CONGESTION MANAGEMENT USING TCSC AND UPFC

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ABSTRACT*—In this paper use of FACTS devices for congestion management in the power systems has been analysed. The comprehensive modelling of most popular FACTS devices has been done. The effectiveness of modelling and its application for congestion management has been tested on a standard 5 bus system without TCSC & UPFC and with TCSC & UPFC. The standard Newton-Raphson method is used to solve the nonlinear power flow equation. Also, the study is extended for IEEE 14 bus system. Programming of the power flow studies stated above is implemented using MATLAB.

***Keywords**:- Load Flow Analysis, Newton-Raphson Method, FACTS, TCSC, UPFC.*

I.INTRODUCTION:

The electricity supply industry is undergoing a profound transformation worldwide. With the rapid development of power system, especially the increased use of transmission facilities due to higher industrial output and deregulation, it becomes necessary to explore new ways of maximizing power transfer in existing transmission facilities, while at the same time maintaining the acceptable levels of the network security, reliability and stability. On the other hand, the fast development of power electronic technology has made FACTS (flexible AC Transmission system) promising solution of future power system. FACTS controllers such as Static Synchronous Compensator (STATCOM), Static VAR Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), Static Synchronous Series Compensator (SSSC) and Unified Power Flow controller (UPFC) are able to change the network parameters in a fast and effective way in order to achieve better system performance [1], [2]. These controllers are used for enhancing dynamic performance of power systems in terms of voltage/angle stability while improving the power transfer capability and voltage profile in steady-state conditions [3]. Thyristor Controlled Series Capacitor (TCSC) is a variable impedance type series compensator and is connected in series with the transmission line to increase the power transfer capability, improve transient stability, reduce transmission losses and mitigate power system oscillations. TCSC is a series compensator, which allows rapid and continuous changes of transmission impedance, controlling power flow in the line and improving system stability. UPFC is a powerful device which can control both transmitted active and reactive power flow as well as bus voltages. Now, for maximum utilization of any FACTS device in power system planning, operation and control, power flow solution of the network that contains any of these devices is a fundamental requirement. As a result, many excellent research works have been carried out in the literature for developing efficient load flow algorithm for FACTS devices. This paper focuses on the development of TCSC and UPFC models and their implementation in Newton-Raphson load flow algorithm, to control voltage of the bus, active power across the line and calculate total losses of the system.

In section (II) of this paper basic of power flow analysis is represented, while section (III) Newton Raphson algorithm is represented. The rest of the sections are organized as follows: in section (IV) modelling of TCSC is presented: in section (V) modelling of UPFC is presented. The system and result are presented in section (VI).Finally; conclusion is discussed in section (VII).

II.POWER FLOW ANALYSIS:

Load flow studies are one of the most important aspects of power system planning and operation. The load flow provides us the sinusoidal steady state of the entire system - voltages, real, reactive powers and line losses. It provides solution of the network under steady state condition subjected to certain inequality constraints such as nodal voltages, reactive power generation of the generators. Load flow study gives the voltage magnitudes and angles at each bus in the steady state. This is rather important as the magnitudes of the bus voltages are required to be held within a specified limit. Once the bus voltage magnitudes and their angles are computed, the real and reactive power flow through each line can be computed. Also based on the difference between power flow in the sending and receiving ends, the losses in particular line can also be computed.

III. THE NEWTON RAPHSON ALGORITHM:

In large scale power flow studies, the Newton Raphson has proved most successful owing to its strong convergence characteristics. In general, power flow Newton Raphson algorithm is expressed by the following relationship [4].

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=-\begin{bmatrix}\Delta P/\Delta\theta & \Delta P/(\Delta v/v)\\ \Delta Q/\Delta\theta & \Delta Q/(\Delta v/v)\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta(\frac{\Delta v}{v})\end{bmatrix} \qquad (1)$$

Consider the 1st element connected between buses k and m in fig.1, for which self and mutual Jacobian terms are given below:

For k#m.

$$\partial P_{k,1}/\partial\theta_{m,1}=V_kV_m[G_{km}\sin(\theta_k-\theta_m)-B_{km}\cos(\theta_k-\theta_m)] \qquad (2)$$

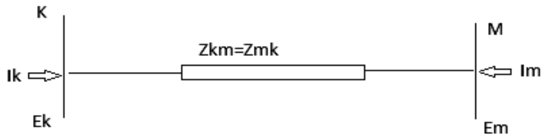

Figure.1.Equivalent impedance

$$\frac{\partial Pk,1}{\partial Vm,1/Vm,1}= V_kV_m[G_{km}\cos(\theta_k-\theta_m)+B_{km}\sin(\theta_k-\theta_m)] \qquad (3)$$

$$\frac{\partial Qk,1}{\partial\theta m,1}=-\frac{\partial Pk,1}{\partial Vm,1/Vm,1}$$

$$\frac{\partial Qk,1}{\partial Vm,1/vm,1}=\frac{\partial Pk,1}{\partial\theta m,1} \qquad (4)$$

For k=m

$$\partial P_{k,l}/\partial\theta_{k,l}=(-Q_k^{cal}-V_k^2B_{kk}) \qquad (5)$$

$$\frac{\partial Pk,1}{\partial Vk,1/Vk,1}=P_k^{cal}+V_k^2G_{kk} \qquad (6)$$

$$\partial Q_{k,l}/\partial\theta_{k,l}=P_k^{cal}-V_k^2G_{kk} \qquad (7)$$

$$\frac{\partial Qk,1}{\partial Vk,1/Vk,1}=Q_k^{cal}-V_k^2B_{kk} \qquad (8)$$

The mutual elements remain the same whether we have one transmission line or n transmission lines terminating at bus k.

IV.MODELLING OF TCSC

Power flow calculations are performed in power systems for planning, operational planning, and operation/control. Flexible AC transmission system (FACTS) controllers are able to change the network parameters in a fast and effective way in order to achieve better system performance. These controllers are used for enhancing dynamic performance of power systems in terms of voltage/angle stability while improving the power transfer capability and voltage profile in steady state. The mathematical models of the FACTS devices are developed mainly to perform the steady-state research [5]. Therefore the TCSC is modelled to modify the reactance of the transmission directly. The function of the TCSC is to alter the value of the transmission line reactance by adding either a capacitive or inductive component to the main transmission line reactance as shown in Fig 2.

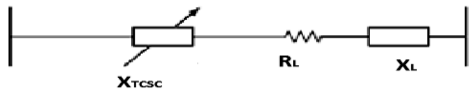

Fig.2 The effect of TCSC on transmission line reactance[5].

The reactance of the line where TCSC is placed is given by:

$$X_{ij}=X_L+X_{TCSC}. \qquad (9)$$

Where X_L is the reactance of the transmission line and X_{TCSC} is the reactance of TCSC. To avoid overcompensation, the working range of TCSC is selected between $-0.7X_L$ and $0.2\ X_L$. After adding TCSC on the line between bus i and bus j of a general power system, the new system admittance matrix Y'_{bus} can be updated as:

$$Y'_{bus}=Y_{bus}+\begin{bmatrix}0 & 0 & 0 & \cdots & 0 & 0 & 0\\ 0 & \Delta Y_{ij} & 0 & \cdots & 0 & -\Delta Y_{ij} & 0\\ & \vdots & & \ddots & & \vdots & \\ 0 & -\Delta Y_{ij} & 0 & \cdots & 0 & \Delta Y_{ij} & 0\\ 0 & 0 & 0 & & 0 & 0 & 0\end{bmatrix} \qquad \ldots\ldots\ldots(10)$$

Because the Y_{bus} has to be updated for each of different locations and the amount of compensation of TCSC, the above formulation is applied to each iteration.

V. MODELLING OF UPFC

The UPFC equivalent circuit consists of two coordinated synchronous voltage sources for the purpose of fundamental frequency steady state analysis. Such an equivalent circuit is shown in Fig. 3. The UPFC voltage sources are:

$$E_{vR}=V_{vR}(cos_{vR}+jsin_{vR}) \qquad (11)$$

$$E_{cR} = V_{cR}(cos_{cR} + jsin_{cR}) \qquad (12)$$

Where, V_{vR} and δ_{vR} are the controllable magnitude ($V_{vRmin} \le V_{vR} \le V_{vRmax}$) and phase angle ($0 \le \delta_{vR} \le \delta 2\Pi$) of the voltage source representing the shunt converter. The magnitude V_{cR} and phase angle δ_{cR} of the voltage source representing the series converter are controlled between limits ($V_{cRmin} \le V_{cR} \le V_{cRmax}$) and ($0 \le \delta_{cR} \le \delta 2\Pi$) respectively. The phase angle of the series injected voltage determines the mode of power flow control [6].

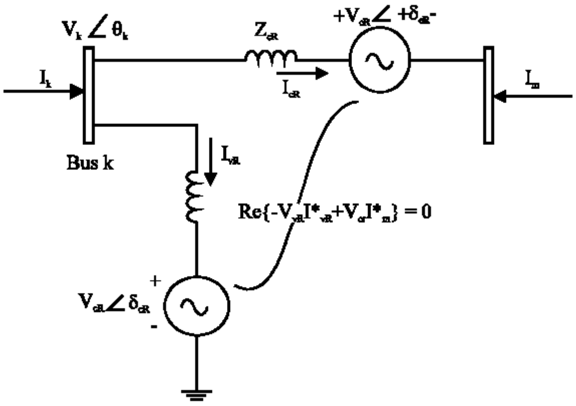

Fig. 3. Unified Power flow controller equivalent circuit [6].

If δ_{cR} is in phase with nodal voltage angle θ_k, the UPFC regulates the terminal voltage. If δ_{cR} is in quadrature with θ_k, it control active power flow, acting as a phase shifter. If $\delta_{cR\ r}$ is in quadrature with line current angle than it control active power flow, acting as a variable series compensator. At any other value of δ_{cR} , the UPFC operates as a combination of voltage regulator, variable series compensator and phase shifter. The magnitude of the series injected voltage determines the amount of power flow to be controlled. Based on the equivalent circuit shown as in fig. 3 the active and reactive power equations are:

At bus K:

$$P_k = V_k^2 G_{kk} + V_k V_m [G_{km} \cos(\theta_k - \theta_m) + B_{km} \sin(\theta_k - \theta_m)] + V_k V_{cR} [G_{km} \cos(\theta_k - \delta_{cR}) + B_{km} \sin(\theta_k - \delta_{cR})] + V_k V_{vR} [G_{vR} \cos(\theta_k - \delta_{vR}) + B_{vR} \sin(\theta_k - \delta_{vR})] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (13)$$

$$Q_k = -V_k^2 B_{kk} + V_k V_m [G_{km} \sin(\theta_k - \theta_m) - B_{km} \cos(\theta_k - \theta_m)] + V_k V_{cR} [G_{km} \sin(\theta_k - \delta_{cR}) + B_{km} \cos(\theta_k - \delta_{cR})] + V_k V_{vR} [G_{vR} \sin(\theta_k - \delta_{vR}) - B_{vR} \cos(\theta_k - \delta_{vR})] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (14)$$

At bus m:

$$P_m = V_m^2 G_{mm} + V_m V_k [G_{mk} \cos(\theta_m - \theta_k) + B_{mk} \sin(\theta_m - \theta_k)] + V_m V_{cR} [G_{mm} \cos(\theta_m - \delta_{cR}) + B_{mm} \sin(\theta_m - \delta_{cR})] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (15)$$

$$Q_m = -V_m^2 B_{mm} + V_m V_k [G_{mk} \sin(\theta_m - \theta_k) - B_{mk} \cos(\theta_m - \theta_k)] + V_m V_{cR} [G_{mm} \sin(\theta_m - \delta_{cR}) - B_{mm} \cos(\theta_m - \delta_{cR})] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (16)$$

Series converter:

$$P_{cR} = V_{cR}^2 G_{mm} + V_{cR} V_k [G_{km} \cos(\delta_{cR} - \theta_k) + B_{km} \sin(\delta_{cR} - \theta_k)] + V_{cR} V_m [G_{mm} \cos(\delta_{cR} - \theta_m) + B_{mm} \sin(\delta_{cR} - \theta_m)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (17)$$

$$Q_{cR} = -V_{cR}^2 B_{mm} + V_{cR} V_k [G_{km} \sin(\delta_{cR} - \theta_k) - B_{km} \cos(\delta_{cR} - \theta_k)] + V_{cR} V_m [G_{mm} \sin(\delta_{cR} - \theta_m) - B_{mm} \cos(\delta_{cR} - \theta_m)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (18)$$

Shunt converter:

$$P_{vR} = -V_{vR}^2 G_{vR} + V_{vR} V_k [G_{vR} \cos(\delta_{vR} - \theta_k) + B_{vR} \sin(\delta_{vR} - \theta_k)] \qquad (19)$$

$$Q_{vR} = V_{vR}^2 B_{vR} + V_{vR} V_k [G_{vR} \sin(\delta_{vR} - \theta_k) - B_{vR} \cos(\delta_{vR} - \theta_k) \quad \ldots\ldots\ldots\ (20)$$

VI. ANALYSIS OF 5 BUS AND IEEE 14 BUS SYSTEM

In case study we have considered the five bus and fourteen bus system.. The results of power flow analysis are shown in table 1. Voltage magnitude and Angle with FACTS device is shown in table 2. Also the result of line flow and total losses in the system is shown in table 3 and table 4 respectively.

Table.1. Power flow result of 5 bus and IEEE 14 bus system.

(a) Voltage magnitude and Angle without FACTS device.

Bus number	Voltage magnitude(p.u.)	Angle(degree)
1	1.060000	0.00000
2	0.980535	-2.683182
3	0.964013	-5.824936
4	0.959828	-6.238987
5	0.943962	-7.305626

(b)Line flows without FACTS device.

From-To	Real power(p.u.)	Reactive power(p.u.)
1-2	1.156703	1.003591
1-5	0.522680	0.243611
2-3	0.288398	-0.017464
2-4	0.328712	-0.005933

2-5	0.656624	0.090635
3-4	0.241180	0.045591
4-5	0.082480	0.013581

(c)Voltage magnitude and Angle without FACTS device

Bus number	Voltage magnitude (p.u.)	Angle(degree)
Bus-1	1.060	0.000
Bus-2	1.045	-4.980
Bus-3	1.010	-12.711
Bus-4	1.019	-10.327
Bus-5	1.020	-8.783
Bus-6	1.070	-14.223
Bus-7	1.062	-13.371
Bus-8	1.090	-13.371
Bus-9	1.056	-14.949
Bus-10	1.051	-15.106
Bus-11	1.057	-14.796
Bus-12	1.055	-15.078
Bus-13	1.050	-12.159
Bus-14	1.036	-16.040

(d)Line flow without FACTS device.

From -To	Pij	Qij	Pji	Qji
1-2	1.568	-0.204	-1.525	0.277
1-5	0.756	-0.038	-0.728	0.029
2-3	0.732	0.039	-0.709	-0.019
2-4	0.561	-0.031	-0.545	0.029
2-5	0.415	0.007	-0.406	-0.016
3-4	-0.233	0.027	0.237	-0.053
4-5	-0.612	0.160	0.617	-0.157
4-7	0.281	-0.094	-0.281	0.111
4-9	0.161	-0.003	-0.161	0.016
5-6	0.441	0.129	-0.441	-0.084
6-11	0.073	0.035	-0.073	-0.033
6-12	0.078	0.025	-0.077	-0.023
6-13	0.177	0.072	-0.175	-0.067
7-8	0.000	-0.169	0.000	0.173
7-9	0.281	0.058	-0.281	-0.050
9-10	0.052	0.043	-0.052	-0.043
9-14	0.094	0.037	-0.093	-0.034
10-11	-0.038	-0.015	0.038	0.015
12-13	0.016	0.007	-0.016	-0.007
13-14	0.056	0.017	-0.056	-0.016

Table 2.Voltage magnitude and Angle with FACTS device.

(a)Voltage magnitude and Angle with TCSC

Bus number	Voltage magnitude	Angle
1	1.060000	0.00000
2	1.000000	-1.811165
3	1.000000	-4.366544
4	0.993686	-4.645884
5	0.978246	-5.005740

(b)Voltage magnitude and Angle with TCSC device

Bus number	Voltage Magnitude (p.u.)	Angle(degree)
Bus-1	1.060000	0.000000
Bus-2	1.045000	-5.091991
Bus-3	1.010000	-12.639217
Bus-4	1.018580	-10.064621
Bus-5	1.020044	-8.396918
Bus-6	1.070000	-13.877920
Bus-7	1.061884	-13.087367
Bus-8	1.090000	-13.087367
Bus-9	1.056209	-14.654830
Bus-10	1.051203	-14.803277
Bus-11	1.057206	-14.472694
Bus-12	1.055218	-14.736483
Bus-13	1.050412	-14.821708
Bus-14	1.035699	-15.727632

(c)Voltage magnitude and Angle with UPFC

Bus number	Voltage magnitude	Angle
1	1.060000	0.000000
2	0.990933	-2.528079
3	0.975588	-5.586790
4	0.97826	-5.964612
5	0.970648	-6.726132

(d)Voltage magnitude and Angle with UPFC device

Bus number	Voltage magnitude (p.u.)	Angle(degree)
Bus-1	1.060	0.00
Bus-2	1.050	-4.034
Bus-3	1.026	-11.009
Bus-4	1.081	-9.008
Bus-5	1.064	-7.667

Bus-6	1.018	-13.211
Bus-7	1.040	-12.170
Bus-8	1.040	-12.170
Bus-9	1.019	-13.933
Bus-10	1.011	-14.123
Bus-11	1.011	-13.820
Bus-12	1.000	-14.138
Bus-13	1.000	-14.236
Bus-14	0.990	-15.154

Table 3. Real and Reactive power of the line.

(a)Real and Reactive power of the line without FACTS device.

Bus system	Line number	Line flow	
		Real Power (p.u.)	Reactive Power(p.u.)
5 Bus	1-3	0.522	0.243
14Bus	2-5	0.009	-0.009

(b)Real and Reactive power of the line with TCSC.

Bus system	Line number	Line flow	
		Real Power(p.u.)	Reactive Power(p.u.)
5 Bus	1-3	0.320	0.187
14Bus	2-5	0.013	-0.008

(c)Real and Reactive power of the line with UPFC.

Bus system	Line number	Line flow	
		Real Power(p.u.)	Reactive Power(p.u.)
5 Bus	1-3	0.495	0.200
14Bus	2-5	0.0147	-0.0247

Table 4.Losses of system with FACTS device.

(a) Total system losses without FACTS device.

Bus system	Total losses.
5 Bus	0.099
14Bus	0.253

(b) Total system losses with TCSC

Bus system	Total losses.
5 Bus	0.053
14Bus	0.135

(c) Total system losses with UPFC

Bus system	Total losses.
5 Bus	0.081
14Bus	0.112

APPENDIX: The input data for the system

(a)Bus Data of 5 bus system

Bus no	Pgen	Qgen	Pload	Qload	Bus type*
1	0.0	0.0	0.00	0.0	1
2	0.4	-0.75	0.24	0.12	2
3	0.0	0.0	0.54	0.18	2
4	0.0	0.0	0.48	0.06	3
5	0.0	0.0	0.72	0.12	3

(b)Line data of 5 bus system

From	To	Resistance	Reactance	Line charging
1	2	0.02	0.06	0.030
1	3	0.08	0.24	0.025
2	3	0.06	0.18	0.020
2	4	0.06	0.18	0.020
2	5	0.04	0.12	0.015
3	4	0.01	0.03	0.010
4	5	0.08	0.24	0.025

(c)Bus Data of the IEEE 14 bus system

Bus no	Pgen	Qgen	Pload	Qload	Bus* type	Qmax	Qmin
1	2.32	0.00	0.000	0.000	1	0.0	0.0
2	0.40	-0.42	0.217	0.127	2	0.50	-0.4
3	0.00	0.00	0.942	0.190	2	0.40	0.0
4	0.00	0.00	0.478	-0.04	3	0.00	0.0
5	0.00	0.00	0.076	0.016	3	0.00	0.0
6	0.00	0.00	0.112	0.075	2	0.24	-0.1
7	0.00	0.00	0.000	0.000	3	0.00	0.0
8	0.00	0.00	0.000	0.000	2	0.24	-0.1
9	0.00	0.00	0.295	0.166	3	0.00	0.0
10	0.00	0.00	0.090	0.058	3	0.00	0.0
11	0.00	0.00	0.035	0.018	3	0.00	0.0
12	0.00	0.00	0.061	0.016	3	0.00	0.0
13	0.00	0.00	0.135	0.058	3	0.00	0.0
14	0.00	0.00	0.149	0.050	3	0.00	0.0

(d)Line Data of the IEEE 14 bus system

From	To	Resistance (p.u.)	Reactance	Line charging	Tap ratio
1	2	0.01938	0.05917	0.0528	1
1	5	0.05403	0.22304	0.0492	1
2	3	0.04699	0.19797	0.0438	1
2	4	0.05811	0.17632	0.0974	1
2	5	0.05695	0.17388	0.0340	1
3	4	0.06701	0.17103	0.0346	1
4	5	0.01335	0.04211	0.0128	1
4	7	0.00000	0.20912	0.0000	0.978
4	9	0.00000	0.55618	0.0000	0.969
5	6	0.00000	0.25202	0.0000	0.932
6	11	0.09498	0.1989	0.0000	1
6	12	0.12291	0.25581	0.0000	1
6	13	0.06615	0.13027	0.0000	1
7	8	0.00000	0.17615	0.0000	1
7	9	0.00000	0.11001	0.0000	1
9	10	0.03181	0.0845	0.0000	1
9	14	0.12711	0.27038	0.0000	1
10	11	0.08205	0.19207	0.0000	1
12	13	0.22092	0.19988	0.0000	1
13	14	0.17093	0.34802	0.0000	1

*(1) Swing bus (2) Generator bus (3)) Load bus

TCSC Data:-

Bus system	X_{TCSC}	Firing angle(degree)
5 Bus	-0.008509	147.807345
14Bus	-0.051555	166.95636

UPFC Data:-

Bus system	Constant active power(p_c)	Constant reactive power(q_c)	Exciting transformer reactive current
14 Bus	0.4	0.4	0.9
5 Bus	0.1	0.02	0.01

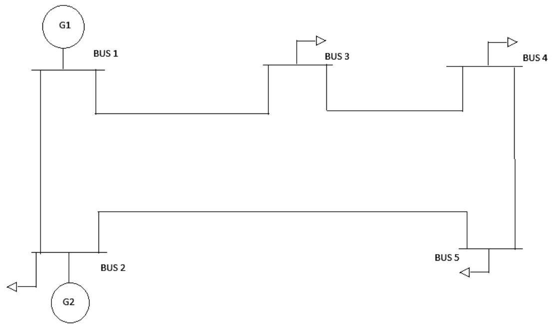

Fig 4. 5Bus test system

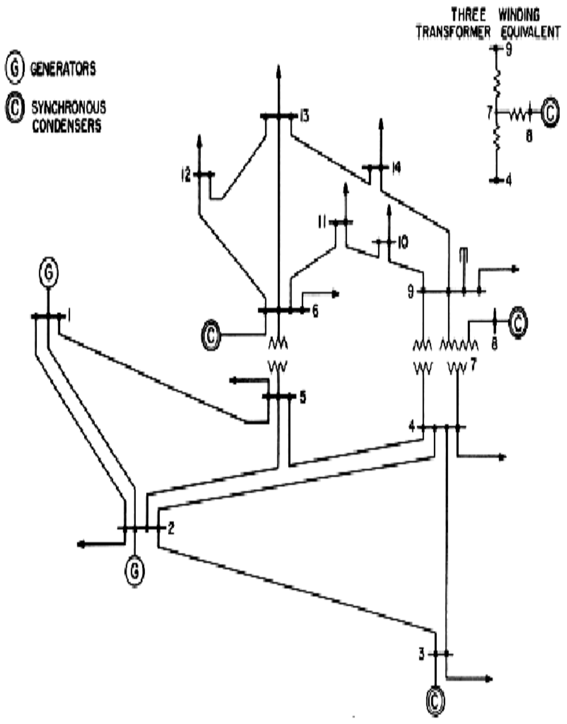

Fig 5.IEEE 14 Bus test system.

VII. CONCLUSION

From the above result it is seen that the TCSC and UPFC are proved quite efficient to minimize losses and improve voltage profile of the system under study.i.e.5 bus & IEEE-14 bus system. The study reveals following conclusion:

- TCSC helps in diverting flow from heavily loaded lines that result in reduction in total system losses.
- UPFC can control both transmitted active and reactive power flow as well as total system losses.

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