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Optimal Location and Cost Analysis of TCSC For Improving Power System Stability & Economy

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Abstract— Due to the deregulation of the electrical market, difficulty in acquiring rights-of-way to build new transmission lines, and steady increase in power demand, maintaining power system stability becomes a difficult and very challenging problem and it may always not be possible to dispatch all of the contracted power transactions due to congestion of the transmission corridors. The ongoing power system restructuring requires an opening of unused potentials of transmission system due to environmental, right-of-way and cost problems which are major hurdles for power transmission network expansion. Flexible ac transmission systems devices can be an alternative to reduce the flows in heavily loaded lines, resulting in an increased loadability, low system loss, improved stability of the network, reduced cost of production and fulfilled contractual requirement by controlling the power flows in the network. A method to determine the optimal location and cost Analysis of thyristor controlled series compensators (TCSC) has been suggested in this paper based on reduction of total system reactive power loss and real power performance index. The proposed method has been demonstrated on IEEE 30 Bus power system in PSAT (Power System Analysis & Simulation Toolbox) for effectiveness of the study.

Keywords- FACTS, PSAT, IEEE 30 Bus System, Optimal Location, Sensitivity Methods

I. INTRODUCTION

In a competitive electricity market, congestion occurs when the transmission network is unable to accommodate all of the desired transactions due to a violation of system operating limits. Congestion does occur in both electrically bundled and unbundled systems but the management in the bundled system is relatively simple as generation, transmission, and in some cases, distribution systems are managed by one utility. The management of congestion is somewhat more complex in competitive power markets and leads to several disputes. In the present day competitive power market, each utility manages the congestion in the system using its own rules and guidelines utilizing a certain physical or financial mechanism The limitations of a power transmission network arising from environmental, right-of-way and cost problems are fundamental to both bundled and unbundled power systems. Patterns of generation that result in heavy flows tend to incur greater losses, and to threaten stability and security, ultimately make certain generation patterns economically undesirable. Hence, there is an interest in better utilization of available power system capacities by installing new devices such as Flexible AC Transmission Systems (FACTS). FACTS devices by controlling the power flows in the network without generation rescheduling or topological changes can improve the performance considerably. The insertion of such devices in electrical systems seems to be a promising strategy to decrease the transmission congestion and to increase available transfer capability. Firstly, the recent development in high power electronics has made these devices cost effective and secondly, increased loading of power systems, combined with deregulation of power industry, motivates the use of power flow control as a very cost effective means of dispatching specified power transactions. It is important to ascertain the location for placement of these devices because of their considerable costs. [2]

There are several methods for finding optimal locations of FACTS devices in both vertically integrated and unbundled power systems. Various Methods are L-index method, Sensitivity methods, Reactive power spot price index method and various Intelligence methods like Fuzzy method, Genetic Algorithm (GA),Particle Swarm Optimization (PSO) etc. A Sensitivity method to determine the optimal location of TCSC has been suggested in this paper. The approach is based on the sensitivity of the reduction of total system reactive power loss and real power performance index. The proposed method has been demonstrated on IEEE 30 Bus system in PSAT.

II. FLEXIBLE AC TRANSMISSION SYSTEM (FACTS)

The FACTS is a generic term representing the application of power electronics based solutions to AC power system. These systems can provide compensation in series or shunt or a combination of both series and shunt. The FACTS can attempt the compensation by modifying impedance, voltage or phase angle. FACTS devices can be connected to a transmission line in various ways, such as in series with the power system (series compensation), in shunt with the power system (shunt compensation), or both in series and shunt.[1]

2.1. Series Facts Devices

The series Compensator could be variable impedance, such as capacitor, reactor, etc. or a power electronics based variable source of main frequency to serve the desired need. Various Series connected FACTS devices are;

- Static Synchronous Series Compensator (SSSC)
- Thyristor Controlled Series Capacitor (TCSC)
- Thyristor Switched Series Capacitor (TSSC)
- Thyristor Controlled Series Reactor (TCSR)
- Thyristor Switched Series Reactor (TSSR)

2.2. Shunt Facts Devices

Shunt Controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt Controllers inject current into the system at the point of connection. Various shunt connected controllers are;

- Static Synchronous Series Compensator (STATCOM)
- Static VAR Compensator (SVC)
- Thyristor Controlled Reactor (TCR)
- Thyristor Switched Capacitor (TCS)

2.3. Combined Series-Shunt Facts Devices

This may be a combination of separate shunt and series controllers, which are controlled in a coordinated manner or a Unified Power Flow Controller with series and shunt elements. In principle, combined shunt and series controllers inject current into the system with shunt part of controller and voltage with the series part of controller. Various combined series shunt Controllers are: Various combined series shunt Controllers are[1]

- Unified Power Flow Controller
- Thyristor Controlled Phase Shifter

III. CHARACTERISTICS OF TCSC

Thyristor Controlled Series Capacitor (TCSC) is a series compensator which increases transmission line capacity by decreasing lines' series impedances and increase network reliability. The TCSC concept is that it uses an extremely simple main circuit. The capacitor is inserted directly in series with the transmission line and the thyristor-controlled inductor is mounted directly in parallel with the capacitor. Thus no interfacing equipment like for example high voltage transformers is required. The bi-directional thyristor valve is fired with an angle α ranging between 90° and 180° with respect to the capacitor voltage. This makes TCSC much more economic than some other competing FACTS technologies. Thus it makes TCSC simple and easy to understand the operation. Series compensation will;[1]

- Increase power transmission capability.
- Improve system stability.
- Reduce system losses.
- Improve voltage profile of the lines.
- Optimize power flow between parallel lines.

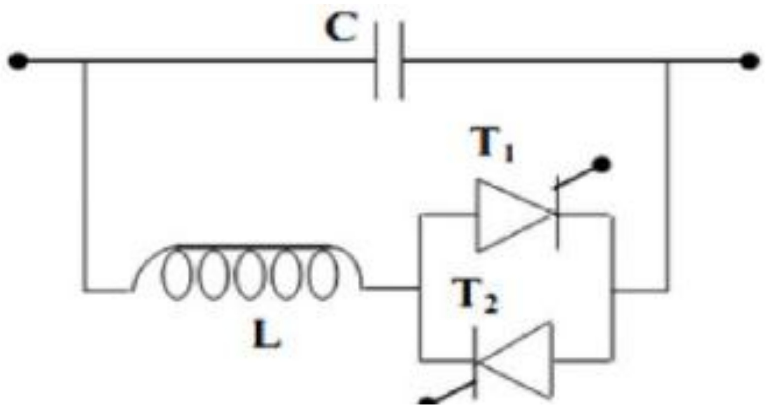

Figure 1. Schematic Diagram of TCSC

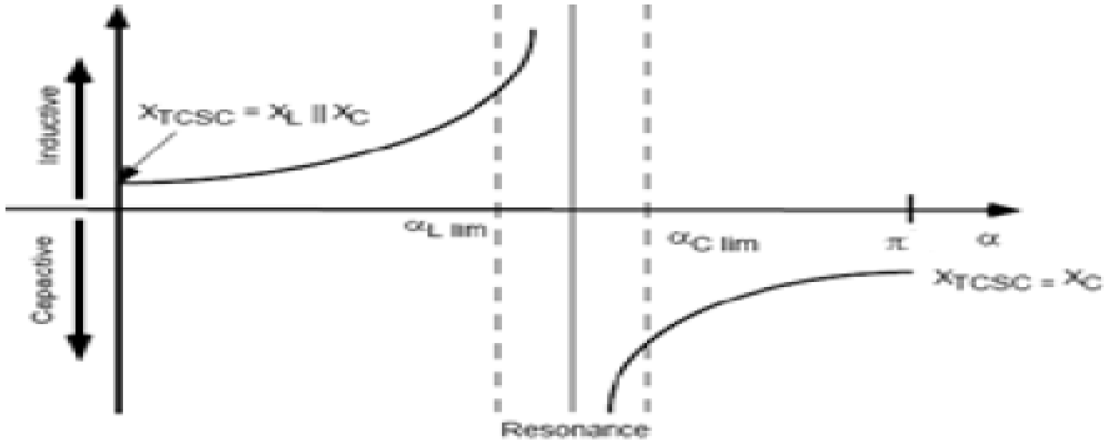

Figure 2. Variation of Impedance in Case of TCSC

Fig.2 shows the impedance characteristics curve of a TCSC device. It is drawn between effective reactance of TCSC and firing angle α. The effective reactance of TCSC starts increasing from X_L value to till occurrence of parallel resonance condition $X_L(\alpha) = X_C$, theoretically X_{TCSC} is infinity. This region is inductive region. Further increasing of $X_L(\alpha)$ gives capacitive region, Starts decreasing from infinity point to minimum value of capacitive reactance X_C. Thus, impedance characteristics of TCSC shows, both capacitive and inductive region are possible though varying firing angle (α).[1]

- $90 < \alpha < \alpha_{Llim}$...................Inductive Region
- $\alpha_{Clim} < \alpha < 180$.................Capacitive Region
- $\alpha_{Llim} < \alpha < \alpha_{Clim}$.................Resonance Region

While selecting inductance, X_L should be sufficiently smaller than that of the capacitorX_C . Since to get both effective inductive and capacitive reactance across the device. Suppose if X_C is smaller than the X_L then only capacitive region is possible in impedance characteristics. In any shunt network, the effective value of reactance follows the lesser reactance present in the branch. So only one capacitive reactance region will appears. Also X_L should not be equal to X_C value; or else a resonance develops that result in infinite impedance an unacceptable condition and transmission line would be an open circuit. The impedance of TCSC circuit is that for a parallel LC circuit and is given by;
The impedance of TCSC circuit is that for a parallel LC circuit and is given by;

$$X_{TCSC}(\alpha) = \frac{Xc\, X_L\,(\alpha)}{X_L(\alpha) - Xc} \qquad (1)$$

Where $X_L\ (\alpha) = X_L.\frac{\pi}{\pi-2\alpha-sin\alpha}$ (2)

α=firing angle

X_L=Inductive reactance

$X_L\ (\alpha)$=Effective reactance of the inductor at firing angle α & is limited thus;[3]

IV. OPTIMAL LOCATION OF TCSC

3.1. Reduction of total system reactive power loss (a_{ij})[2]

Here we have used method based on the sensitivity of the total system reactive power loss with respect to the control variable of the TCSC. For TCSC placed between buses i and j we consider net line series reactance as a control parameter. Loss sensitivity with respect to control parameter of TCSC placed between buses i and j can be written as

$$a_{ij} = \frac{\partial Q_L}{\partial x_{ij}} = \left[V_i^{\ 2} + V_j^{\ 2} - 2V_iV_j\ cos\ \delta_{ij}\right].\frac{r_{ij}^2-x_{ij}^2}{(r_{ij}^2+x_{ij}^2)^2} \tag{3}$$

3.2 Real power flow performance index sensitivity indices (bij)[2]

The severity of the system loading under normal and contingency cases can be described by a real power line flow performance index as given below.

$$\mathrm{PI} = \sum_{m=1}^{N_L} \frac{W_m}{2n}\left(\frac{P_{Lm}}{P_{Lm}^{max}}\right)^{2n} \tag{4}$$

Where P_{Lm} is the real power flow and P_{Lm}^{max} is the rated capacity of the line-m. n is the exponent and W_m a real non negative weighting coefficient which may be used to reflect the importance of lines.

PI will be small when all the lines are within their limits and reach a high value when there are overloads. Thus, it provides a good measure of severity of the line overloads for given state of the power system. Most of the works on contingency selection algorithms utilize the second order performance indices which, in general, suffer from masking effects. The lack of discrimination, in which the performance index for a case with many small violations may be comparable in value to the index for a case with one huge violation, is known as masking effect. By most of the operational standards, the system with one huge violation is much more severe than that with many small violations. Masking effect to some extent can be avoided using higher order performance indices, that is n > 1. However, in this study, the value of exponent has been taken as 2 and $W_i = 1$.

The real power flow PI sensitivity factors with respect to the parameters of TCSC can be defined as

$$b_{ij} = \frac{\partial PI}{\partial x_{ck}}\ /x_{ck=0} \tag{5}$$

Where x_{ck} is the value of the reactance, as provided by the TCSC installed on line k.
The sensitivity of PI with respect to TCSC parameter connected between bus-i and bus-j can be written as

$$\frac{\partial PI}{\partial x_{ck}} = \sum_{m=1}^{N_L} w_m \, P_{Lm}{}^{3} \left(\frac{1}{P_{Lm}{}^{max}}\right)^4 \frac{\partial P_{Lm}}{\partial x_{ck}} \tag{6}$$

The real power flow in a line-m can be represented in terms of real power injections using DC power flow equations where s is slack bus as.

$$P_{Lm} = \begin{cases} \sum_{\substack{n=1 \\ n\neq s}}^{N} S_{mn} P_n & for\ m \neq k \\ \sum_{\substack{n=1 \\ n\neq s}}^{N} S_{mn} P_n + P_s & for\ m = k \end{cases} \tag{7}$$

Using equation (5) the following relationship can be derived.

$$\frac{\partial P_{Lm}}{\partial x_{ck}} = \begin{cases} \left(S_{mi} \frac{\partial P_i}{\partial x_{ck}} + S_{mj} \frac{\partial P_j}{\partial x_{ck}}\right) & for\ m \neq k \\ \left(S_{mi} \frac{\partial P_i}{\partial x_{ck}} + S_{mj} \frac{\partial P_j}{\partial x_{ck}}\right) + \frac{\partial P_j}{\partial x_{ck}} & for\ m = k \end{cases} \tag{8}$$

The term ,

$$\frac{\partial \mathrm{P_i}}{\partial \mathrm{x_{ck}}} \,\Big|\, x_{ck=0} \ , \ \frac{\partial \mathrm{P_j}}{\partial \mathrm{x_{ck}}} \,\Big|\, x_{ck=0}$$

Can be derived as below,

$$\frac{\partial \mathrm{P_i}}{\partial \mathrm{x_{ck}}} \,\Big|\, \mathrm{x_{ck=0}} \ \frac{\partial \mathrm{P_{ic}}}{\partial \mathrm{x_{ck}}} \,\Big|\, \mathrm{x_{ck=0}}$$
$$= -2\left(V_i^2 - V_i V_j \cos\delta_{ij}\right) \frac{r_{ij} x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} - V_i V_j \sin\delta_{ij} \frac{x_{ij}^2 - r_{ij}^2}{(r_{ij}^2 + x_{ij}^2)^2} \tag{9}$$

Same as,

$$\frac{\partial \mathrm{P_j}}{\partial \mathrm{x_{ck}}} \,\Big|\, x_{ck=0} = \frac{\partial \mathrm{P_{jc}}}{\partial \mathrm{x_{ck}}} \,\Big|\, \mathrm{x_{ck=0}}$$
$$= -2\left(V_j^2 - V_i V_j \cos\delta_{ij}\right) \frac{r_{ij} x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} + V_i V_j \sin\delta_{ij} \frac{x_{ij}^2 - r_{ij}^2}{(r_{ij}^2 + x_{ij}^2)^2} \tag{10}$$

V. CRITERION FOR OPTIMAL LOCATION OF TCSC

The TCSC device should be placed on the most sensitive line. With the sensitivity indices computed for TCSC, following criteria can be used for its optimal location.

1. In reactive power loss reduction method **(a_{ij})** TCSC should be placed in a line having the most positive loss sensitivity index.

2. In real power flow performance sensitivity indices (bij) method TCSC should be placed in a line having most negative sensitivity index.

VI. TEST SYSTEM –IEEE 30 BUS SYSTEM

For the validation of the proposed FACTS's devices, TCSC have been tested on the IEEE 30 Bus test System. An IEEE 30 bus test system including 30 buses, 6 generators, 41 lines, and 24 loads is simulated using PSAT is presented. The generators are modeled as standard PV buses with both P and Q limits; loads are represented as constant PQ loads. In this Analysis we simulated IEEE 30 bus system with base case ,and different loading conditions like 75 % and 125% Loadings and check the system performance and then calculate the Sensitivity index for all the lines and then check the performance without and with TCSC to improve voltage profile and congestion management and also calculate the energy saving by the TCSC.

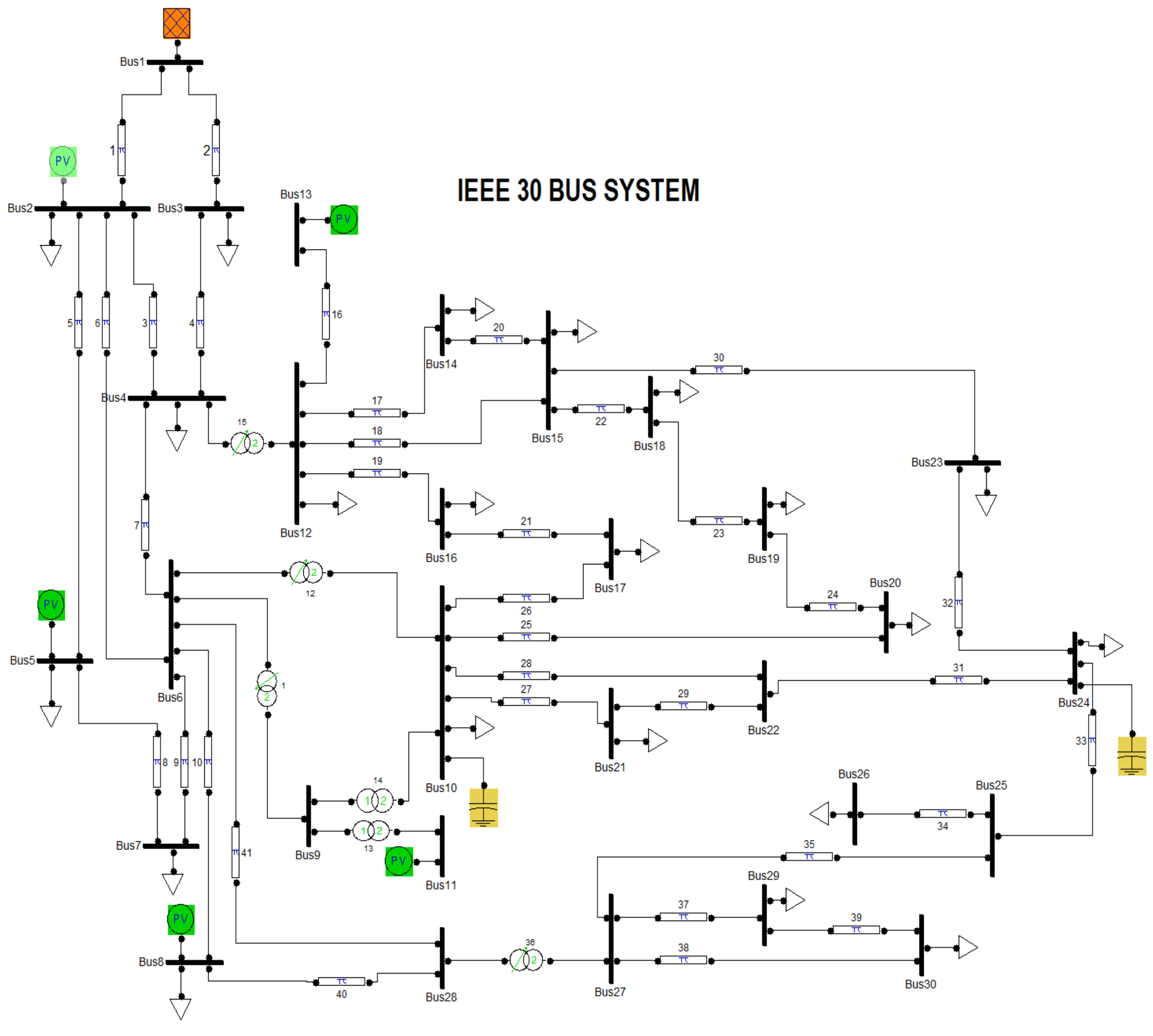

Figure 1. IEEE 30 Bus Test System

VII. SIMULATION RESULTS

From calculated sensitivity indices as in table 1. Reduction of total system reactive power loss (aij) in which most positive sensitivity index is taken as the location of TCSC and in Real Power flow performance index (bij) most negative PI index is taken for the optimal location of TCSC. In this analysis Line 20 which is between buses 14-15 and Line 10 which is between buses 6-8.in both the condition performance of the system is analysed and found that Line 20 which is between buses 14-15 is the best location for the TCSC as shown in fig.2.

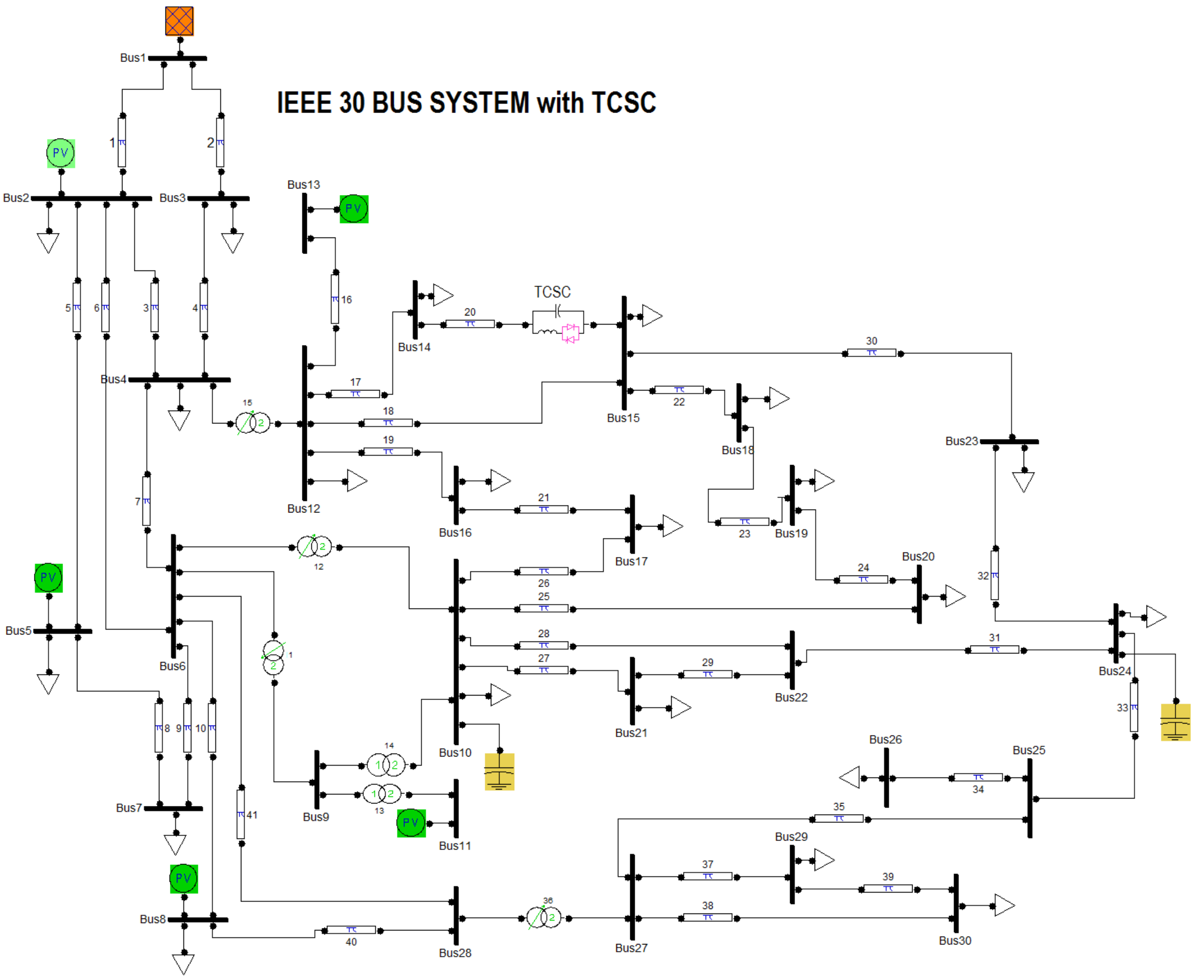

Figure 2. IEEE 30 Bus Test System with TCSC

Table 1. Calculated Sensitivity Indices

Line	From Bus	To Bus	Sensitivity Index	Sensitivity PI Index
			aij	bij
1	Bus1	Bus2	-8.4212	129.30
2	Bus1	Bus3	-2.0584	22.92
3	Bus2	Bus4	-1.0196	18.86
4	Bus3	Bus4	-2.1890	247.69
5	Bus2	Bus5	-2.4271	13.73
6	Bus2	Bus6	-1.8820	20.66
7	Bus4	Bus6	-2.7338	61.51
8	Bus5	Bus7	-0.3434	30.56
9	Bus6	Bus7	-0.2845	16.42
10	**Bus6**	**Bus8**	-6.5524	**-918.35**
11	Bus6	Bus9	-0.9359	8.56
12	Bus6	Bus10	-0.3513	1.23
13	Bus9	Bus11	-0.0216	-0.59
14	Bus9	Bus10	-1.6224	100.11
15	Bus4	Bus12	-1.4560	6.12
16	Bus12	Bus13	-0.9028	-91.37
17	Bus12	Bus14	-0.4254	4.18
18	Bus12	Bus15	-2.1902	35.53
19	Bus12	Bus16	-0.3388	6.98
20	**Bus14**	**Bus15**	**0.0646**	-0.11
21	Bus16	Bus17	-0.1521	4.64
22	Bus15	Bus18	-0.5065	5.33
23	Bus18	Bus19	-0.0297	2.85
24	Bus19	Bus20	-0.5355	-46.28
25	Bus10	Bus20	-0.7753	9.67
26	Bus10	Bus17	-0.5161	66.17
27	Bus10	Bus21	-2.1120	122.83
28	Bus10	Bus22	-0.4638	12.93
29	Bus21	Bus22	-0.1058	-851.55
30	Bus15	Bus23	-0.5174	6.14
31	Bus22	Bus24	-0.8161	3.65
32	Bus23	Bus24	-0.0322	0.02
33	Bus24	Bus25	-0.4067	-0.11
34	Bus25	Bus26	-0.4884	0.82
35	Bus25	Bus27	-1.1261	-6.11
36	Bus28	Bus27	-0.1080	1.51
37	Bus27	Bus29	-0.2487	1.10
38	Bus27	Bus30	-0.1510	0.41
39	Bus29	Bus30	-0.0076	0.15
40	Bus8	Bus28	-0.2065	11.09
41	Bus6	Bus28	-0.5580	85.09

Table 1.shows the Calculated Sensitivity indices in which most positive sensitivity index in aij and most negative PI index bij is taken for location of TCSC.from table 1.Line 20 and Line 10 is the optimal location for TCSC.

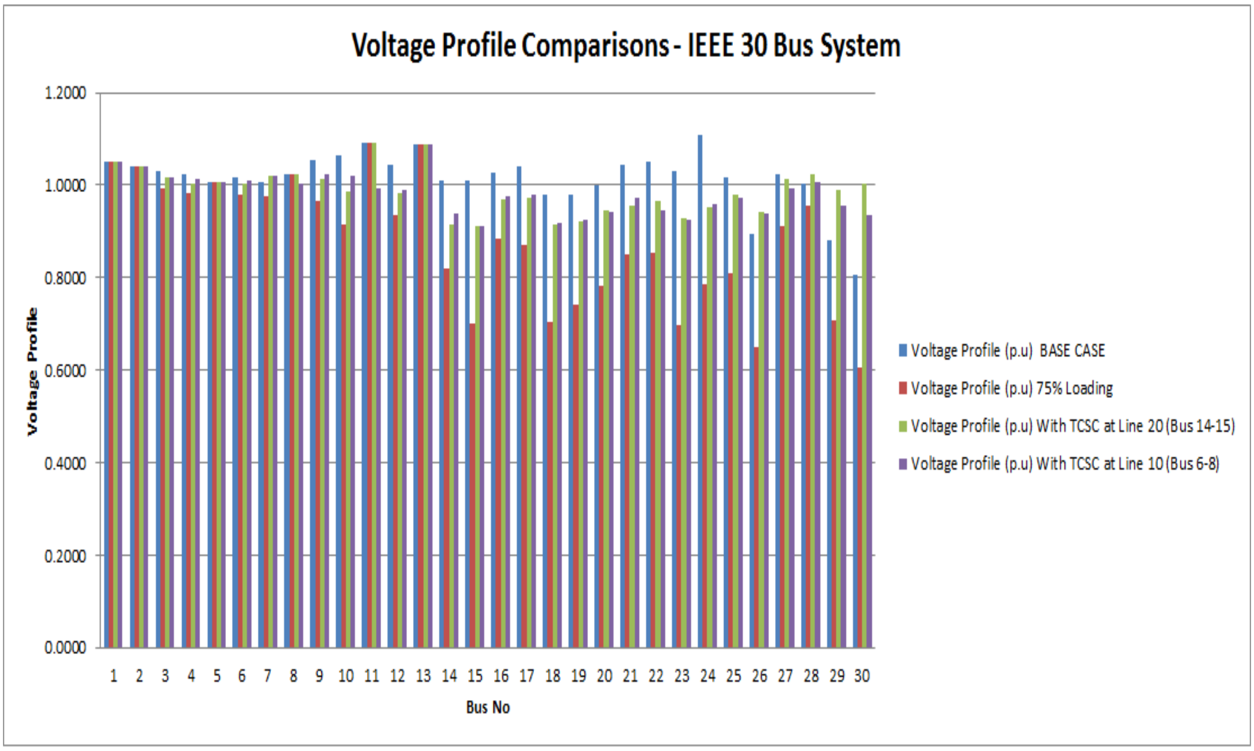

Figure 3. Comparisons of Voltage Profile

From fig.3 we conclude that voltage profile is maintained within 0.9 p.u. to 1.1 p.u after placement of TCSC in Line 20.so we can say that voltage stability is maintained in power system.

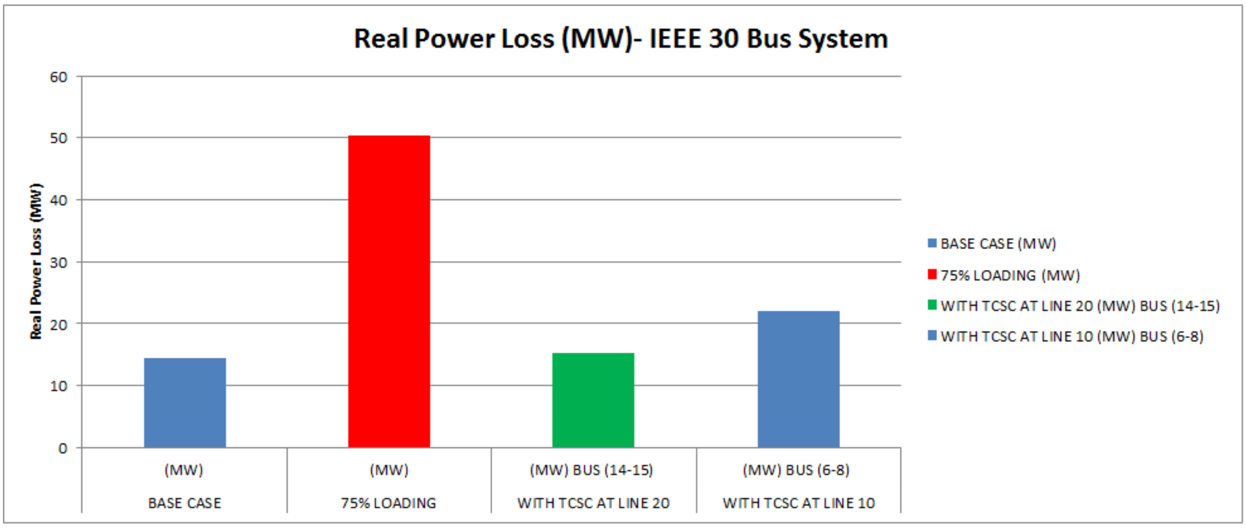

Figure 4. Comparisons of Real Power loss

From fig.4 it is clear that at 75% loading Real power loss is 50.38 MW which is reduced to 15.25 MW after placement of TCSC in Line 20 which is in between buses (14-15)

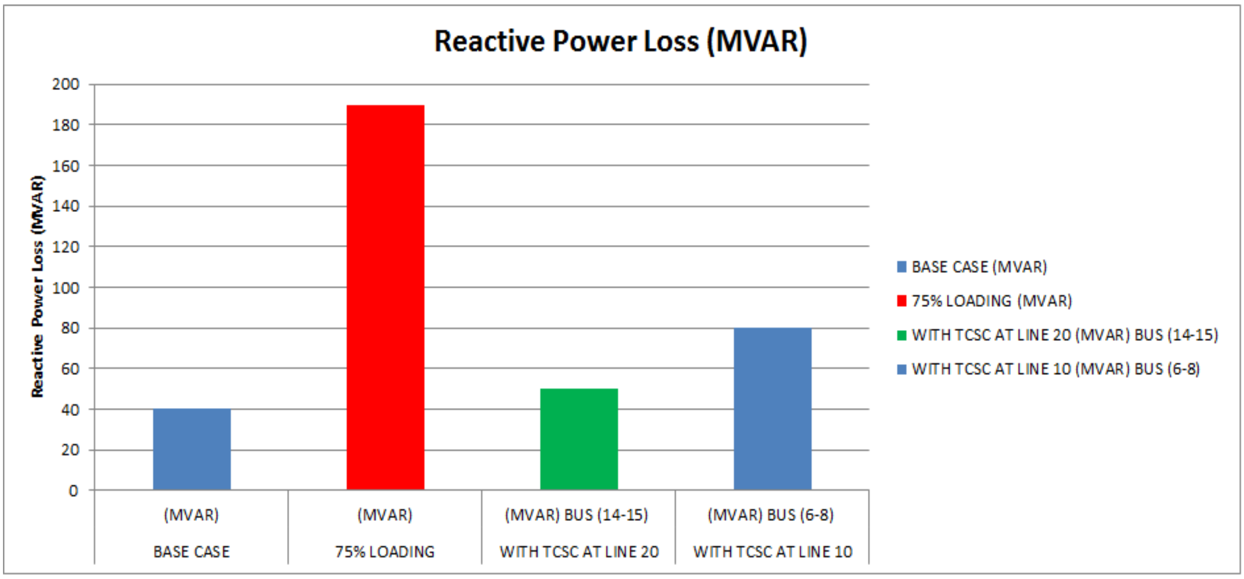

Figure 5. Comparisons of Reactive Power loss

From fig.5 it is clear that Reactive power loss is decrease from 189.38 MVAR to 50.25 MVAR after locating TCSC in Line 20.

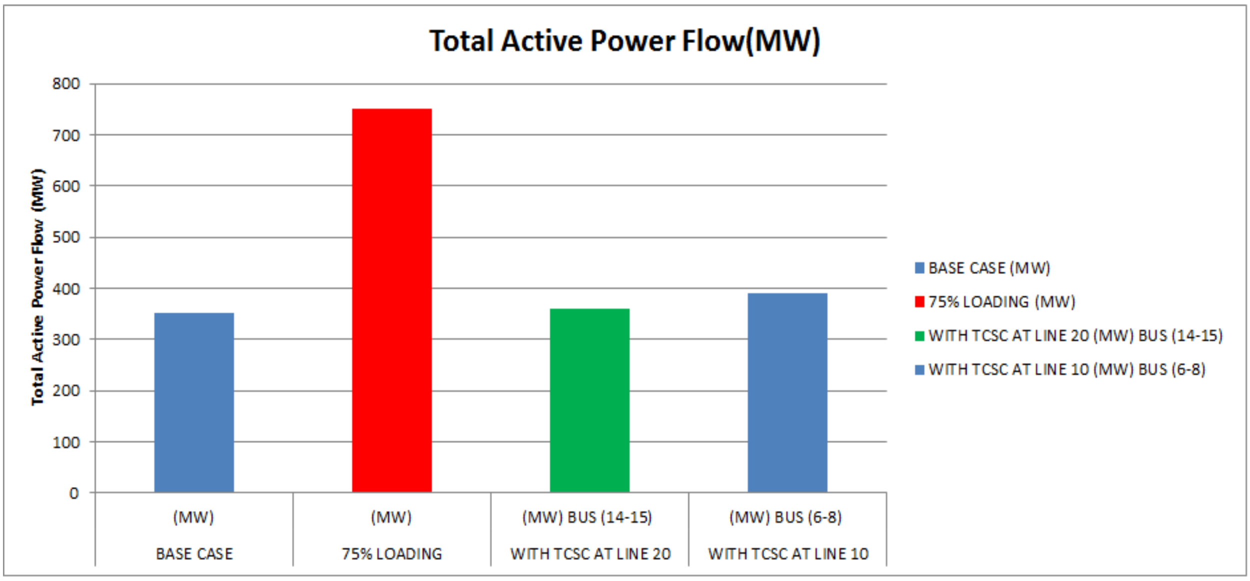

Figure 6. Comparisons of Total Active Power Flow

From fig.6 it is clear that Total Active power Flow is decrease from 751.29 MW to 360.25 MW after locating TCSC in Line 20. So we can say that Congestion & overload is reduced after placement of TCSC.

VIII. COST ANALYSIS

Table 2. Change in Active and Reactive Power loss

Power Loss	Without TCSC (75% Loading)	With TCSC	Change in Losses (p.u)
Active power Losses (p.u)	0.50379	0.152	0.35
Reactive power Losses (p.u)	1.8939	0.5023	1.39

Table 3. Cost Analysis With TCSC in the system

sr no	Terms	Values	Units
1	Active power	0.35	pu
2	Reactive power	1.39	pu
3	Apperent power	1.44	pu
4	Apperent power in MVA	143.54	MVA
5	power factor	0.95	na
5	Total power saving through year	1194520.63	Mwh
6	Total unit saving	1194520632.71	Kwh
7	Unit price/Kwh	6.00	Rs./Kwh
8	Total saving in amount	7167123796.27	Rs.
9	Total saving in USD	119452063.27	$
10	Cost of TCSC	5000000.00	$/MVAR
11	Interest	10	%
12	Depriciation	10	%
13	Total cost of TCSC	6000000.00	$
14	Payback period	0.05	year

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