US Open Electrical & Electronics Engineering Journal
Vol. 1, No. 1, July 2015, pp. 1-15
Available online at http://arepub.com/Journals.php

Research article

VOLTAGE STABILITY IMPROVEMENT OF POWER TRANSMISSION SYSTEM IN NIGERIA USING TCSC

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ABSTRACT

This thesis deals with voltage stability improvement of power transmission system in Nigeria using TCSC. The TCSC model is an application of a power electronics device used to control the power flow and to improve voltage stability of a system under static condition. Power flow solution is developed in MATLAB program using Newton Raphson iterative method and simulated on existing 28- bus 330kV transmission network. The results were achieved without and with TCSC where voltage drops were noticed, at buses Ayede (0.9892), Jos (0.9800), Kaduna (0.9810), Kainji (0.9968) and Kano (0.9992). TCSC was incorporated and the new voltage magnitudes of these affected buses improved as 1.1883, 1.0319, 1.0327, 1.1682 and 1.2267 respectively. The results showed a considerable improvement in the voltage magnitude with the incorporation of TCSC and consequently a significant reduction in the system losses. In this way, the efficiency of the system is enhanced while the prolonged and frequent voltage collapses in the transmission network are minimized.

Keywords: Voltage stability, FACTS, voltage collapse, MATLAB , Load Flow.

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1 INTRODUCTION

The exponential increase in load demand, economical and environmental constraints in transmission lines has made modern power system to be exposed to dangers of voltage instability (Sakthivel, Mary and Deivarajamani, 2011). This adversely affects the transmitted power and cause instability in the transmission system, meaning that, the system is no longer able to regain synchronism after its normal operating condition is distorted. Loss of synchronism or system instability can be caused by a number of factors. For instance, increase in demand may make the transmission system become more stressed, which in turn, makes the system more vulnerable to voltage instability. Voltage collapse is the

process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant part of the power system.
The voltage instability may be classified into transient and steady state, the main concern in this thesis is the steady state instability. Steady state voltage stability or Small-disturbance voltage stability refers to the system’s ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load. According to (Hadi, S., 2006), the In other word, Stability is the ability of a system to regain synchronism after the system is disturbed. In essence, power system stability can be defined as the ability of a power system to return to its normal operating condition after a disturbance (Hadi, S., 2002). Tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium is termed as Stability.

In view of this, a system will remain stable only if the forces tending to hold the machines in synchronism with one another are sufficient to overcome the disturbing forces. To meet the increasing load demand of electricity in a power system, it is essential to increase the transmitted power either by installing new transmission lines or by improving the existing transmission lines by adding devices. Installation of new transmission lines in a power system leads to technological complexities such as economic and environmental consideration that includes cost, delay in construction etc.
FACTS technology gave up new ways for controlling power flows and enhancing the usable capability of transmission lines. FACTS are system comprised of static equipment used for the AC transmission of electrical of electrical energy. It is meant for power transfer capability of power system network. The concept of FACTS was first defined by (Hingorani, N.G., 1998). It is usually refers to the application of high power semi conductor devices to control different parameters and electrical variables such as voltages, impedance, phase angle, current, active and reactive power (Adepoju, G.A and Komolafe,2008).

2 LITERATURE REVIEW

In many countries, problem due to voltage instability is one of the major concerns in power system planning, design and operation. Voltage instability may result in voltage collapse and sometimes lead to a complete blackout of the system. The basic precaution for preventing such severe system incident is the identification of voltage instability.

2.1 Voltage Stability Improvement

Several Studies have shown that Facts devices can be used to improve voltage stabilities for both steady state and transient stabilities. A static VAR compensator is used to improve voltage stability because of the opening line in the presence of the induction motor or due to start induction motor or because of recoveries of short circuit motor terminals or due to heavy load capacity.
(EI-Sadek, M.Z., et al, 1998) presented a scheme of improving steady state voltage stability via scheme of series compensation along with SVC. The appropriate percentage of series compensation was obtained from the voltage stability point of view. Combined use of tap changing transformer SVC was also presented by the same authors in order to enhance the voltage stability of the transmission lines.
(Walid and Takashi, 1998) presented a work on Placement of static VAR compensators to minimize power system losses. They have also proposed a screening method of finding the optimal location of static VAR compensator and other reactive elements in a power system to minimize power injection at all the system buses.

(Kumar, N., et al, 2003) have presented a work on Determination of optimal amount location of series compensation SVS for an AC transmission system. They have determined the optional location of series compensation SVS for this, they have developed generalized expressions for maximum receiving end power compensation efficiency, optional value of series compensation in terms of the line’s constants capacitive reactance used for the different schemes of the series compensation..

(Kumar and Dave, 1996) presented a work on application of static VAR system auxiliary controllers to improve the transient performance of series compensated long transmission lines. This paper presents a comparative assessment of static VAR system (SVS) bus frequency line reactive power auxiliary controllers for the performance enhancement of series compensated long transmission lines.
“Enhancement of steady state voltage stability by using static VAR compensators” (El-Sadek, et al, 1997) discussed the improvement of voltage stability in balance using static compensators. Instability voltage balance can certainly be improved by static compensators that may contain some node voltages constant create infinite buses within the system nodes..

Voltage stability improvement using static VAR compensator in power system by (Ndubuka, M., 2009) discussed the voltage stability improvement using static VAR compensator in power system. He investigated the effects of static VAR compensator (SVC) on voltage stability of power system. The functional structure for SVC built with a Thyristor Controlled Reactor (TCR) and its model is described. The model is based on representing the controller as variable impedance that changes with the firing angle of the TCR.

In paper “Selection of static VAR compensator location size for system voltage stability improvement” by (Thukaram and Abraham ,2000), the author have derived the methodology of assessing the location of compensation device in accordance with the L- index through indices of the transmission can be known with no-load conditions with the other end of high load resulting in voltage collapse. Through the study, the location design parameters can be known for stability of the system.

Modeling Application Studies for a Modern Static VAR system installation by (Pourbeik, et al 2006). In this paper simulation studies have been carried out by the authors for installation of modern static VAR systems with a view to ensure automatic switched capacitor banks with sophisticated control mechanism for effective compensating of the compensating system. Capacitors are controlled by individual circuit breakers. The objective was to examine the modality of incorporating slow susceptance regulator with coordinated/automatic capacitor actuation for ensuring an effective control mechanism for safe reliable transmission system taking into account interventions of the generator.

All the journal papers and textbooks reviewed and cited in this research work during the literature survey, were based on steady state performance of the system using FACTS device called Static VAR compensator. In the Literature, it is also observed that viable degree of series compensation has not been employed in Nigerian power transmission network and the system behaviour under varying degrees of compensation requires further research. The TCSC model has not been thoroughly explained with regards to its practical usage for voltage stability improvement.

My research work is focused on voltage stability improvement of power transmission network in Nigeria using TCSC. This will ameliorate the age longed problem of energy crisis in the country which has impeded socio cultural development and industrialization.

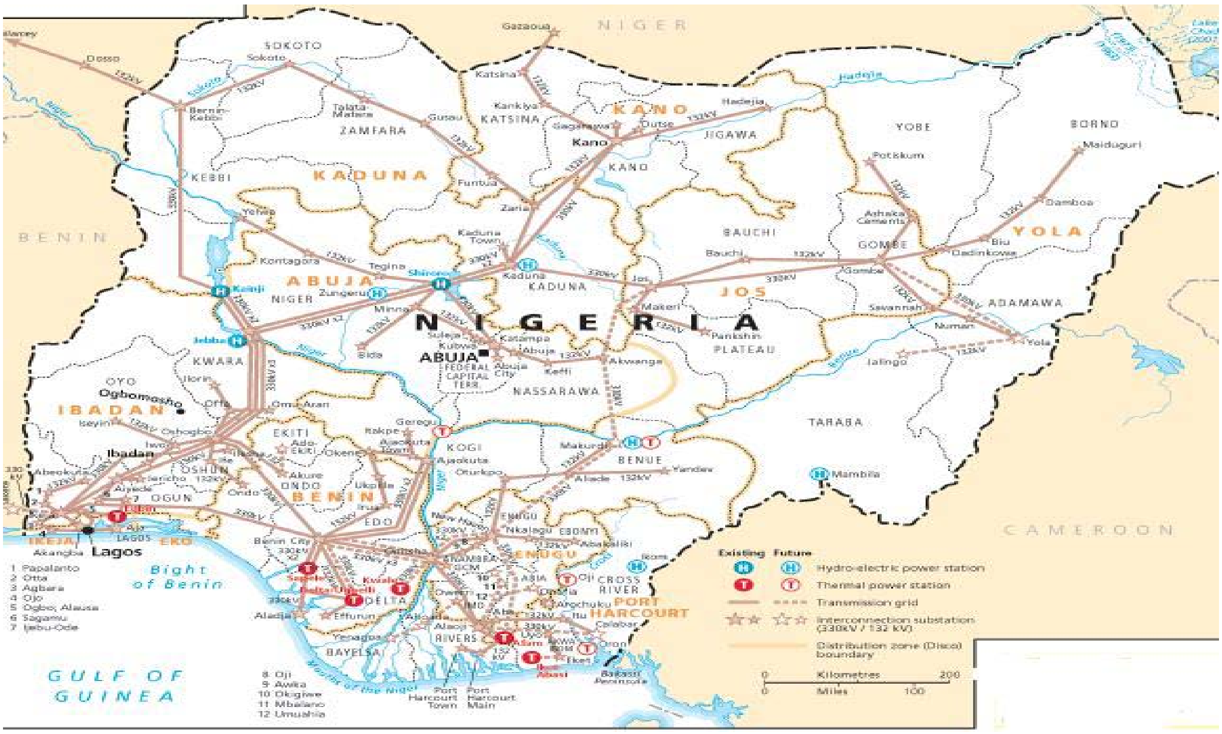

Figure 2.2: Map of Nigeria showing transmission grid layout (Nigerian Power sector review report, 2009, Dec)

2.2 Current Power Situation

Nigeria has more than enough energy sources to meet the power demand of the people. However, only a small percentage of the populace has constant access to power. According to the Nigerian power sector review of 2010, only about 45 % of the population is connected to the grid. On an average basis, approximately 45% of demand is met. This means that most homes have access to electricity only 60% of the time while some even have power only 30 % of the time. Firms and companies also report outages and it is very common for homes and firms to have their own generation units. Aside from the economic implications of these current power problems, there are also environmental and health issues associated with.

Table 2.1 Power Generation capacity of the current Nigerian grid

Power plant	Installed capacity (MW)	Average availability (MW)
	HYDRO POWER PLANTS	
Kainji	760	412,55
Jebba	578.4	431,83
Shiroro	600	390,21
	THERMAL POWER PLANTS	
Egbin	1320	819,55
Sapele	720	125,17
Delta II-IV	900	342,95
Afam II, IV, V, VI	1166	457,2
Geregu	414	208,69
Omotosho	335	118
Olorunshogo I,II	710	324
Okpai	480	441,57
Omoku	150	80,18
Ajaokuta G.S	110	0
Ibom G.S	155	82,89
AES	302	208,20
Trans-Amadi	100	32,63
Total	**8800.4**	**4475.87**

As shown in table 2.1 above, the average availability of the power plant is around 50%. This according to information from the Power Holding Company of Nigeria is due to faulty generators, lack of machine maintenance and generally aging generators in the old power plants e.g. Kainji hydro power plant which was commissioned in 1968. Due to the government's commitment to improve the power situation of the country, there are a number of projects under way to expand the generation and consequently the grid. There are several government owned and independent power plant projects under way. Table 2.2 shows the power plants under construction at the moment and expected to be connected to the grid between 2012 and 2020 which were considered in this study.

Table 2.2 Generation capacity of proposed new plants

Power plant	Installed capacity, MW
Calabar	561
Egbema	338
Ihovbor	451
Gbarian	225
Alaoji I	504
Eket	500
Obite	450
TOTAL	3029

2.2.2 Transmission

Currently, the Transmission Company of Nigeria (TCM), projected to have the capacity to deliver about 12,500 MW in 2014, has the capacity of delivering 4475.87 MW of electricity. Nigeria has a generating capacity of 5,228 MW but with peak production of 4500 MW against a peak demand forecast of 10,200MW. This shows that if the generation sector is to run at full production, the transmission grid will not have the capacity to handle the produced power reliably (PHCN daily report, 2010, Nov). This goes a long way to tell that the 330 KV transmission systems are not running effectively as expected. Therefore to maintain and ensure a secure operation of this delicate system, the need for power control cannot be over emphasized (Nigeria power Sector report 2009).

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2.3 Voltage Stability phenomenon

Voltage stability is therefore believed to be of greater concern in the future. Nearly all types of contingencies and even slow-developing load increases could cause a voltage stability problem. The time scale for the course of events which develop into a collapse varies from seconds to several tens of minutes. This makes voltage collapse difficult to analyses since there are many phenomena that interact during this time as in Figure 2.3 Important factors that cause interaction during a voltage decline are among others: generation limitation, behaviour of on-load tap changers and load behaviour. (Cutsem, T.V., Vournas, C., 2001).

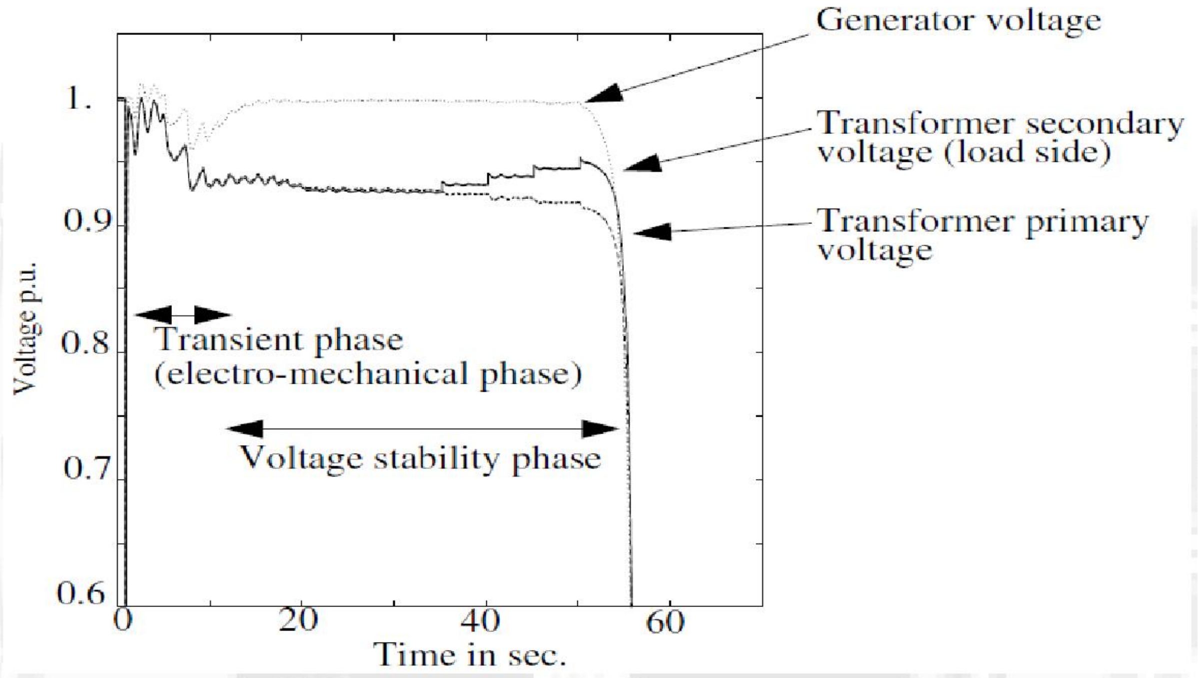

Figure 2.2: Voltage collapse phenomenon (Glavitsch, H., 1994).

3 METHODOLOGY

Static power flow method is adopted for this research work. This is basically a load flow problem which involves solving the set of non-linear algebraic equations. In carrying out this analysis, the Newton Raphson iterative algorithm was adopted because of its fast convergence and accuracy with a small number of iteration.

MATLAB program was used to perform the load flow computation to optimize the computing time for corrective action to be taken in order to maintain stable and reliable power supply. The Load flow result will identify buses with voltage magnitude less than 1.0pu. Those are the buses termed as weak or deficient buses.

Those deficient buses and lines are considered as the possible locations for placement of a FACTS device called TCSC with a view of improving voltages in those buses to acceptable limits (i.e. 1pu).

3.1 Structure of 28-Bus 330kV Nigerian Transmission System

The Single line diagram of the existing 330kV Nigerian Transmission network used as the case study is shown in fig 3.1. It consists of nine generating stations, fourteen loads stations and thirty one transmission Lines.

The system is divided into three 3 sections: - North, South-East and the South-West sections. The North is connected to the South through one triple circuit lines between Jebba and Oshogbo while the West is linked to the East through one transmission line from Oshogbo to Benin and one double circuit line from Ikeja to Benin (Adebayo, et al 2013 ; Onohaebi, O.S and S.T. Apeh, 2007).

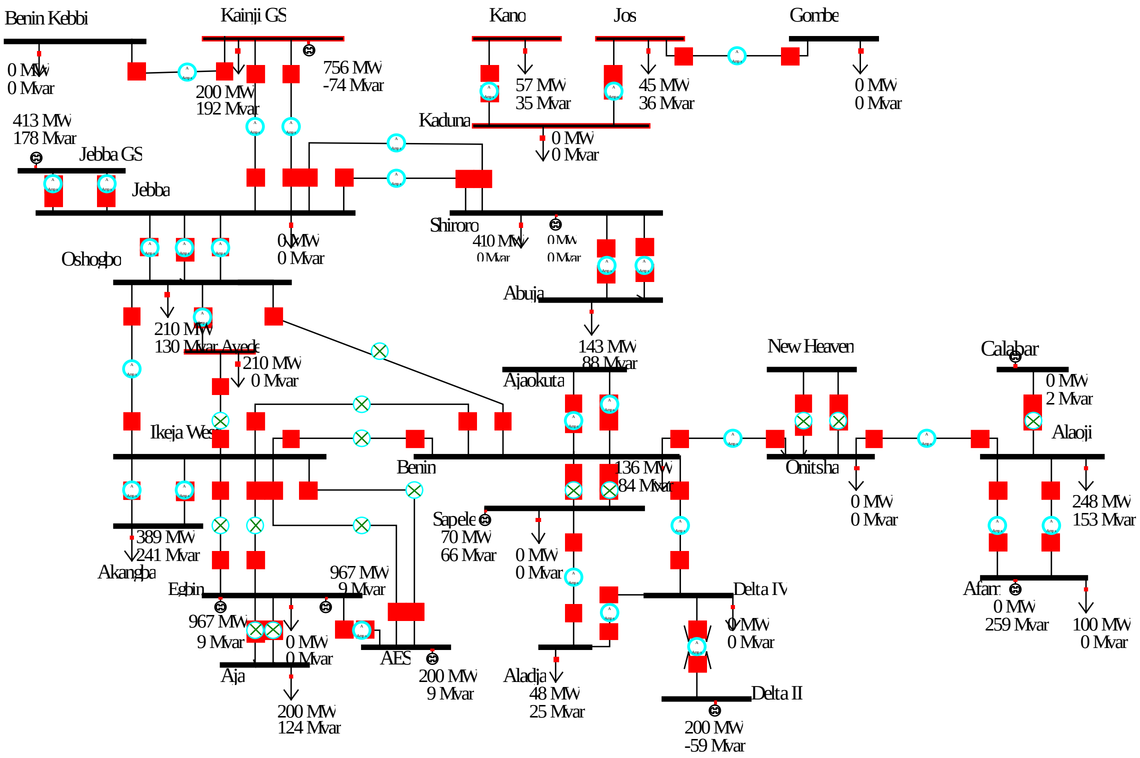

Figure 3.1: One-line diagram of the Nigeria 28 Bus, 330-kV transmission grid

3.2 Implementation of TCSC Models in NRLF Algorithm.

The TCSC power equations are combined with the network equations and linearised with respect to the state variables. The linearized power flow equations can be represented as $[F(x)] = [J][\Delta x]$ where [F(X)] is power flow mismatch vector, [J] is the Jacobian matrix; [ΔX] is the state variable correction vector. The device parameters are used as state variable. For the TCSC the variable reactance is taken as state variable. The inclusion of these variables increases the dimension of the jacobian.

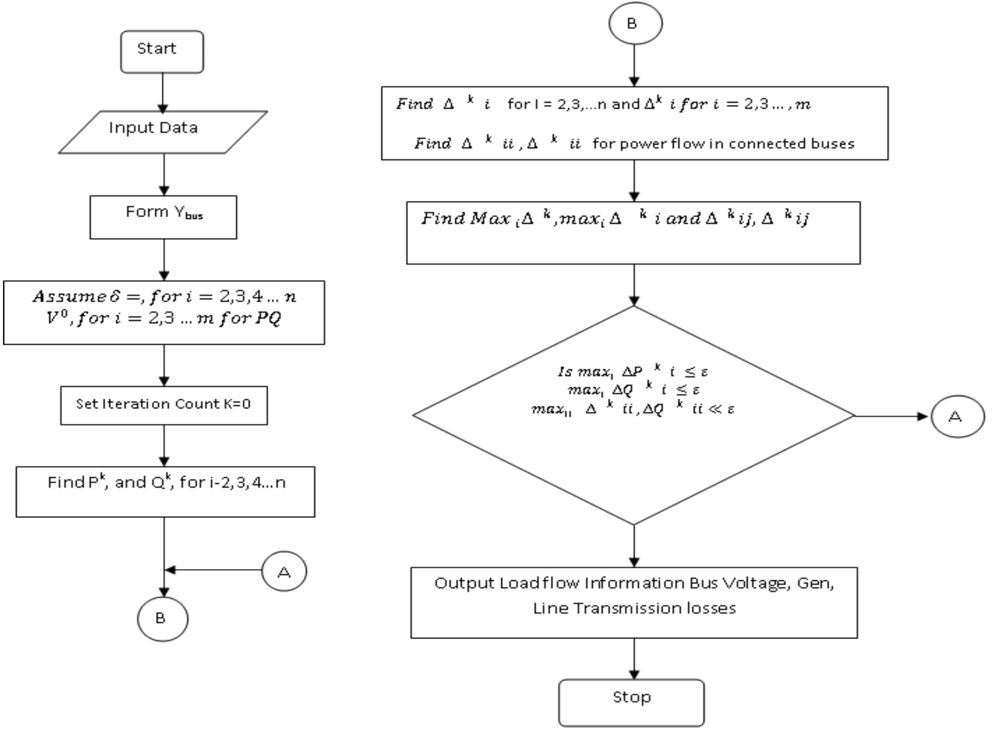

Fig 3.2: Newton Raphson power flow Algorithm without TCSC (Hingorani, N.G, 2009).

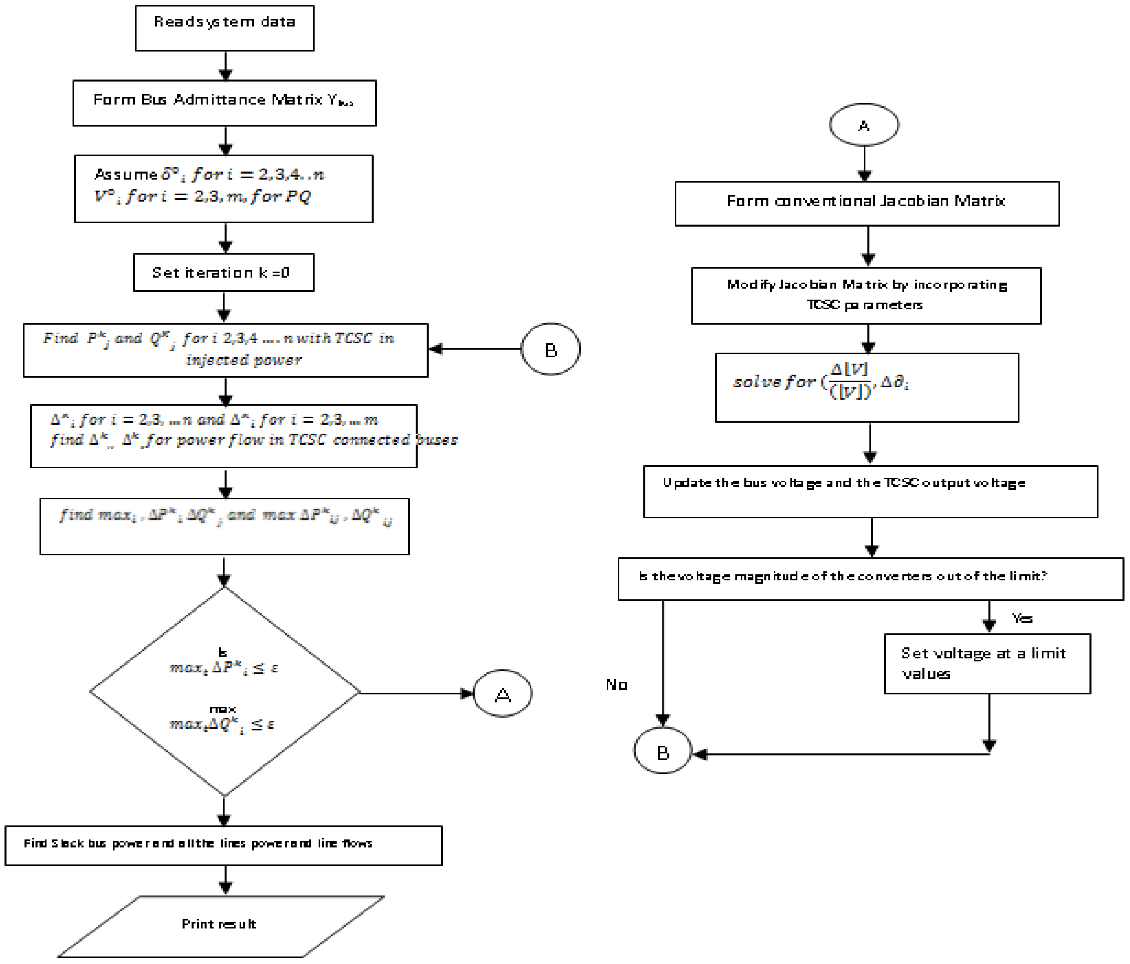

Fig 3.3: Newton Raphson power flow Algorithm with TCSC (Abdel, M.A 2013).

3.3 Thyristor-Controlled Series Compensator (TCSC)

The TCSC varies the electrical length of the compensated transmission line with little delay**.** Owing to this characteristic, it may be used to provide fast active power flow regulation. It also increases the stability margin of the system and has proved very effective in damping Sub-Synchronous Resonance (SSR) and power oscillation. The TCSC is the parallel combination of Thyristor Controlled reactor (TCR) and a fixed capacitor. So before discussing in details about TCSC, let us discuss about TCR.

3.3.1 Physical Model of TCSC

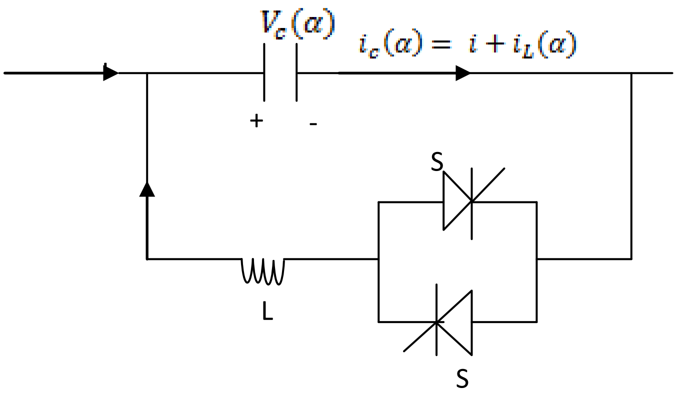

Figure 3.4: Thyristor controlled series compensator (TCSC)

The TCSC consists of the series-compensating capacitor shunted by a Thyristor-controlled reactor (TCR) as shown in fig. 3.4. The impedance of the reactor X_L is sufficiently smaller than that of the capacitor impedance X_c is taken. By varying the delay angle or firing angle(α) of TCR, the inductive impedance of TCR can be varied. Thus TCSC can provide variable capacitance by means of canceling the effective capacitance by the TCR. Therefore, the steady state impedance of TCSC is simply that of the parallel LC circuit, consisting of fixed capacitive impedance X_c and variable inductive impedance X_L.

The effective impedance of the TCSC is given by

$$X_T(\alpha) = \frac{X_c X_L(\alpha)}{X_L(\alpha) - Xc} \tag{3.1}$$

where $X_L(\alpha)$ is the variable impedance of TCR which can be taken from equ.(3.4) that is

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin 2\alpha} \qquad \text{for } X_L \leq X_L(\alpha) \leq \infty \tag{3.2}$$

where $X_L = \omega L$ and α is the delay angle measured from the crest of the capacitor voltage or the zero crossing of the line current.

3.4 Analysis of the TCSC Equivalent Circuit:

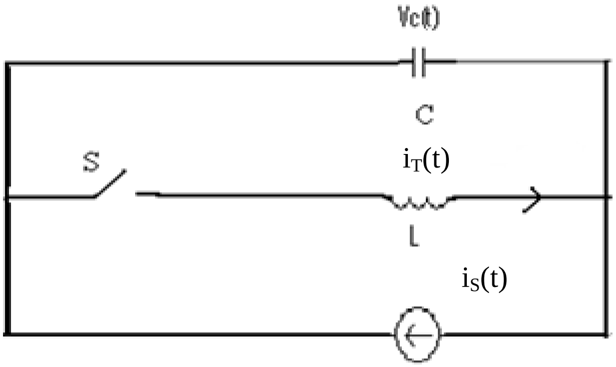

Figure 3.5: Simplified TCSC Circuit

The analysis of TCSC operation in the vernier-control mode is performed based on the simplified TCSC circuit as shown in Fig 3.5

$i_S(t)$ = Transmission line current which is modeled as an external current source
and assumed to be sinusoidal current.
$i_T(t)$ = Thyristor-valve current
u = switching variable
when u =1, thyristor is conducting i.e. switch S is closed
when u = 0, thyristor is blocked i.e switch S is open
C = Fixed capacitor used in parallel with TCR circuit
L = Inductance used in series with Thyristor bidirectional switch
$V_c(t)$ = voltage across the capacitor C

The current through the fixed capacitor C is expressed as

$$C\frac{dv_c}{dt} = i_S(t) - i_T(t)\cdot u \tag{3.3}$$

The current through thyristor is given by

$$L\frac{di_T}{dt} = v_C \cdot u \tag{3.4}$$

Let the line current $i_S(t)$ be represented by

$$i_S(t) = I_m \cos wt \tag{3.5}$$

In equidistant firing-pulse control, for balanced TCSC operation, the thyristors are switched on twice in each cycle of the line current at instants t_1 and t_3 and these are given by

$$t_1 = -\frac{\beta}{w}, \qquad t_3 = \frac{\pi - \beta}{w}$$

where β is the angle of advance (before the forward voltage becomes zero) or,

$$\beta = \pi - \alpha\,; \qquad 0 < \beta < \beta_{\max}$$

where α is the firing angle of the thyristor. This angle is generated using a reference signal that can be in phase with the capacitor voltage. The thyristor switch S turns off at the instants t_2 and t_4, defined as

$$t_2 = t_1 + \frac{\sigma}{w} \;,\; t_4 = t_3 + \frac{\sigma}{w}$$

where σ is the conduction angle, which is assumed to be the same in both the positive and the negative cycle of conduction. Also, $\sigma = 2\beta$

Solving the TCSC equations (3.3)-(3.4) results in the steady state thyristor current $i_{T,}$ as

$$i_T(t) = \frac{\varpi^2}{\varpi^2 - 2} I_m \left[\cos wt - \frac{\cos\beta}{\cos\varpi\beta} \cos w_r t \right];\; -\beta \le wt \le \beta \qquad (3.6)$$

where w_r is called resonance frequency and is given by

$$w_r = \frac{1}{\sqrt{LC}} \quad \text{and} \quad \varpi = \frac{w_r}{w} = \left(\frac{X_C}{X_L} \right)^{1/2}$$

where X_C and X_L are capacitive reactance and inductive reactance respectively.

The steady state capacitor voltage at the instant $wt = -\beta$ is expressed as

$$v_{C1} = \frac{\operatorname{Im} X_C}{\varpi^2 - 1} \left(\sin\beta - \varpi \cos\beta \tan\varpi\beta \right) \qquad (3.7)$$

At $wt = \beta, i_T = 0$, the capacitor voltage is given by

$$v_C(wt = \beta) = v_{C2} = -v_{C1} \qquad (3.8)$$

Finally the capacitor voltage is given by

$$v_C(t) = \frac{\operatorname{Im} X_C}{\varpi^2 - 1} \left(-\sin wt + \varpi \frac{\cos\beta}{\cos\varpi\beta} \sin w_r t \right);\;\; -\beta \le wt \le \beta \qquad (3.9)$$

$$v_C(t) = v_{C2} + \operatorname{Im} X_C (\sin wt - \sin\beta); \qquad \beta < wt < \pi - \beta \qquad (3.10)$$

Because the non-sinusoidal capacitor voltage, $v_{c,}$ has odd symmetry about the axis wt = 0, the fundamental component, $V_{CF,}$ is obtained as

$$V_{CF} = \frac{4}{\pi} \int_0^{\pi/2} v_C(t) \sin wt \; d(wt) \qquad (3.11)$$

The equivalent TCSC reactance is computed as the ratio of V_{CF} to I_m :

$$X_{TCSC} = \frac{V_{CF}}{I_m} = X_C - \frac{X_C^2}{(X_C - X_L)} \frac{2\beta + \sin 2\beta}{\pi} + \frac{4X_C^2}{(X_C - X_L)} \frac{\cos^2\beta}{(\varpi^2 - 1)} \frac{(\varpi \tan\varpi\beta - \tan\beta)}{\pi} \qquad (3.12)$$

If we apply $\beta = \pi - \alpha$, in equation (16) the reactance of TCSC becomes as :

$$X_{TCSC} = -X_C + C_1 \{ 2(\pi - \alpha) + \sin[2(\pi - \alpha)] \} - C_2 \cos^2(\pi - \alpha) \{ \varpi \tan[\varpi(\pi - \alpha)] - \tan(\pi - \alpha) \} \qquad (3.13)$$

where

$$C_1 = \frac{X_C + X_{LC}}{\pi}, C_2 = \frac{4X_{LC}^2}{X_L \pi}, X_{LC} = \frac{X_C X_L}{X_C - X_L}, \varpi = \left(\frac{X_C}{X_L} \right)^{1/2}$$

From the equation (3.13) it is clear that the reactance of TCSC is dependent on the firing angle of thyristor and this reactance varies from inductive region to capacitive region between firing angle 90^0 to 180^0 and at around 140^0 there is a condition of resonance.

3.5 Active and Reactive Power Flow through TCSC:

As Thyristor Controlled Series Capacitor (TCSC) will control the power flow in the transmission line of a large electrical network, here we will model the TCSC as a variable reactance which varies in terms of firing angle of thyristor**.**

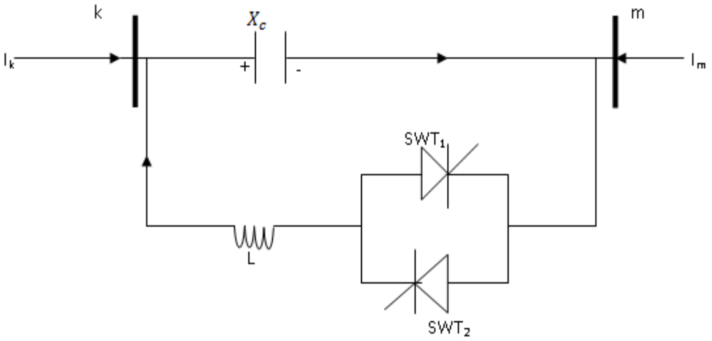

Fig 3.7: TCSC connected between two buses k and m

The fundamental frequency equivalent reactance X_{TCSC} of the TCSC which is already derived in equation (3.17) is given by:

$$X_{TCSC} = -X_C + C_1\{2(\pi-\alpha)+\sin[2(\pi-\alpha)]\} - C_2\cos^2(\pi-\alpha)\{\varpi\tan[\varpi(\pi-\alpha)]-\tan(\pi-\alpha)\}$$

The TCSC active and reactive power equations at bus k are

$$P_k = V_k V_m B_{km}\sin(\theta_k-\theta_m), \tag{3.14}$$

$$Q_k = -V_k^2 B_{kk} - V_k V_m B_{km}\cos(\theta_k-\theta_m) \tag{3.15}$$

where

$$B_{kk} = -B_{km} = B_{TCSC} = \frac{1}{X_{TCSC}}$$

Similarly the active and reactive power equations at bus m are:

$$P_m = V_m V_k B_{mk}\sin(\theta_m-\theta_k), \tag{3.16}$$

$$Q_m = -V_m^2 B_{mm} - V_m V_k B_{mk}\cos(\theta_m-\theta_k) \tag{3.17}$$

where

$$B_{mm} = -B_{mk} = B_{TCSC} = \frac{1}{X_{TCSC}}$$

For the case when the TCSC controls active power flowing from bus k to bus m at a specified value, the set of linearised power flow equations is:

$$\begin{bmatrix}\Delta P_k\\ \Delta P_m\\ \Delta Q_k\\ \Delta Q_m\\ \Delta P_{km}^{\alpha TCSC}\end{bmatrix} = \begin{bmatrix}\frac{\partial P_k}{\partial\theta_k} & \frac{\partial P_k}{\partial\theta_m} & \frac{\partial P_k}{\partial V_k}V_k & \frac{\partial P_k}{\partial V_m}V_m & \frac{\partial P_k}{\partial\alpha}\\ \frac{\partial P_m}{\partial\theta_k} & \frac{\partial P_m}{\partial\theta_m} & \frac{\partial P_m}{\partial V_k}V_k & \frac{\partial P_m}{\partial V_m}V_m & \frac{\partial P_m}{\partial\alpha}\\ \frac{\partial Q_k}{\partial\theta_k} & \frac{\partial Q_k}{\partial\theta_m} & \frac{\partial Q_k}{\partial V_k}V_k & \frac{\partial Q_k}{\partial V_m}V_m & \frac{\partial Q_k}{\partial\alpha}\\ \frac{\partial Q_m}{\partial\theta_k} & \frac{\partial Q_m}{\partial\theta_m} & \frac{\partial Q_m}{\partial V_k}V_k & \frac{\partial Q_m}{\partial V_m}V_m & \frac{\partial Q_m}{\partial\alpha}\\ \frac{\partial P_{km}^{\alpha TCSC}}{\partial\theta_k} & \frac{\partial P_{km}^{\alpha TCSC}}{\partial\theta_m} & \frac{\partial P_{km}^{\alpha TCSC}}{\partial V_k}V_k & \frac{\partial P_{km}^{\alpha TCSC}}{\partial V_m}V_m & \frac{\partial P_{km}^{\alpha TCSC}}{\partial\alpha^{TCSC}}\end{bmatrix}\begin{bmatrix}\Delta\theta_k\\ \Delta\theta_m\\ \frac{\Delta V_k}{V_k}\\ \frac{\Delta V_m}{V_m}\\ \Delta\alpha^{TCSC}\end{bmatrix} \tag{3.18}$$

where $\Delta P, \Delta Q, \Delta P_{km}^{\alpha TCSC}$ constitute *'power mismatch equation'* and these are expressed as:

$$\Delta P_k = P_{Gk} - P_{Lk} - P_k^{cal} = P_k^{sch} - P_k^{cal} = 0$$

$$\Delta Q_k = Q_{Gk} - Q_{Lk} - Q_k^{cal} = Q_k^{sch} - Q_k^{cal} = 0$$

$$\Delta P_{km}^{\alpha TCSC} = P_{km}^{reg} - P_{km}^{\alpha TCSC,cal}$$

where

P_{km}^{reg} = The active power to be controlled from bus k to bus m

$P_{km}^{\alpha TCSC,cal}$ = calculated active power of the TCSC at bus k

Similarly $\Delta\theta, \Delta V, \Delta\alpha^{TCSC}$ constitute state variables and expressed as :

$$\Delta\theta = \theta^{i+1} - \theta^{i}$$

$$\Delta V = V^{i+1} - V^{i}$$

$$\Delta\alpha^{TCSC} = \alpha^{TCSC\,(i+1)} - \alpha^{TCSC\,(i)}$$

$\Delta\alpha^{TCSC}$ is the incremental change in the TCSC firing angle at the ith iteration.

The Jacobian elements for the series reactance, as a function of the firing angle α_{TCSC} are given below.

Partial derivatives of the variable series impedance model are :

$$\frac{\partial P_k}{\partial X} X = -V_k V_m B_{km} \sin(\theta_k - \theta m) \qquad (3.19)$$

$$\frac{\partial Q_k}{\partial X} X = V_k^2 B_{kk} + V_k V_m B_{km} \cos(\theta_k - \theta m) \qquad (3.20)$$

$$\frac{\partial P_{km}}{\partial X} X = \frac{\partial P_k}{\partial X} X \qquad (3.21)$$

Partial derivatives of the firing angle model is given by :

$$\frac{\partial P_k}{\partial \alpha} = P_k B_{TCSC} \frac{\partial X_{TCSC}}{\partial \alpha} \qquad (3.22)$$

$$\frac{\partial Q_k}{\partial \alpha} = Q_k B_{TCSC} \frac{\partial X_{TCSC}}{\partial \alpha} \qquad (3.23)$$

$$\frac{\partial B_{TCSC}}{\partial \alpha} = B_{TCSC}^2 \frac{\partial X_{TCSC}}{\partial \alpha} \qquad (3.24)$$

$$\frac{\partial X_{TCSC}}{\partial \alpha} = -2C_1[1+\cos(2\alpha)] + C_2 \sin(2\alpha)\{\varpi \tan[\varpi(\pi-\alpha)] - \tan\alpha\} + C_2\left\{\varpi^2 \frac{\cos^2(\pi-\alpha)}{\cos^2[\varpi(\pi-\alpha)]} - 1\right\} \qquad (3.25)$$

4.1 RESULTS AND DISCUSSIONS

This chapter presents the result of load flow analysis using Newton Raphson iterative method with the MATLAB Software. The analysis was based on 28-bus 330kV power transmission line in Nigeria used as a case study, taking into consideration IEEE standard acceptable limits of ± 10% tolerance. In this work, the per unit voltage V was taken as 1.0.

4.1.1 Result of load flow with and without TCSC

The first procedure was to run a load flow computation of the case study programmed in MATLAB software. The Figures 4.1 shows the graphical representation voltage magnitude of the Newton Raphson Load Flow Simulation with and without incorporation of TCSC device. The pastel blue colors of the Bar graph in Fig 4.1 shows voltage magnitude without TCSC while the crimson color indicates voltage magnitude with TCSC.

Table 4.1 Voltage profile with and without TCSC device

Bus No	Bus Name	V_m without TCSC	V_m with TCSC
1	Egbin	1.0000	1.0000
2	Delta	1.0200	1.1300
3	Aja	1.0400	1.0400
4	Akangba	1.0500	1.0800
5	Ikeja	1.0400	1.1300
6	Ajaokuta	1.0100	1.0100
7	Aladja	1.0200	1.2600
8	Benin	1.0000	1.0000
9	Ayede	0.9892	1.1600
10	Osogbo	1.0500	1.3300
11	Afam	1.2070	1.0000
12	Alaoji	1.0121	1.0042
13	New Heav	1.2073	1.0137
14	Onitsha	1.0588	1.0770
15	Birnin Kebi	1.0103	1.0527
16	Gombe	1.0240	1.0626
17	Jebba	1.0464	1.1300
18	Jebba gs	1.0504	1.1374
19	Jos	0.9900	1.0319
20	Kaduna	0.9880	1.0327
21	Kainji	0.9904	1.1682
22	Kano	0.9992	1.2062
23	Shiroro	1.0115	1.2530
24	Sapele	1.0294	1.1299
25	Katampe	1.0004	1.0004
26	Okpai	1.0823	1.0823
27	Calabar	1.1265	1.0509
28	AES	1.1514	1.0000

** The affected buses with voltage magnitude before compensation are identified with “red” font while the corresponding voltage magnitudes after compensation are shown on blue font respectively. **

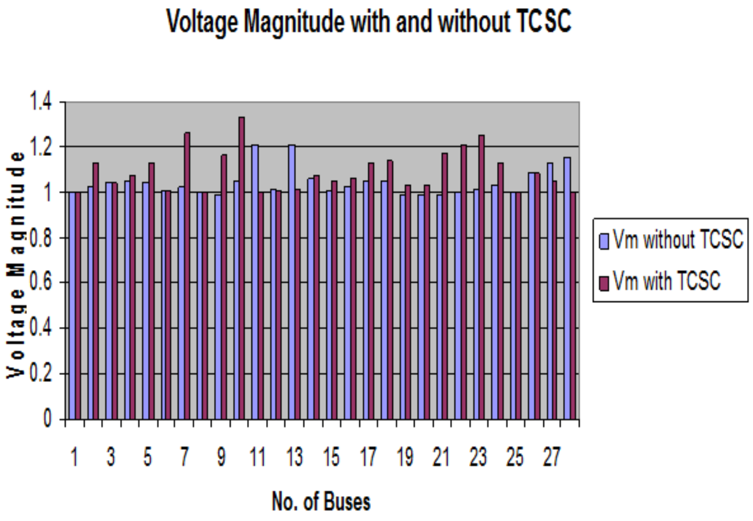

Fig 4.1 Voltage Magnitude with and without TCSC against No. of Buses

4.1.2 Comparison of Angle profile with and without TCSC

The figures 4.2 show the graphical representation of the angle profiles of the Newton Raphson Load Flow Simulation with and without incorporation of TCSC device. The pastel blue colors of the Bar graph in figure 4.2 shows angle profiles without TCSC while the crimson color indicates angles with TCSC.

Table 4.2 Angle profile with and without TCSC device

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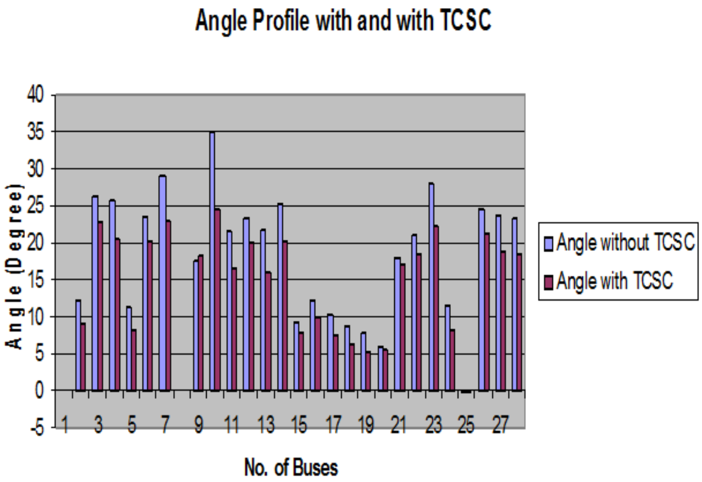

Fig 4.2 Angle profile with and without TCSC against No. of Buses

It was observed that the voltage of the buses i.e. buses 0.9892(Ayede), 0.9800 (Jos), 0.9810(Kaduna) 0.9968 (Kanji) and 0.9992(Kano) were deficient because they have low voltages less than 1.0pu and thus has to be strengthened in order to maintain the bus voltage at 1.0pu. Reinforcement was done by incorporating TCSC into the system. The updated voltages at the affected buses improved as 1.1883, 1.0319, 1.0327, 1.1682 and 1.2267 respectively, which confirmed that the specified amount of active power flow is controlled by the use of TCSC.

5 Conclusions:

With the expansion of power system, fragile nature of transmission lines, poor system protection along with restructuring in Nigerian power system, the complexity of system has increased exponentially. As a result of these, strengthening of the system by incorporating TCSC has helped to enhance the stability in the system. In this thesis, the power flow analysis of Nigerian 330kv grid system was done and incorporation of TCSC into the power flow program developed was carried out successfully. Simulation carried out confirmed that TCSC provided improvement to the voltage instability and voltage collapse at the weak buses. However, the analysis carried out did not consider multi-line FACTS such as Inter-line Power flow controller (IPFC) and generalized Unified power flow Controller (GUPFC).

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