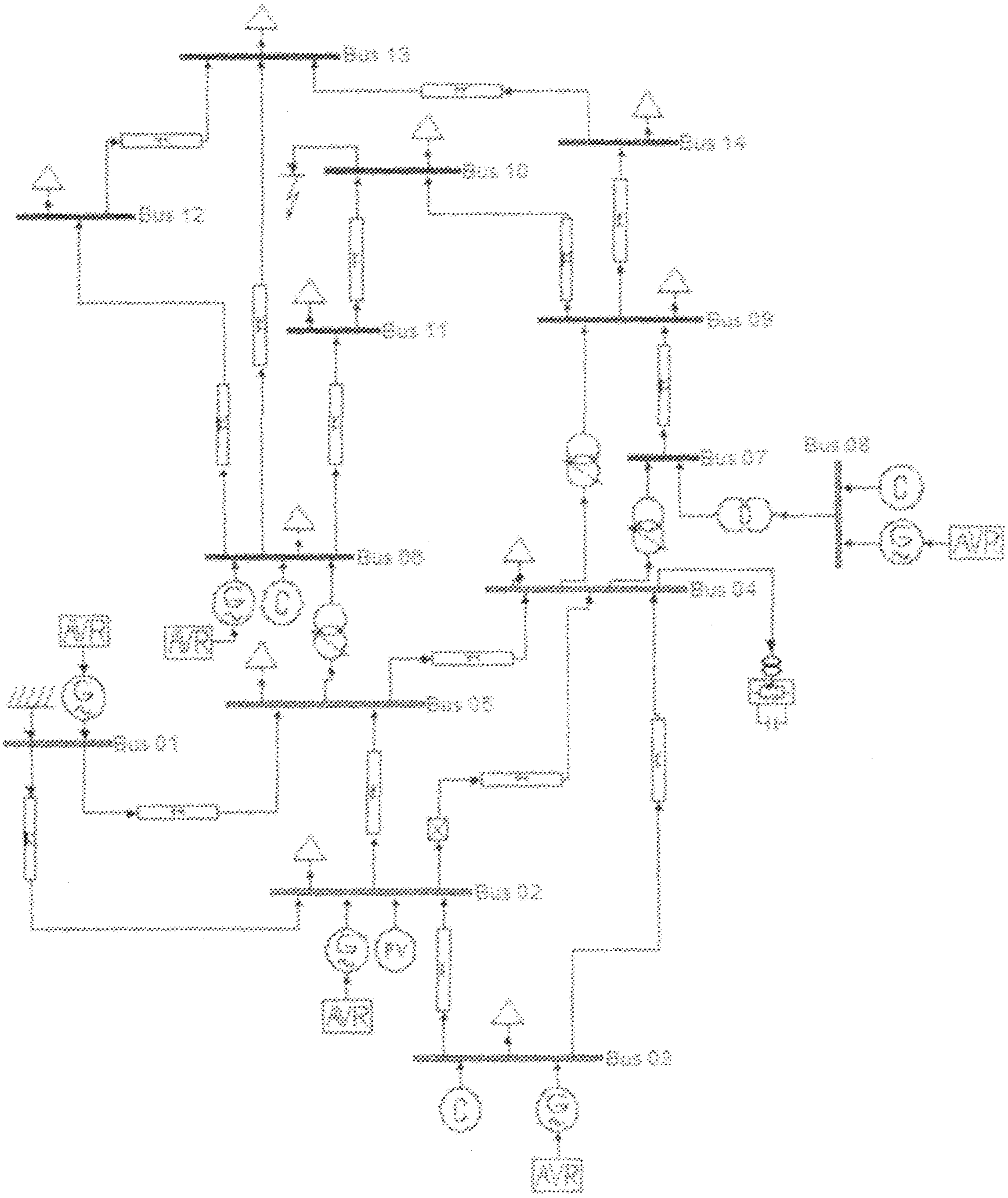


Figure 4.5: IEEE 14-bus model with fault at bus 10 and STATCOM at bus 4.

Figure 4.6 shows the graphical representation of Voltage profile oscillations of the case study network been damped: with and without STATCOM installed.

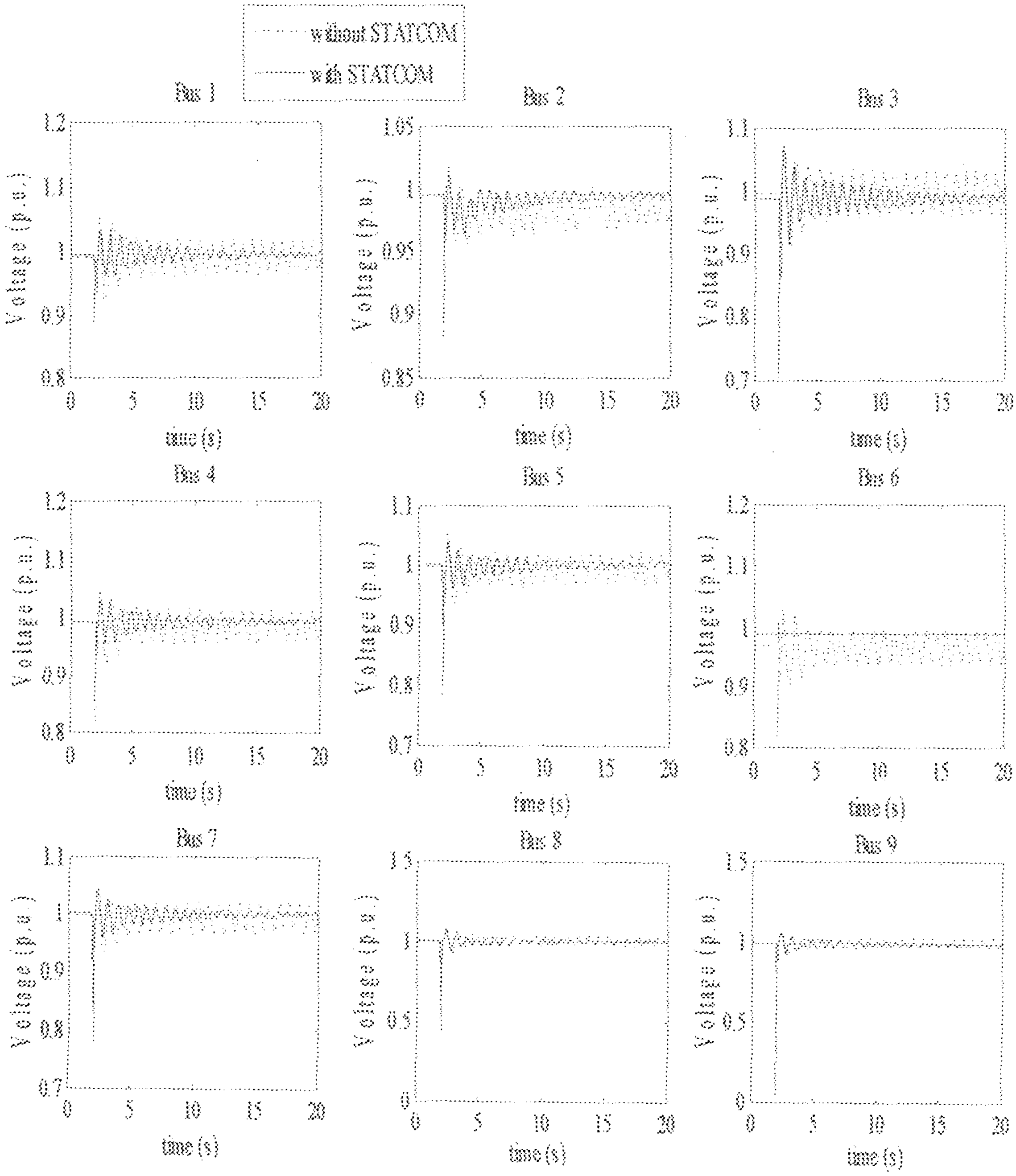


Figure 4.6: Voltage profile of the case study network, with and without STATCOM

4.3 Discussion of Results

This chapter also presents the discussion of results obtained on the performance evaluation of power systems with the placement of STATCOM and PSS. The installation of STATCOM has been studied for its optimal placement using GA. The performance of STATCOM has been studied on the case study, modified IEEE 9-bus and 14-bus. Also, the location of PSS was based on the dominant eigenvalues and their damping coefficients. The performance of PSS has been studied on the case study.

4.3.1 Optimization

A GA-based optimization in a MATLAB environment was performed on the case study to determine the optimal point of placing STATCOM. For optimal location of the device, the bus that returns the highest power losses is considered as most suitable point of locating the device. The optimization result as presented in Table 4.1 returned bus six as the most suitable candidate. Similarly, modified IEEE 9-bus and 14-bus networks were considered to ascertain the effectiveness of this technique for the optimal placement of STATCOM. IEEE 9-bus model after the optimization, it returned bus five, from Table 4.2 as the optimal point of locating the device while IEEE 14-bus returned bus four as the optimal point of locating the device from Table 4.3.

With the above analysis we can conclude that the objective function used and the GA based optimization technique were appropriate.

4.3.2 Simulations

The case study which is a 9-bus 330kV North-Central network of the Nigeria grid system with fault located at bus9 was simulated in PSAT environment. The PSAT models of the power network considered were as shown in Figure 4.1, Figure 4.2 and Figure 4.3. The load flow was of these networks were determined after running PSAT simulation with which results in Tables 4.4 to 4.7 were obtained. Eigenvalues analysis was later run and the results of interest (electromechanical oscillation components of frequency ranges 0.2-2.0Hz) were obtained as shown in Tables 4.8 to 4.10. The results are discussed below:

4.3.3.1 Voltage Profile

Table 4.4 shows the voltage magnitudes of the studied network obtained after the power flow simulations. The voltage magnitudes were however, improved with STATCOM optimally placed. There were no changes between the network without a controller and when PSS was placed on the network. We can conclude that STATCOM improves voltage profile where PSS does not.

Figure 4.6 shows how the electromechanical oscillations were damped on all the buses and there was voltage improvement on bus six. Figure 4.9 shows the damping effect of PSS on the electromechanical oscillation of the case study network. It is also observed that the voltage profile improved considerably.

4.3.3.2 Active Power

Table 4.5 shows how the introduction of STATCOM into the network improved the active power of buses 1 and 6. As for PSS there was no difference with the original network.

Figure 4.7 shows the STATCOM effects on the network by damping the active power on all the buses with more effect on buses 1, 4, 5, 6, 7, 8 and 9. Figure 4.10 shows the effect of PSS in damping the electromechanical oscillations affecting the active power on buses. It is not as effective as the STATCOM due to its limitation of being a generator based installed device.

4.3.3.3 Lines flow

Table 4.7 shows how the lines active power was improved as against what was obtained in Table 4.6. Also, the losses incurred in Table 4.7 are lesser when compared with the one of Table 4.6.

Lines Flow and lines losses of the case study network (Figure 4.8) shows how effective the damping of oscillations by STATCOM appears to be on all the lines.

PSS has no effect on inter-area oscillations only local modes. Hence it can hardly improve lines flow of any network.

4.3.4 Location of PSS

As stated in chapter three that for a system to become stable, its damping coefficient must not be less than 5% or 0.05. Also, for it to be stable all the real eigenvalues must be on the left hand side of the real axis of a complex plane. The PSAT model of Figure 4.1 was simulated and the results obtained were in Table 4.8. From Table 4.8 modes associated to machine 3 (e1q_Syn_3, vr3_Exc_3) appear to have a far less damping ratio of -0.011117787 and eigenvalues having their real parts on the positive side of a complex plane. Hence it appears to be the best candidate as against machine 1 and 2.

4.3.5 Eigenvalues Analysis

Table 4.8 shows that the electromechanical oscillations are mostly of the local modes. This is true because for inter-area modes, the frequency range is from 0.2Hz to 0.7Hz, where as the local modes frequency range is from 0.7Hz to 2.0Hz and the two modes are referred to as electromechanical oscillations. With STATCOM optimally placed at bus 6, Table 4.9 shows how the damping ratio has been improved tremendously and the eigenvalues have been shifted to the left hand side of the complex plane, hence increasing the stability of the system. With PSS at generator 3, Table 4.10 shows that there was significant improvement of the damping ratio and the unstable eigenvalues moved to stability but not as effective as that of STATCOM on Table 4.10.

4.3.6 Modified IEEE 9-bus and 14-bus

Figures 4.11 to 4.14 show the effectiveness of the optimal placement of STATCOM using GA on the modified IEEE 9-bus and 14-bus. The oscillations were damped and system performance improved. This was done in order to further test for the viability of the optimization technique considered.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The work has carried out Performance Evaluation of PSS and STATCOM in electromechanical oscillation damping of the case study network. Optimizations were carried out to determine the optimal location of STATCOM. Also, eigenvalues analysis was performed on the unstable generators and the generator with the worst damping coefficient was identified as the best candidate for locating the PSS. Simulations were carried out in which case: electromechanical oscillations were damped, voltage profile improved; active power and active power flow were improved and there was a reduced active power loss by the optimal placement of STATCOM. Also; with PSS properly located, oscillations were damped but, not as effective as STATCOM despite the fact that almost all the electromechanical oscillations were of the local modes.

The objectives of the research were considerably met and the following conclusions were drawn:

- GA optimization technique employed in the optimal placement of STATCOM was sufficient in damping of the electromechanical oscillations in the areas of interest.
- Eigenvalues analysis and Damping ratio techniques were employed in locating the best generator to place the PSS.
- Incessant power mode swings were damped by both STATCOM and PSS. STATCOM was established to have better oscillations damping capability than PSS.

- STATCOM enhanced the stability limits of the system under review and helps in improving voltage profile of the system and also results in reduced active power losses.
- The installations of PSS and STATCOM lead to the improvement of stability margin, greater flexibility, and better utilization of existing power systems in the North-Central region of the Nigerian grid. STATCOM was established as a better controller than PSS when employed to eliminate oscillations in the network considered.

5.2 Contributions to Knowledge.

The following contributions were made:

1. The use of GA optimization technique to locate the STATCOM at the appropriate place on the network was determined.
2. The use of the components of eigenvalues in analyzing and establishing unstable generators for the placement of PSS was established.

5.3 Recommendations

The completion of this research project gives rise to work in many other related areas. The following areas are identified for future work.

1. The allocation of STATCOM by cost implications and other economic considerations.
2. Exploring other optimization techniques to further establish the viability of the optimal placement of the device.

3. A different objective function should be explored as well.
4. A larger network should be used with placement of more than one controller at a time.

REFERENCES

Abido, M. A. (2009). *Power System Stability Enhancement Using FACTS Controllers A* Review. The Arabian Journal for Science and Engineering, Volume 34, Number 1B, April 2009.

Allen, W. S., Brent, K.O., et al (2003). *A ±150MVar STATCOM for Northeast Utilities Glenbrook Substation*. IEEE/PES PE-0-7803-7990-X/. 20: pp1-5.

Arabi S. and Kundur P, (2001). *Stability modeling of storage devices in FACTS Applications. IEEE PES Summer Meeting*, Vol.2, 2001, pp. 767 – 771.

Bamasak, S. M. and Abido, M. A. (2005). *Robust Coordinated Design of PSS &* STATCOM Controllers for Damping Power System Oscillation. 15th PSCC, Liege, 22-26 August Session 32, Paper 5, Page 1-7.

Barati, J., Saeedian, A. and Mortazavi, S. S. (2010). *Damping Power System Oscillations improvement by FACTS Devices*. World Academy of Science, Engineering and Technology, pp. 62.

Cañizares, C. A. and Hranilovic, S. (1994). *Transcritical and Hopf Bifurcations in AC/DC Systems*. Proc. Bulk Power System Voltage Phenomena III-Voltage Stability and Security, Davos, Switzerland, pp. 105–114, Aug.

Cañizares, C. A. (1999). Editor: *Voltage Stability Assessment, Procedures and Guides*. IEEE/PES Power Systems Stability Subcommittee, Draft, July. Retrieved from http://www.power.uwaterloo.ca

Cañizares, C.A. (2000). *Power Flow and Transient Stability Models of FACTS Controllers for Voltage and Angle Stability Studies*. IEEE/PES WM Panel on Modeling, Simulation and Application of FACTS Controllers in angle and Voltage Stability studies. 115: pp. 123-128.

Eriksson, R. (2008). Security-Centred coordinated Control in AC/DC Transmission Systems. Master thesis, TRITA-EE_2008_034.

Ghasemi Claudio H. G. and Canizares, A. (2008). *Validation of a STATCOM Transient Stability Model through Small-Disturbance Stability Studies*. N2L 3G1.

Gotham D. and Heydt. G.T. (1998). Power Flow control and Power Flow Studies for Systems with FACTS devices. IEEE Transaction on Power Systems, vol.13.no.1 , pp. 60-65.

Graham, R. (2000). *Power System Oscillation*. Kluwer Academic Publishers, 2000, pp. 328.

Griffo, A., Lauria, D., and Carpinelli, G. (2006). Novel FACTS controllers for power system stability enhancement. Università degli Studi di Napoli Federico II November 2006, pp. 45-48.

Hingorani N. G. and Gyugyi L. (2000). Understanding FACTS: Concepts and Technology of Flexible AC Transmission System. IEEE Press, pp. 136-206.

Hingorani N.G. and Gyugi L. (2001). Understanding FACTS –Concepts and Technology of Flexible Ac Transmission Systems. Standard Publishers Distributors, IEEE Press, New York.

Houck C., Joines J. and Kay M. (1995). *A genetic algorithm for function optimization: A MTLAM implementation.* NCSU-IE, TR 95–09. Retrieved from http://www.ise.ncsu.edu/mirage/GAToolBox/gaot, pp. 1-14.

Jamaluddin H., (2009). Genetic Algorithm. Faculty of Mechanical Engineering Unuversiti Teknologi, Malaysia (unpublished). pp. 1-13.

Kanojia, A. S. P. and Chandrakar, B. D. V. K. (2009). *Damping of Power System Oscillations by using coordinated tuning of POD and PSS with STATCOM.* World Academy of Science, Engineering and Technology. pp. 1067-1072.

Klaus H. and O'leary, D. (2000). *FACTS for Cost Effective and Reliable Transmission of Electrical Energy.* A paper reviewed by the World Bank. April, 2000. pp. 1-11.

Koseterev, D.N. (1997). *Modeling Synchronous Voltage Source Converters in Transmission System Planning Sudies.* IEEE Trans. Power Delivery, 12: pp. 947-952.

Kundur, P. (1994). *Power System Stability and Control.* McGraw Hill, New York, pp. 817-822.

Lautenberg, M. J., Pai, M. A. and Padiyar, K. R. (1997). *Hopf Bifurcation Control in Power System with Static Var Compensators,* Int. J. Electric Power and Energy Systems, Vol. 19. No. 5, pp. 339–347.

Manfred Gilli, (2004). Seminar: *An Introduction to Optimization Heuristics. Retrieved from* www.unige.ch/ses/metri/gilli, pp. 20.

Mithulananthan, N., Cañizares, C. A., Reeve, J. and Rogers, G. J. (2001). *Comparison of PSS, SVC and STATCOM Controllers for Damping Power System Oscillations.* Mitsubishi Electric, Mitsubishi Power System Stabilizer (PSS), Sept. pp. 1-7.

Mustafa, M. W., Magaji, N. (2009). *Optimal Location of Static Var Compensator Device for Damping Oscillations.* American J. of Engineering and Applied Sciences 2 (2): 353-359.

Nettleton L. & Padilla R. (1999). *WSCC Control Work Group, WSCC Tutorial On Power System Stabilizers.* September 1999, pp. 1.

Norouzi, A. H., and Sharaf, A. M. (2005). *Two Control Schemes to enhance the dynamic Performance of the STATCOM and SSSC.* IEEE Transactions on Power delivery, Vol. 20, No. 1, January.

Nwohu, M. N. (2009). Voltage Stability Enhancement of the Nigerian grid system using Flexible Alternating Current Transmission System (FACTS) devices. PHD thesis. Abubakar Tafawa Balewa University, Bauchi, Nigeria, pp. 7-12.

Panda, S. and Padhy, N. P. (2007). *Power System with PSS and FACTS Controller: Modelling, Simulation and Simultaneous Tuning Employing Genetic Algorithm.* International Journal of Electrical, Computer, and Systems Engineering 1:1 © www.waset.org. winter, pp. 9-18.

Panda, S., Padhy, N. P. and Patel, R. N. (2007). *Application of Genetic Algorithm for FACTS based Controller Design.* International Journal of Computer, Information, and Systems Science, and Engineering 1:1.

Panda, S. and Ardil, C. (2008). *Real-Coded Genetic Algorithm for Robust Power System Stabilizer Design.* World Academy of Science, Engineering and Technology 45.

PSAT. (2005). Power System Analysis Toolbox Documentation for PSAT version 1.3.4. July 14, 2005, pp. 156-168.

Qiao, W., Harley, R. G. and Venayagamoorthy, G. K. (2006). *Effects of FACTS Devices on a Power System Which Includes a Large Wind Farm.* PSCE, pp. 2070-2076.

Reddy, I. P., Ram, B. V. S. (2010). *STATCOM with FLC for Damping of Oscillations of Multi Machine.* Power System Journal of Theoretical and Applied Information Technology © 2005 - 2010 JATIT. All rights reserved. www.jatit.org

Robak, S., Januszewski, M., Rasolomampionona, D.D. (2003). *Power System Stability Enhancement Using PSS and UPFC Lyapunov-based controllers: A Comparative Study.* Paper Presented IEEE Bologna Power Tech Conference, June 23th-26th, Bologna, Italy.

Rogers, G. (2000). *Power System Oscillations.* Kluwer, Norwell, MA.

Saadat H. (2004). Power System Analysis: Second edition. McGraw-Hill companies, pp.1-2.

Sedghisigarchi K. and Feliachi A. (2004). *Dynamic and transient analysis of power distribution systems with fuel cells – part II control and stability enhancement. IEEE Trans. on Energy Conversion*, Vol.19, No.2, 2004, pp. 429-434.

Siever, W., Kalyani, R.P., Crow M.L., Tauritz, D.R. (2003). *UPFC control employing Gradient Descent search.* IEEE. 87: pp. 1-4.

Snyder, A.F. (1997). Inter-Area Oscillation Damping with Power System Stabilizers and Synchronized Phasor Measurements. Thesis (Msc. in Elect.), Faculty of Virginia State University, Feb. 10, 1997.

Tan Y. T., Kirschen D. S. and Jenkins N. (2004). *A Model of PV Generation Suitable for Stability Analysis. IEEE Transaction on Energy Conversion*, Vol. 19, No.4, 2004, pp. 748-755.

Thakurta, P. G. (2009). An Approach for Optimal Placement of SVC to Minimize Load Curtailment. Master Thesis. XR-EE-ES_2009_016.

Weise T. (2009). Global Optimization Algorithms Theory and Application. 2nd Edition, Version: -Newest Version. Retrieved from http://www.it-weise.de/, pp. 415-436.

Woodford, D. (2004). *How FACTS Controllers Function in an AC Transmission System.* IEEE/PES GM-0-7803-8465-2-2004. 17: pp. 40-51.

Yu Y. N. (1983). *Electric Power System Dynamics.* Academic Press Inc.

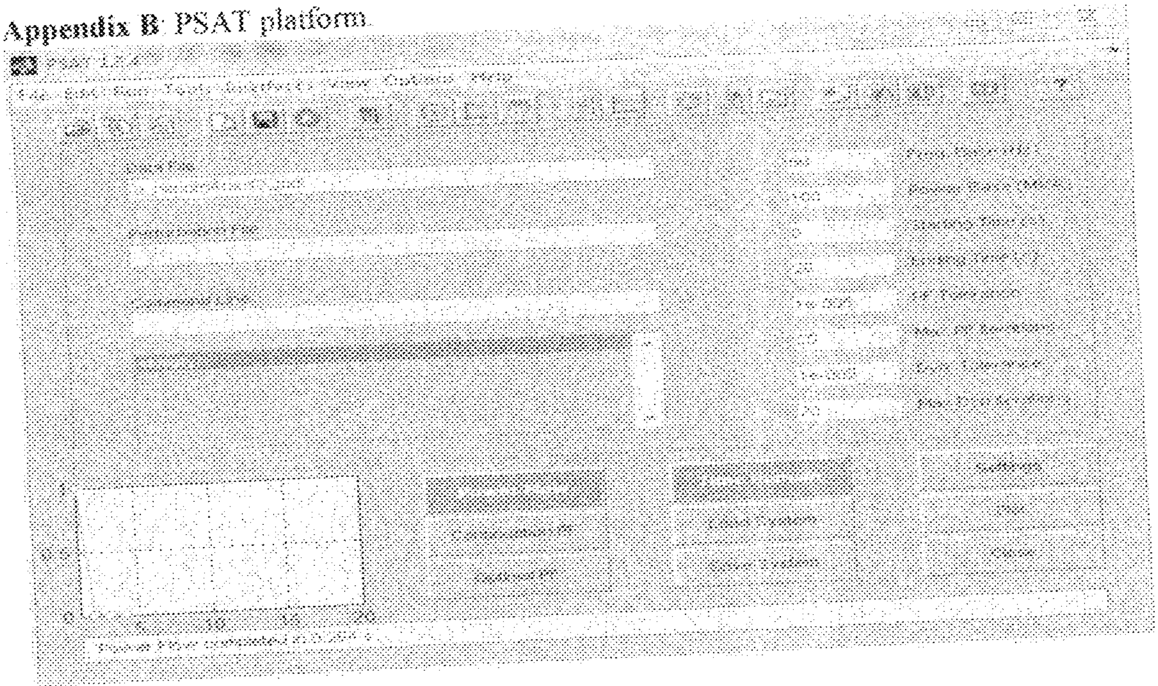
Appendices

Appendix A: GA SOURCE CODE FOR OPTIMAL PLACEMENT OF STATCOM.

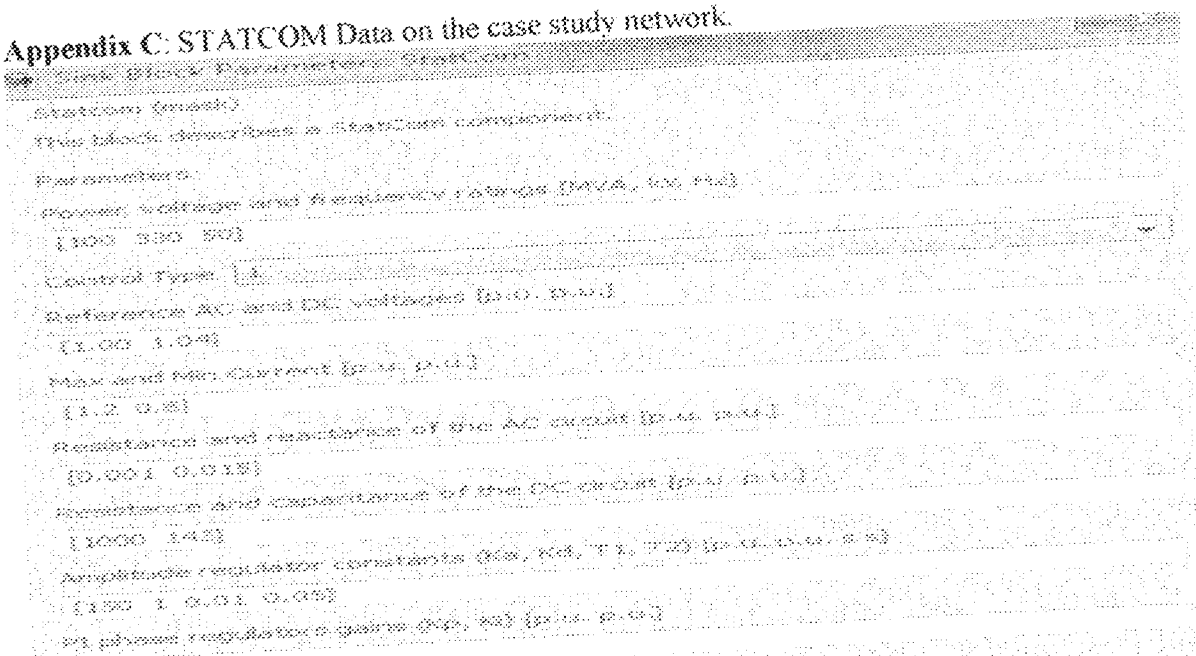
```
clear all
close all
clc
% CODES WRITTEN BY AMBAFI, James Garba: GA BASED OPTIMIZATION TO
%DETERMINE THE OPTIMAL POINT OF STATCOM PLACEMENT IN A POWER
%NETWORK.
% this function encode data v within the range b and c.
% v is the input data
% b is the lower limit
% c is the upper limit
% y is the output bits
% p is the number of bits
% d is the decimal resolution
%stepA is the decimal position of the binary bit
b=0.98; c=1.0; d=4;
%Generation
Gen=9
x=b + (c-b).*rand (Gen,1)
k=1:Gen
%function[delta,p,stepA,y]=MyEncoding(x,b,c,d)
p=ceil(log2((c-b)*10^d+1))
delta=(c-b)/((2^p)-1)
stepA=(x-b)/delta
y = dec2bin(floor(stepA),p)
%function[y]=MyDecoding(x,b,c,d)
v=(b+bin2dec(y)*((c-b)/(2^p-1)))
R=[0;0;0;0.01377;0.00016;0.01218;0.00655;0.00669;0.00189]
P=[-6.313;4.5;4.9;0;0;0.603;0.086;0.615;1.662]
Q=[0.1036;-0.51719;0.36975;0;0;0.598;0.056;0.103;0.978]
z=[R,P,Q,v]
L=StatcomObjFun (z)
F=sum (L)
P=L./F
[q,z]=StatcomCummulative (P)
N=length(q)
U=rand(N,1)
Gr=StatcomInLoc (q,U)
for h=1:length (Gr)
   ILoc=Gr (h)
   F= v (ILoc,:)
   Newdata (h,:)=F
% New chromosomes ready for evaluation
   E=Newdata (:)
end
```

```
v=E
z=[R,P,Q,v]
f1=StatcomObjFun(z)
X=E


function L=StatcomObjFun(z)
for k =1:length(z)
   L(k,1)=((z(k,1).*(z(k,2).^2+z(k,3).^2))/((abs(z(k,4))).^2))
end


function[q,z]=StatcomCummulative(P)
A=P(:)
q=cumsum(A)
z=[A,q]


function[Gr]=CallInLoc(q,U)
N=length(q)
for k=1:N
   A=U(k,1)
   B=A>q
   C=sum(B)+1
   Gr(k)=C
end
```

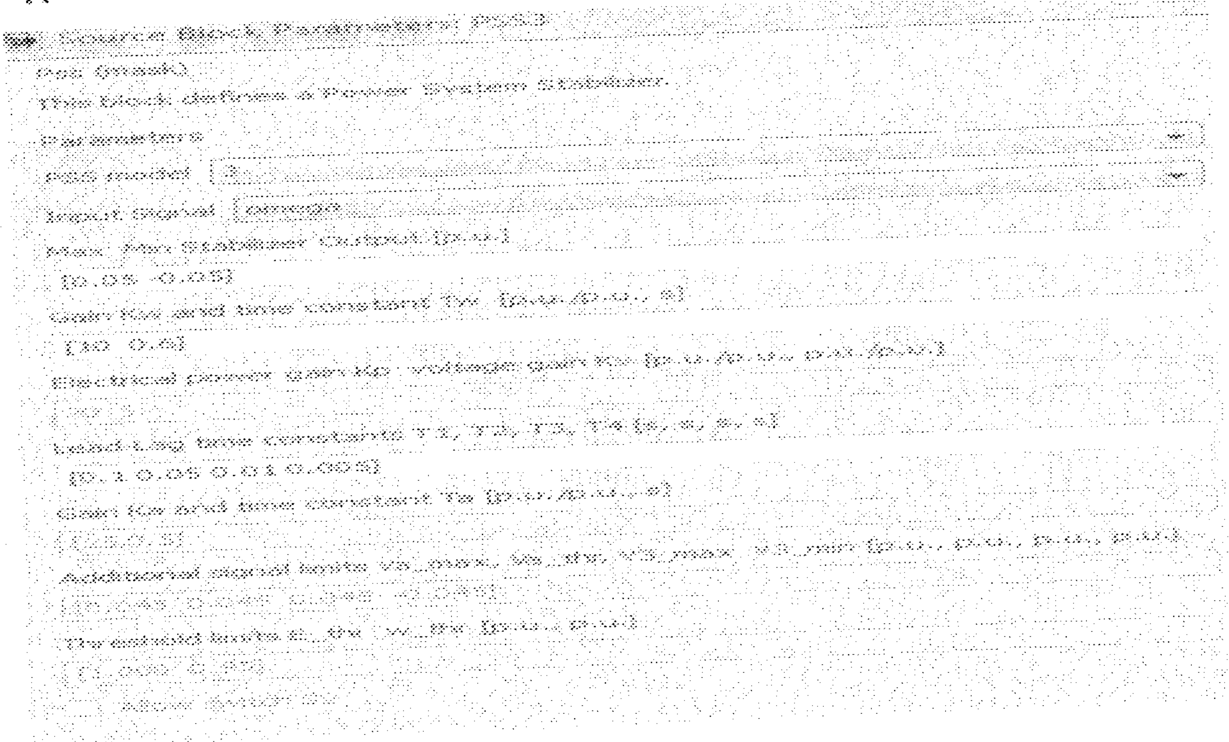
Appendix B: PSAT platform.



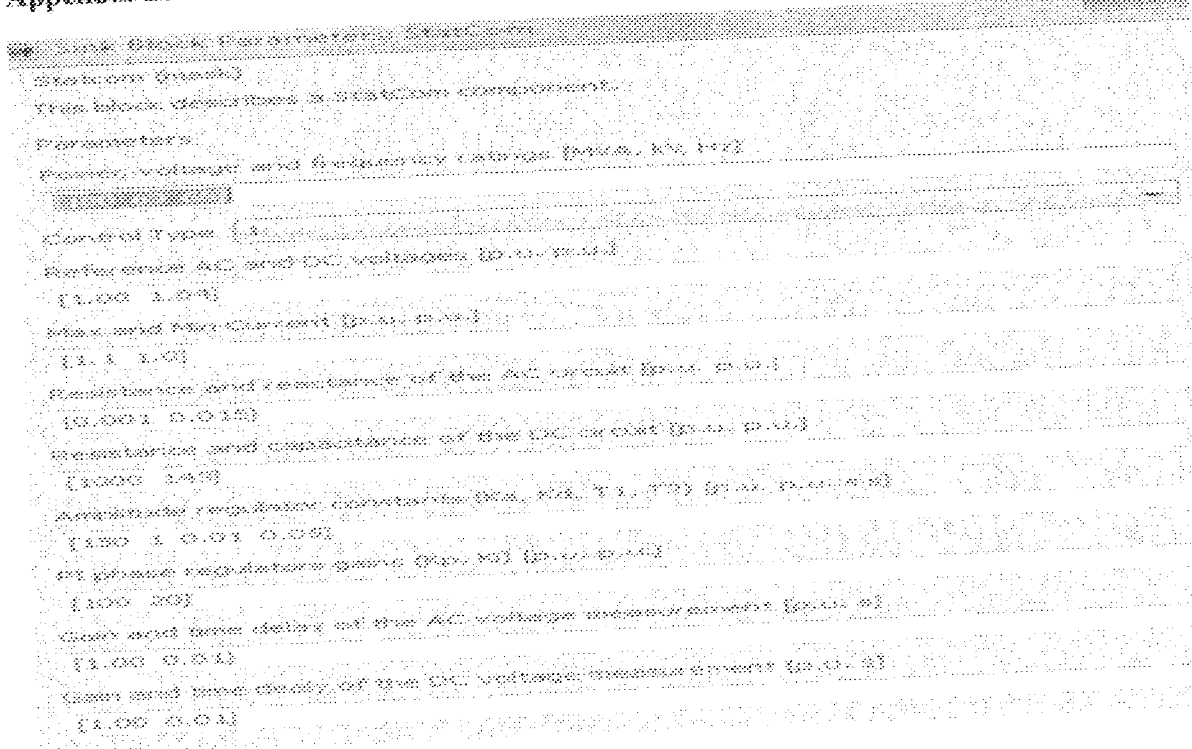
Appendix C: STATCOM Data on the case study network.



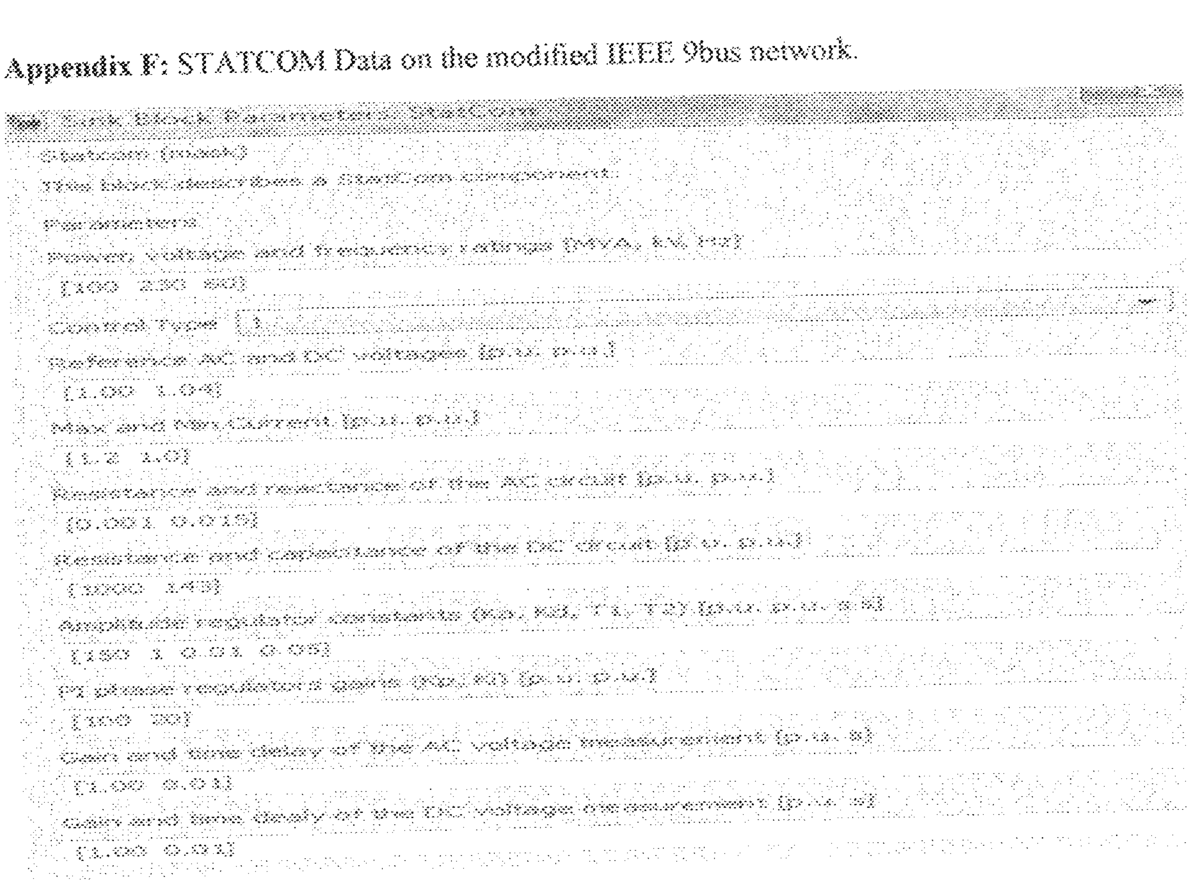
Appendix D: PSS data of on the case study network.



Appendix E: STATCOM Data on the modified IEEE 14bus network.



Appendix F: STATCOM Data on the modified IEEE 9bus network.



Appendix G: List of Thesis Publications.

a. *Published:*

   i. **J. G. Ambafi**, Nwohu M. N., Ohize H. O., Tola, O. J.(2012) *Performance Evaluation of PSS and STATCOM on Oscillation Damping of a North-Central Power Network of Nigeria Grid System.* International Journal of Engineering and Technology Volume 2 No. 2, Pp 209-219. Retrieved from http://iet-journals.org/archive/2012/feb_vol_2_no_2/855121326496621.pdf

b. Under review:

   i. **J. G. Ambafi**, Nwohu, M. N. and Olatomiwa, L. J. *Enhancing Voltage Stability Limits of a North-Central Power Network of Nigeria Grid System by use of STATCOM.* Elsevier Editorial System™ for Alexandria Engineering Journal. Manuscript Number: AEJ-D-12-00045

c. On-going:

   i. Performance of PSS in curtailing Rotor Angle swing and System Stability.