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Power Flow Analysis and Voltage Stability Enhancement Using Thyristor Controlled Series Capacitor (TCSC) Facts Controller

Adebayo, I.G., Adejumobi, I.A., Olajire, O.S.

Abstract: ***Power demand increased steadily while the expansion of power generation and transmission has been severely limited due to the inadequate resources and environmental forces. As a result of this, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Hence, power flow analysis and Voltage stability enhancement are of paramount essential for a secure power system operation. Presented in this paper is the application of Thyristor Controlled Series Capacitor (TCSC) for power flow analysis and voltage control of Nigerian 330kV grid system . Power flow equations involve solution to nonlinear algebraic equations using mathematical algorithms. In this work, the Newton Raphson iterative algorithm was used for solving the power flow problems due to its ability to converge very fast with small number of iteration. Simulation of power flow solutions with and without TCSC was done using MATLAB 7.90 based programme . Where voltage drops were noticed at the load bus, especially, voltages at buses 9 (Ayede.), 13(New Heaven), 14(Onitsha),and 16(Gombe),TCSC was incorporated to regulate the voltage magnitude at those buses. The application of TCSC improved the voltage profile of the system and furthely enhanced the power flow .***

Keywords. TCSC; FACTS; Voltage Stability;Power flow, voltage magnitude

I. INTRODUCTION

Modern power systems are at dangers of voltage instability problems due to highly stressed operating conditions caused by increased load demand and economical and environmental constraints in the transmission lines[1]. This effect 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. [2].

The voltage instability may be classified into transient and steady state, the latest is the main concern in this paper. 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 [2], The 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 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 [3].

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.

Many approaches used to prevent voltage instability[4], such as (1) Placement of FACTS Controllers.(2) Placement of series and parallel capacitors.(3) Rescheduling of the generation (4) Under-voltage load shedding. The use of FACTS devices is considered in this paper work.

FACTS are devices use to control the parameters such as voltage magnitudes and their angles, line impedances, active and reactive power flows[5]. Various forms of FACTS are available such as, Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM),Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Series Compesator(SSSC), Interline Power Flow Controller (IPFC), Unified Power Flow Controller(UPFC), Superconducting Magnetic Energy Storage(SMES) [4].

Many researchers like [3], [6], [7], [8], [9], [10], [11], [12], [13], [14], have worked tremendously on the improvement of the voltage magnitude and reduction of active power loss on the transmission system. Meanwhile, this paper addressed the power flow analysis and voltage stability enhancement incorporating TCSC.

II. BASIC STRUCTURE AND OPERATIONAL PRINCIPLES OF TCSC

Thyristor Controlled Series Capacitor (TCSC) Vary the electrical length of the compensated transmission line which enables it to enhance accurate power flow regulation.

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Adebayo, I.G. Department of Electronic and Electrical Engineering, Ladoke Akintola University of Technology, Ogbomoso. P.M.B. 4000, Ogbomoso, Nigeria.
Adejumobi, Department of Electrical and Electronic Engineering, Federal University of Agriculture, Abeokuta, Nigeria
Olajire, O.S. Department of Electronic and Electrical Engineering, Ladoke Akintola University of Technology, Ogbomoso. P.M.B. 4000, Ogbomoso, Nigeria.

The basic structure of TCSC is a Thyristor Controlled Reactor (TCR) connected in parallel with a capacitor as shown in Figure 2 [15]

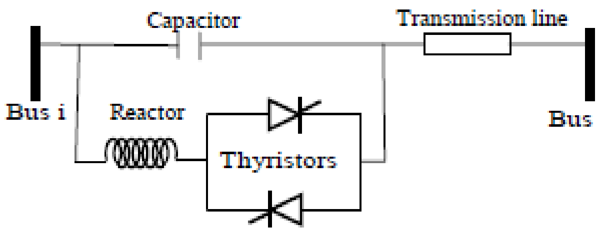

Figure 2; Schematic diagram of TCSC between bus i and bus j.

The principle of TCSC is to compensate the transmission line in order to adjust the line impedance, increase load ability, and prevent the voltage collapse. The characteristic of the TCSC depends on the relative reactance of the capacitor bank and thyristor branch. The resonance frequency (ω_r) of LC is expressed as in (1) [4]:

$$\omega_r = \frac{1}{LC} = \omega_n \sqrt{\frac{-X_c}{X_v}} \tag{1}$$

$$x_C = -\frac{1}{\omega_n c} \tag{2}$$

$$X_{L.} = \omega L \tag{3}$$

The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, normally in response to some system parameter variations. When the thyristors are fired, the TCSC can be mathematically described as in (4), (5) and (6) [4]:

$$i_C = C\frac{\partial v}{\partial t} \tag{4}$$

$$V = L\frac{\partial i_L}{\partial t} \tag{5}$$

$$i_S = i_C + i_L \tag{6}$$

where i_C and i_L are the instantaneous value of the currents in the capacitor banks and inductor,respectively; i_S the instantaneous current of the controlled transmission line; v is the instantaneous voltage across the TCSC.

III. PROBLEM FORMULATIONS

Many countries have been experiencing partial darkness due to the failure of power system. One of the major causes of this is the losses incurred during transmission,which has an adverse influence on the transmitted voltage. Hence, the problem faced can be majorly corrected with the aid of using TCSC forms of FACTS devices.

A. Power Flow Equations

Power flow equations with Newton-Raphson Iterative algorithmn is presented in [3]. The linearized form of the equation is as given by (7):

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \left[\begin{array}{ccc|ccc} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial V_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial V_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial V_n} \\ \hline \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial V_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial V_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial V_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial V_n} \end{array}\right] \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \hline \Delta \left|V_2^{(k)}\right| \\ \vdots \\ \Delta \left|V_n^{(k)}\right| \end{bmatrix} \tag{7}$$

B. Modelling Of TCSC For Static Voltage Stability

TCSC is a series compensation component which consists of a series capacitor bank shunted by thyristor controlled reactor. The basic idea behind power flow control with the TCSC is to decrease or increase the overall lines effective series transmission impedance, by adding a capacitive or inductive reactance correspondingly. The TCSC is modeled as variable reactance, where the equivalent reactance of line X_{ij} is defined as in (8):

$$X_{ij} = -0.8X_{line} \le X_{TCSC} \le 0.2X_{line} \tag{8}$$

where, X_{line} is the transmission line reactance, and X_{TCSC} is the TCSC reactance. The level of the applied compensation of the TCSC usually varies between 20% inductive and 80% capacitive [15]. The TCSC power flow model presented in this paper work is based on the simple concept of a variable series reactance, the value of which is adjusted automatically to constrain the power flow across the branch to a specified value. The amount of reactance is determined efficiently using Newton Raphson iterative method.

C. Power Flow Including TCSC

The diagrams showing the changing reactance X_{TCSC}, representing the equivalent reactance of all the series-connected modules making up the TCSC, when operating in either the inductive or the capacitive regions are presented in [16]. The transfer admittance matrix of the variable series compensator is given by (9) [4]:

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} jB_{KK} & jB_{km} \\ JB_{mk} & jB_{mm} \end{bmatrix} \begin{bmatrix} V_K \\ V_m \end{bmatrix} \tag{9}$$

Equation (10) holds for the inductive operation,:

$$B_{kk} = B_{mm} = -\frac{1}{X_{TCSC}}, B_{km} = B_{mk} = \frac{1}{X_{TCSC}}, \tag{10}$$

where, i_k=Current at bus k
i_m=Current at bus m
V_k=Voltage at bus k
V_m=Voltage at bus m.
ΔX_{TCSC} =Incremental change in series reactance.

and for capacitive operation the sign are reversed.The active and reactive power equations at bus k are as in equations (11) and (12) [4]:

$$P_k = V_k V_m B_{km} sin(\theta_k - \theta_m), \tag{11}$$

$$Q_k = -V_k^2 B_{kk} - V_k V_m B_{km} Cos(\theta_k - \theta_m). \tag{12}$$

For the power flow equations at bus *m*, the subscript *k* and *m* are interchanged in equations 11 and 12.

In Newton–Raphson solutions these equations are linearized with respect to the series reactance. For the condition shown in Figure 3 where the series reactance regulates the amount of active power flowing from bus k to bus m at a value P , the set of linearized power flow equation is as in (13) [4]:

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \Delta P_{km}^{X_{TCSC}} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_K}{\partial V_K} V_k & \frac{\partial P_k}{\partial V_m} V_m & \frac{\partial P_k}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial P_m}{\partial \theta_k} & \frac{\partial P_m}{\partial \theta_m} & \frac{\partial P_m}{\partial V_k} V_k & \frac{\partial P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial V_m} V_m & \frac{\partial Q_k}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial Q_m}{\partial \theta_k} & \frac{\partial Q_M}{\partial \theta_m} & \frac{\partial Q_m}{\partial V_k} V_k & \frac{\partial Q_m}{\partial V_m} V_m & \frac{\partial Q_m}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial P_{km}^{X_{TCSC}}}{\partial \theta_K} & \frac{\partial P_{km}^{X_{TCSC}}}{\partial \theta_m} & \frac{\partial P_{km}^{X_{TCSC}}}{\partial V_K} V_k & \frac{\partial P_{km}^{X_{TCSC}}}{\partial V_m} V_m & \frac{\partial P_{km}}{\partial X_{TCSC}} X_{TCSC} \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \Delta \theta_m \\ \frac{\Delta V_k}{V_k} \\ \frac{\Delta V_m}{V_m} \\ \frac{\Delta X_{TCSC}}{X_{TCSC}} \end{bmatrix} \qquad (13)$$

$$\Delta P_{km}^{X_{TCSC}} = P_{km}^{reg} - P_{km}^{X_{TCSC},Cal}, \qquad (14)$$

where, $\Delta P_{km}^{X_{TCSC}}$ is the active power flow mismatch for the series reactance;

ΔX_{TCSC}, given by (15):

$$\Delta X_{TCSC} = X_{TCSC}^{(i)} - X_{TCSC}^{(i-1)}, \qquad (15)$$

ΔX_{TCSC} is the incremental change in series reactance; and $P_{km}^{X_{TCSC},CAL}$ is the calculated power as given by (11).

The state variable X_{TCSC} of the series controller is updated at the end of each iterative step according to (16):

$$X_{TCSC}^{(i)} = X_{TCSC}^{(i-1)} + \left(\frac{\Delta X_{TCSC}}{X_{TCSC}}\right)^{(i)} X_{TCSC}^{(i-1)}. \qquad (16)$$

$$\Delta P_{KM}^{X_{TCSC}} = P_{KM}^{reg} - P_{KM}^{X_{TCSC,CAL}} \qquad (17)$$

where

$\Delta P_{KM}^{X_{TCSC}}$ = is the active power flow mismatch for the series reactance.

$P_{KM}^{X_{TCSC,CAL}}$ =Active power flow mismatch for the series reactance calculated

ΔX_{TCSC} =Incremental change in series reactance.

Voltage stability enhancements using TCSC FACTS devices is done through the simulation of 28 Bus Nigerian system.All the results were simulated using MATLAB software package.

IV. RESULTS AND DISCUSSION

A. *Power Flow Solutions By Newton Raphson Method Without TCSC*

Table 1: Shows the power flow solutions obtained for 330kV Nigerian 28-bus systems. Accuracy of $1.0000e-003$ was specified in the power flow program. The maximum power mismatch of **5.62078e-013** was obtained from the power flow solutions . The power flow solutions converged after the sixth iterations.

Table 1 : Power Flow Solutions with the incorporation of TCSC .

Bus No	Bus Name	V mag	Angle	Load		Generation		Injected Mvar
				MW	Mvar	MW	Mvar	
1	Egbin	1.05	0	68.9	51.7	157.077	534.301	0
2	Delta	1.05	11.840	0	0	670	-20.072	0
3	Aja	1.045002	-0.284	274.4	205.8	0	0	0
4	Akangba	1.019000	0.641000	344.7	258.5	0	0	0
5	Ikeja	1.026000	1.065000	633.2	474.9	0	0	0
6	Ajaokuta	1.062000	5.964000	13.8	10.3	0	0	0
7	Aladja	1.046000	10.274000	96.5	72.4	0	0	0
8	Benin	1.041988	6.322526	383.3	287.5	0	0	220
9	Ayede	0.990000	1.971000	275.8	206.8	0	0	0
10	Osogbo	1.031329	7.598075	201.2	150.9	0	0	0
11	Afam	1.050	10.228506	52.5	39.4	431	317.533	0
12	Alaoji	1.038576	9.568036	427	320.2	0	0	0
13	New Heaven	0.977405	2.442125	177.9	133.4	0	0	0
14	Onitsha	0.994111	3.766746	184.6	138.4	0	0	0
15	Benin-Kebbi	1.065158	13.60812	114.5	85.9	0	0	0
16	Gombe	0.994309	3.685436	130.6	97.9	0	0	0
17	Jebba	1.050429	13.29209	11	8.2	0	0	0
18	Jebbag	1.050	13.55508	0	0	495	-101.197	0
19	Jos	1.051115	9.797341	70.3	52.7	0	0	0
20	Kaduna	1.040614	5.939039	193	144.7	0	0	0
21	Kainji	1.050	16.46028	7	5.2	624.7	-267.215	0
22	Kano	1.010324	1.96829	220.6	142.9	0	0	0
23	Shiroro	1.050	8.110324	70.3	36.1	388.9	55.221	0

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24	Sapele	1.050	7.870147	20.6	15.4	190.3	113.876	0
25	Abuja	1.049208	13.63107	110	89	0	0	0
26	Okpai	1.029469	6.032123	290.1	145	0	0	0
27	AES	1.050	25.28007	0	0	750	-106.810	0
28	Calabar	1.050	3.274112	0	0	750	319.204	0
				4371.8	3173.2	4456.977	844.842	0

There was voltage Drop at Ayede, New Heaven,Onitsha,Gombe, therefore it was neccessary to apply TCSC to these busses at the sending end while the voltage magnitude at the recieving end was observed. The maximum power mismatch was found to be equal to **= 5.62078e-013** and the reinforced power flow solution converged after the sixth iteration. It is observed from the power flow solution of Table 2, that the set of voltage magnitudes of Ayede, New Heaven, Onitsha, Gombe, have drastically increased, therefore the reactive power generated by the system has decreased from 844.842Mvar to 756.5735Mvar, which shows that the system is generating less reactive power.

The power flow results obtained for 330kV Nigerian 28-bus system when a TCSC was applied to the low voltage busses is as shown in Table 2. TCSC was used in this work to regulate the voltage magnitude where needed, taking into consideration IEEE standard acceptable limits of ± 10% tolerance.In this work, the per unit voltage V was taken as 1.0.

Table 2 : Power flow solution for Nigerian 330kV 28-bus power systems with TCSC

Bus No	Bus Name	V mag	Angle	Load		Generation	
				MW	Mvar	MW	Mvar
1	Egbin	1.05	0	68.9	51.7	159.2963	512.8523
2	Delta	1.05	10.5161	0	0	670	-21.9478
3	Aja	1.045002	-0.284	274.4	205.8	0	0
4	Akangba	1.020349	0.616772	344.7	258.5	0	0
5	Ikeja	1.027723	1.039514	633.2	474.9	0	0
6	Ajaokuta	1.062105	4.638789	13.8	10.3	0	0
7	Aladja	1.045663	8.950866	96.5	72.4	0	0
8	Benin	1.041988	4.996256	383.3	287.5	0	0
9	Ayede	1.011047	4.723496	275.8	206.8	0	0
10	Osogbo	1.030329	4.478075	201.2	150.9	0	0
11	Afam	1.05	8.274506	52.5	39.4	431	303.5987
12	Alaoji	1.038576	7.610936	427	320.2	0	0
13	New Heaven	0.989405	2.288125	177.9	133.4	0	0
14	Onitsha	0.996111	2.135746	184.6	138.4	0	0
15	Benin-Kebbi	1.064558	10.59482	114.5	85.9	0	0
16	Gombe	1.041309	7.695436	130.6	97.9	0	0
17	Jebba	1.050429	10.27959	11	8.2	0	0
18	Jebbag	1.05	10.54158	0	0	495	-95.5973
19	Jos	1.056115	7.486341	70.3	52.7	0	0
20	Kaduna	1.040614	3.267539	193	144.7	0	0
21	Kainji	1.05	13.44698	7	5.2	624.7	-266.749
22	Kano	1.011324	-0.69529	220.6	142.9	0	0
23	Shiroro	1.05	5.346324	70.3	36.1	388.9	45.81979
24	Sapele	1.05	6.547647	20.6	15.4	190.3	105.7879
25	Abuja	1.051608	11.46547	110	89	0	0
26	Okpai	1.029469	3.268123	290.1	145	0	0
27	AES	1.05	23.10507	0	0	750	-115.12

28	Calabar	1.05	3.258512	0	0	750	287.9288
				4371.8	3173.2	4459.196	756.5735

Table 3 shows the summary of the results of the voltage magnitude obtained with and without TCSC.

Table 3 : Comparison of the Results with and without TCSC.

Bus no	Bus Name	V mag(without TCSC)	V mag (with TCSC)
1	Egbin	1.05	1.05
2	Delta	1.05	1.05
3	Aja	1.04	1.04
4	Akangba	1.01	1.02
5	Ikeja	1.02	1.02
6	Ajaokuta	1.06	1.06
7	Aladja	1.04	1.04
8	Benin	1.04	1.04
9	Ayede	**0.99**	**1.01**
10	Osogbo	1.03	1.03
11	Afam	1.05	1.05
12	Alaoji	1.03	1.03
13	NewHeaven	**0.977**	**0.989**
14	Onitsha	**0.994**	**0.996**
15	Benin-kebbi	1.06	1.06
16	Gombe	**0.994**	**1.04**
17	Jebba	1.05	1.05
18	Jebbag	1.05	1.05
19	Jos	1.05	1.05
20	Kaduna	1.04	1.04
21	Kainji	1.05	1.05
22	Kano	1.01	1.01
23	Shiroro	1.05	1.05
24	Sapele	1.05	1.05
25	Abuja	1.04	1.05
26	Okpai	1.02	1.02
27	AES	1.05	1.05
28	Calabar	1.05	1.05

The Bar Chart Showing the Difference in Voltage Profile with and without TCSC is shown in Figure 4.

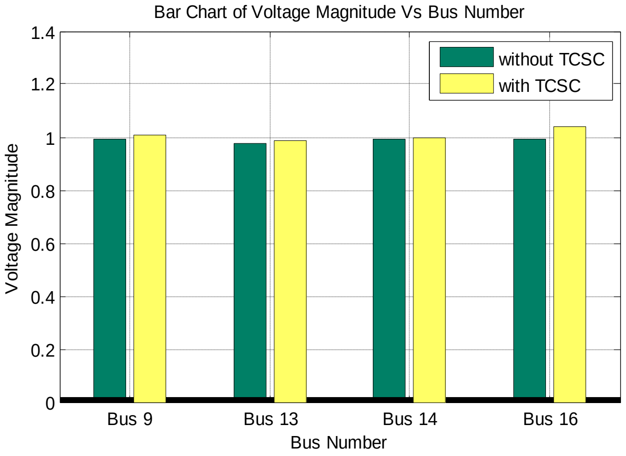

Figure 4 : Bar chart reprentation of the difference in voltage profile

V. CONCLUSION

Voltage stability is neccesary due to insufficient generation, fragile nature of transmission lines and poor system protection. As a result of these, the strengthening of the system by incorporating TCSC has helped to improved voltage stability in the system. In this work, the power flow analysis of the Nigerian 330kV grid system was done and the incorporation of TCSC into the power flow programme developed was carried out successfully. Simulations carried out confirmed that TCSC provide improvement to the voltage instability and voltage collase at the weak buses. However, the analysis carried out did not consider multi-line FACTS devices such as, Inter-line Power Flow Controller(IPFC) and Generalized Unified Power Low Controller(GUPFC).

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