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Full Length Research Paper

Congestion management in high voltage transmission line using thyrister controlled series capacitors (TCSC)

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Congestion management is one of the technical challenges in power system deregulation. In deregulated electricity market transmission congestion occurs when there is insufficient transmission capacity to simultaneously accommodate all constraints for transmission of a line. Flexible alternative current transmission system (FACTS) 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 flow in the network. Proper location of a FACTS controller is key to maximize its benefits. This paper also demonstrates the ability of FACTS devices to reduce the overall operating cost and their impact on transmission pricing. A sensitivity factor based approach is used for the optimal placement of the thyrister controlled series capacitors (TCSC) to minimize the congestion cost. The sensitivity of the congested line flow with respect to flow in other lines has been used for the placement of the TCSC. The effectiveness of the proposed method has been demonstrated on IEEE 14-bus system.

Key words: Congestion management, flexible alternative current transmission system (FACTS), thyrister controlled series capacitors (TCSC), sensitivity analysis, matpower.

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. 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 (Harry et al., 1998). 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) (Narain and Laszlo, 2001). 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. FACTS devices controls the power flows in the network without generation rescheduling or topological 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. Using controllable components such as controllable series capacitors line flows can be changed in such a way that thermal limits are not violated, losses minimized, stability margins increased, contractual requirement fulfilled etc, without

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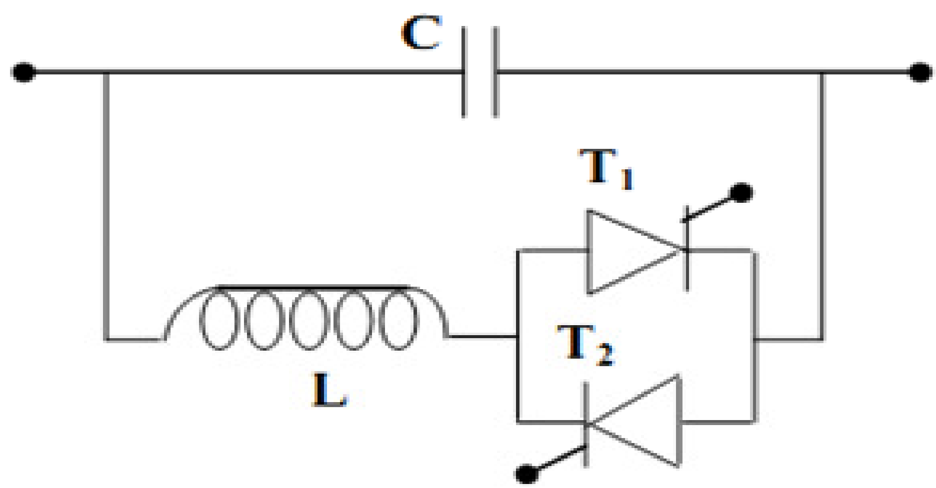

Figure 1. Circuit diagram of thyrister controlled series capacitors TCSC (10).

violating specific power dispatch. The increased interest in these devices is essentially due to two reasons. 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.

Thyrister controlled series capacitors (TCSC)

FACTS devices are introduced in the transmission line to enhance its power transfer capability; either in series or in shunt. The series compensation is an economic method of improving power transmission capability of the lines. According to Taher (2008), Thyrister-controlled series capacitors (TCSC) (Figure 1) is a type of series compensator that can provide many benefits for a power system including controlling power flow in the line, damping power oscillations, and mitigating sub-synchronous resonance. 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 thyrister-controlled inductor is mounted directly in parallel with the capacitor (Naresh and Mithulananthan, 2006). Thus no interfacing equipment like for example high voltage transformers is required. 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.
2) Improve system stability.
3) Reduce system losses.
4) Improve voltage profile of the lines.
5) Optimize power flow between parallel lines.

Figure 2 shows the impedance characteristics curve of a TCSC device. It is drawn between effective reactance of TCSC and firing angle α (Lehmkoster, 2002).

Net reactance of TCR, X_L (α) is varied from its minimum value X_L to maximum value infinity. Likewise effective reactance of TCSC starts increasing from TCR 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).

$90 < \alpha < \alpha L_{lim}$	Inductive region
$\alpha L_{lim} < \alpha < \alpha C_{lim}$	Capacitive region
$\alpha L_{lim} < \alpha < \alpha C_{lim}$	Resonance region

While selecting inductance, X_L should be sufficiently smaller than that of the capacitor X_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 (Xia et al., 2002).

Figure 3 shows a simple transmission line represented by its lumped π equivalent parameters connected between bus-i and bus-j. Let complex voltage at bus-i and bus-j are Vi and Vj respectively. The real and reactive power flow from bus-i to bus-j can be written (Harry et al., 1998).

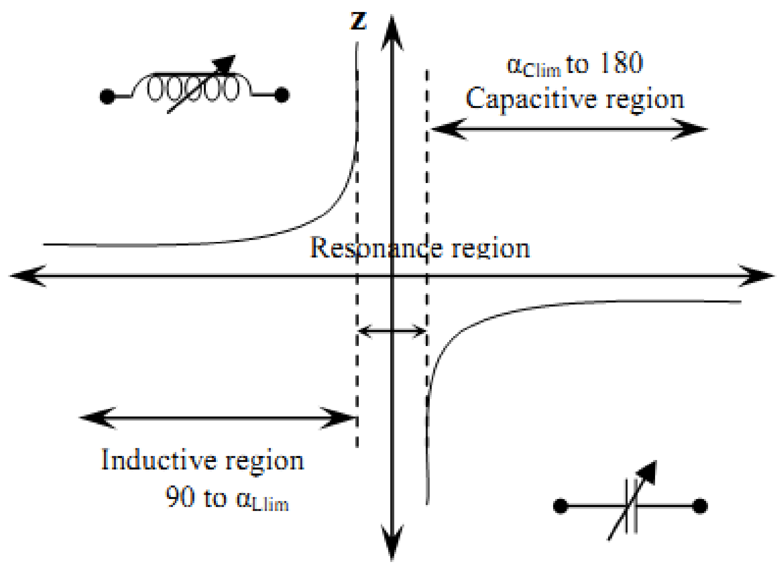

Figure 2. Variation of impedance in case of thyrister controlled series capacitors TCSC (10).

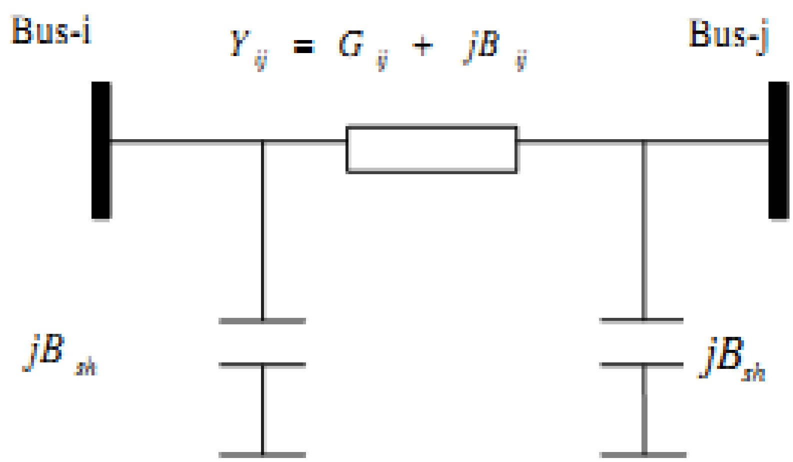

Figure 3. Model of transmission line.

$$P_{ij} = V_1^2 G_{ij} - V_i V_j \left[G_{ij}\cos(\delta_{ij}) + B_{ij}\sin(\delta_{ij})\right] \ldots \quad (1)$$

$$Q_{ij} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j \left[G_{ij}\sin(\delta_{ij}) - B_{ij}\cos(\delta_{ij})\right] \ldots \quad (2)$$

Where P_{ij} and Q_{ij} are the real and reactive power flow from bus-i to bus-j. Similarly real and reactive power flow from bus-j to bus-i is:

$$P_{ji} = V_j^2 G_{ij} - V_i V_j \left[G_{ij}\cos(\delta_{ij}) - B_{ij}\sin(\delta_{ij})\right] \ldots \quad (3)$$

$$Qj_{ji} = -V_j^2 (B_{ij} + B_{sh}) + V_i V_j \left[G_{ij}\sin(\delta_{ij}) + B_{ij}\cos(\delta_{ij})\right] \ldots \quad (4)$$

The model of transmission line with a TCSC connected between bus-i and bus-j is shown in Figure 4. During the steady state the TCSC can be considered as a static reactance -jXc.

The real and reactive power flow from bus-i to bus-j, and from bus-j to bus-i of a line having series impedance and a series reactance are:

$$P_{ij}^C = V_i^2 G'_{ij} - V_i V_j \left(G'_{ij}\cos\delta_{ij} + B'_{ij}\sin\delta_{ij}\right) \quad (5)$$

$$Q_{ij}^C = -V_i^2 (B'_{ij} + B_{sh}) - V_i V_j \left(G'_{ij}\sin\delta_{ij} - B'_{ij}\cos\delta_{ij}\right) \ldots \quad (6)$$

$$P_{ji}^C = V_j^2 G'_{ij} - V_i V_j \left(G'_{ij}\cos\delta_{ij} - B'_{ij}\sin\delta_{ij}\right) \ldots \quad (7)$$

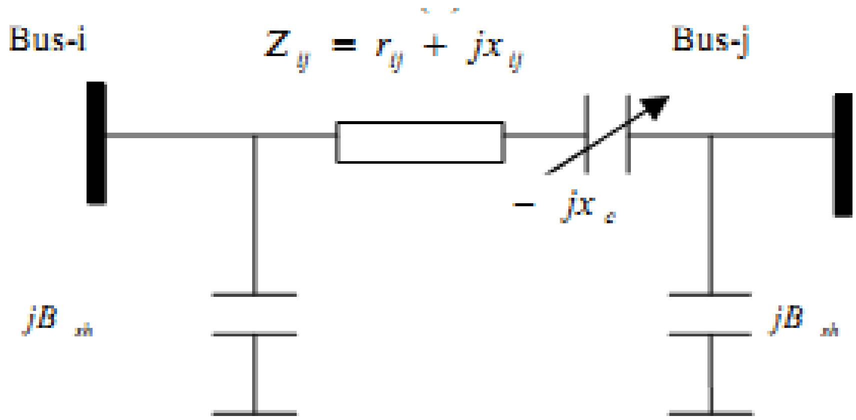

Figure 4. Model of transmission line with thyrister controlled series capacitors (TCSC).

$$Q_{ji}^C = -V_j^2(B'_{ij} + B_{sh}) + V_iV_j(G'_{ij}\sin\delta_{ij} + B'_{ij}\cos\delta_{ij}) \quad \cdots \quad (8)$$

The active and reactive power loss in the line having TCSC can be written as:

$$P_L = P_{ij} + P_{ji} = G'_{ij}(V_i^2 + V_j^2) - 2V_iV_jG'_{ij}\cos\delta_{ij} \quad \cdots \quad (9)$$

$$Q_L = Q_{ij} + Q_{ji} = -(V_i^2 + V_j^2)(B'_{ij} + B_{sh}) + 2V_iV_jB'_{ij}\cos\delta_{ij} \quad \cdots \quad (10)$$

Where

$$G'_{ij} = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_C)^2}$$

And

$$B'_{ij} = \frac{-(x_{ij} - x_C)}{r_{ij}^2 + (x_{ij} - x_C)^2}$$

The real and reactive power injections at bus-i and bus-j can be expressed as:

$$P_{ic} = V_i^2\Delta G_{ij} - V_iV_j[\Delta G_{ij}\cos\delta_{ij} + \Delta B_{ij}\sin\delta_{ij}] \quad \cdots \quad (11)$$

$$P_{jc} = V_j^2\Delta G_{ij} - V_iV_j[\Delta G_{ij}\cos\delta_{ij} - \Delta B_{ij}\sin\delta_{ij}] \quad \cdots \quad (12)$$

$$Q_{ic} = -V_i^2\Delta B_{ij} - V_iV_j[\Delta G_{ij}\sin\delta_{ij} - \Delta B_{ij}\cos\delta_{ij}] \quad \cdots \quad (13)$$

Where

$$\Delta G_{ij} = \frac{x_c r_{ij}(x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$$

And

$$\Delta B_{ij} = \frac{-x_c(r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$$

Optimal power flow (OPF) formulation

Optimal power flow (OPF) has been used in this work to calculate generation dispatch and load schedules, to manage congestion in the systems. It is based on the power flow limits by accommodating all power constraints for transmission of line and the network data (Acharya et al., 2005). The generally accepted objective is to minimize the generation cost, if loads are inelastic. In this work, it is assumed that the loads are inelastic to the price variations. Therefore, the optimal function becomes the total cost of supplying electricity. The problem is stated mathematically as (Yog, 2006; Zimerman et al., 2010).

$$\min\left(\sum_{i=1}^{N_G} C_i(P_{G_i})\right) \quad \cdots \quad (15)$$

Subject to power balance equation:

$P_i(\theta,V) - P_{G_i} + P_{D_i} = 0$, for any node i

$Q_i(\theta,V) - Q_{G_i} + Q_{D_i} = 0$, for any node i

If TCSC is located in line between buses *i* and *j*, the power balance equations at nodes *i* and *j* are given by apparent line flow limit:

$$S_{ij}(\theta,V) \le S_{ij}^{\max} \quad \cdots \quad (16)$$

$P_i(\theta,V) - P_{Gi} + P_{Di} + P_i^F = 0$, for node i

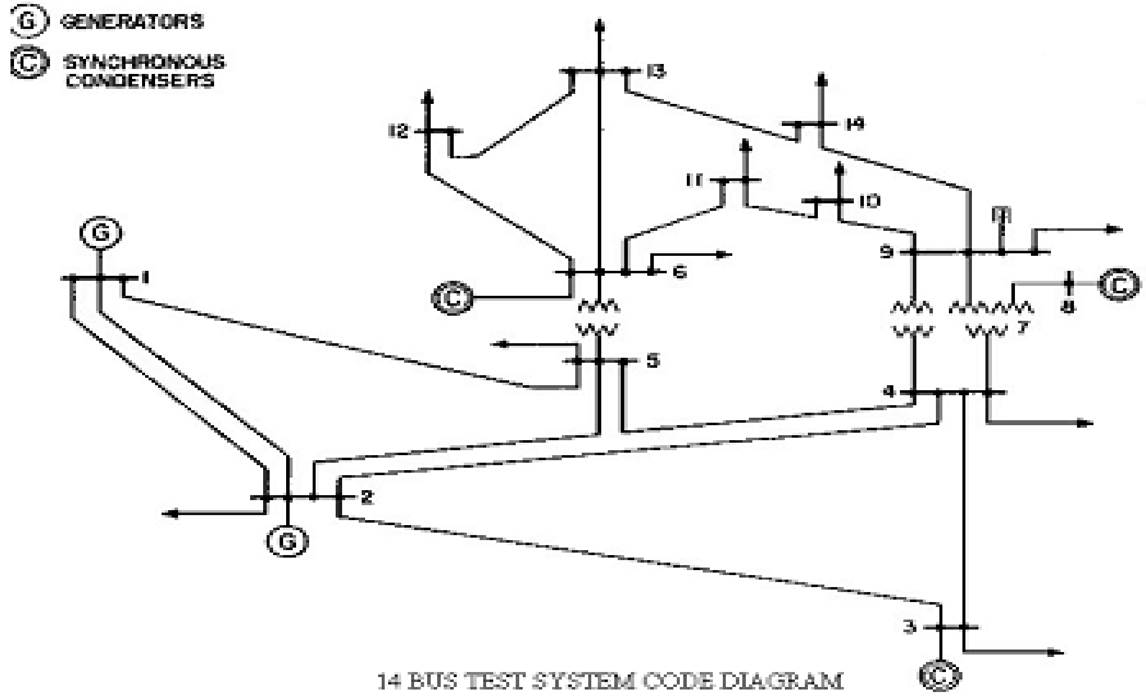

Figure 5. IEEE 14 bus system.

$Q_i(\theta,V)-Q_{Gi}+Q_{Di}+Q_i^F=0$, for node i

$P_j(\theta,V)-P_{Gj}+P_{Dj}+P_j^F=0$, for node j

$Q_j(\theta,V)-Q_{Gj}+Q_{Dj}+Q_j^F=0$, for node j

Power generation limits

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}$$
$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad \ldots \quad (17)$$

TCSC reactance limit

$$x_C^{\min} \le x_C \le x_C^{\max} \quad \ldots \quad (18)$$

Where, N_G is the number of generators, C_i (P_{Gi}) is the cost curve of i[th] generator, $P_{Gi}^{\min}$ and $P_{Gi}^{\max}$ are the minimum and the maximum active power generation limits of a generator at bus i, $Q_{Gi}^{\min}$ and $Q_{Gi}^{\max}$ are the minimum and the maximum reactive power generation limits of generating unit at bus i, $V_i^{\min}$ and $V_i^{\max}$ are the minimum and the maximum voltage limits at bus i, S_{ij} is the apparent power flow in transmission line connected between nodes i and j, and $S_{ij}^{\max}$ is its maximum limit. P_{Gi} and Q_{Gi} are the active and reactive power generations at node i, P_{Di} and Q_{Di} are the active and reactive power loads at node i, P_i and Q_i are the net active and reactive power injections at node i, $x_C^{\min}$ and $x_C^{\max}$ are the minimum and maximum limits of the TCSC reactance and N is the number of nodes in the system (Acharya et al., 2005).

Due to high cost of FACTS devices, it is necessary to use cost-benefit analysis to analyze whether new FACTS device is cost effective among several candidate locations where they actually installed. The TCSC cost in line-k is given by Equation (19).

$$C_{TCSC}(k)=c.x_C(k)P_L^2 / Base\_Power \quad \ldots \quad (19)$$

where c is the unit investment cost of FACTS $x_c(k)$ is the series capacitive reactance and P_L is the power flow in line-k. The objective function for placement of TCSC will be

$$\min \sum_i C_i(P_i)+C_{TCSC} \quad \ldots \quad (20)$$

This analysis has been implemented on institute of electrical and electronics engineers (IEEE) 14 bus system, shown in Figure (5). MATPOWER, a toolbox of MATLAB, has been used for simulations (Singh and David, 2001; Xia et al., 2002).

Table 1. Loss sensitivity index.

(Line)	Bus (i-j)	aij	Line	Bus (i-j)	aij
1	5-6	-0.2868	11	7-8	-0.6283
2	4-7	-0.2281	12	7-9	-0.2654
3	4-9	-0.0364	13	9-10	-0.1036
4	1-2	-0.8796	14	6-11	-0.1325
5	2-3	-0.0971	15	6-12	-0.1085
6	2-4	-0.1488	16	6-13	-0.4791
7	1-5	-0.2743	17	9-14	-0.2049
8	2-5	-0.1213	18	10-11	-0.1803
9	3-4	-0.0352	19	12-13	-0.1554
10	4-5	-0.1179	20	13-14	-0.2662

Optimal location of TCSC

FACTS controllers are utilized in the system to perform their primary task of stability control and also improve the steady state performance of the system. The present work has only considered their impact on the congestion management, formulated as a steady state problem. A static power injection model (PIM) of the TCSC has been used. The injection model represents the TCSC as a device that injects certain amount of active and reactive power in a node.

For the reduction of total system reactive power loss a parameter based on the sensitivity of the total system reactive power loss with respect to the control variable of the TCSC has been developed. Loss sensitivity with respect to control parameter of TCSC placed between buses i and j can be written as:

$$a_{ij} = \frac{\partial Q_L}{\partial x_{ij}} = \left[V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij}\right]\frac{r_{ij}^2 - x_{ij}^2}{\left(r_{ij}^2 + x_{ij}^2\right)^2} \quad \cdots \qquad (21)$$

Simulation and results

The FACTS device should be placed on the most sensitive line. With the sensitivity index computed for TCSC, the TCSC should be placed in a line having the most positive loss sensitivity index. The proposed method has been simulated on IEEE 14 bus system. Optimizations are carried out with a tool developed in MATLAB language. Power flows are solved with a modified version of the free MATLAB power simulation package MATPOWER 2.0 (Zimerman et al? Seyed et al., 2010).

The sensitivity of reactive power loss reduction with respect to TCSC control parameter has been computed and is shown in Table 1; the sensitive line in each case is presented in bold type. It is observed from Table 1 that line-9 is highly sensitive. It can be observed from Table 2 that placement of TCSC in line-9 is suitable for reducing the total reactive power loss. System power flow result after placing TCSC in line-9 is shown in Table 3 the value of control parameter of TCSC for computing power flow is taken as 0.09406 pu.

It can be observed from Table 3 that congestion in line-6 and line-7 has been relieved. Placement of TCSC in line-3 also will reduce the total system reactive power loss but it will be less effective than placing a TCSC in line-9 as can be seen from its sensitivity factors.

It is observed from Table 1 that line-3 is also sensitive but it is less sensitive than line- 9 as seen from loss sensitive index. System power flow result after placing TCSC in line-3 is shown in Table 4. The value of control parameter of TCSC for computing power flow is taken as 0.33308 pu. It can be observed from Table 4 that congestion in line-4 and line-7 has been relived.

Reduction in real and reactive power loss

Power losses in the transmission line without TCSC are shown in Table 5. The total real power loss in the system is 158.052 MW and total reactive power loss in the system is 838.526 MVAR.

Reduction in real and reactive power loss in each line after placing TCSC in line-9 is shown in Table 6. The net reduction in real power loss is comes out to be 2.792MW and in reactive power loss is 59.076 MVAR.

Graphical representation

Figure 6 shown below is the graphical representation of power flow in different lines after placing TCSC in line 9. In the graph it is graphically demonstrated that congestion in line 9 has been successfully removed after the placement of TCSC accommodating all constraints for transmission of a line. Similar representation is in Figures 7 and 8.

Table 2. Power flow in line without TCSC.

S. No.(Line)	Bus (i-j)	P_{ij} (MW)	Q_{ij} (MVAR)	S_{ij} (MVA)	S_{ij}^{max} (MVA)
1	5-6	206.127	-7.270	206.255	210.00
2	4-7	170.051	32.328	173.095	189.00
3	4-9	66.995	18.652	69.5429	150.00
4	1-2	494.628	22.344	495.132	500.00
5	2-3	126.606	5.212	126.713	146.00
6	2-4	172.378	83.2233	191.417	195.00
7	1-5	230.424	125.065	262.193	260.00
8	2-5	151.659	79.863	171.402	174.00
9	3-4	42.192	79.162	89.703	182.00
10	4-5	-77.114	8.680	77.601	195.00
11	7-8	90.000	-89.781	127.124	135.00
12	7-9	29.531	21.533	36.548	145.00
13	9-10	15.282	-15.977	22.109	106.00
14	6-11	53.047	51.075	51.324	118.20
15	6-12	66.932	33.355	74.786	112.00
16	6-13	116.948	59.299	131.122	145.00
17	9-14	31.744	-0.619	31.750	137.00
18	10-11	-3.958	-22.414	22.761	125.00
19	12-13	-5.775	2.005	6.113	126.00
20	13-14	16.632	19.876	25.916	165.00

Table 3. Power flow after placing TCSC in line 9.

S. No. (Line)	Bus (i-j)	P_{ij} (MW)	Q_{ij} (MVAR)	S_{ij} (MVA)	S_{ij}^{max} (MVA)
1	5-6	201.338	-5.389	201.410	210.00
2	4-7	171.322	34.223	174.706	189.00
3	4-9	68.230	19.902	71.073	150.00
4	1-2	494.380	22.354	494.885	500.00
5	2-3	165.298	6.956	165.444	146.00
6	2-4	162.948	60.818	173.927	195.00
7	1-5	227.879	108.664	252.459	260.00
8	2-5	142.191	62.801	155.442	174.00
9	3-4	58.107	110.313	124.681	182.00
10	4-5	-75.355	26.156	79.765	195.00
11	7-8	90.000	-80.597	120.813	135.00
12	7-9	31.322	22.463	38.544	145.00
13	9-10	16.812	-13.077	21.299	106.00
14	6-11	50.643	46.282	68.606	118.20
15	6-12	66.291	32.597	73.872	112.00
16	6-13	115.204	56.427	128.281	145.00
17	9-14	33.239	1.217	33.261	137.00
18	10-11	-2.397	-19.434	19.581	125.00
19	12-13	-6.256	1.579	6.451	126.00
20	13-14	14.864	17.491	22.954	165.00

Calculation of total cost

Due to high cost of FACTS devices, it is necessary to use cost-benefit analysis to analyze whether new FACTS device is cost effective among several candidate locations where they actually installed. The TCSC cost in

Table 4. Power flow in line with TCSC in line 3.

S. No. (Line)	Bus (i-j)	P_{ij} (MW)	Q_{ij} (MVAR)	S_{ij} (MVA)	S_{ij}^{max} (MVA)
1	5-6	181.163	-19.587	182.219	210.00
2	4-7	136.456	6.836	136.627	179.00
3	4-9	123.225	16.622	124.341	150.00
4	1-2	487.673	22.634	488.198	500.00
5	2-3	144.713	5.078	144.802	146.00
6	2-4	173.289	71.403	187.423	195.00
7	1-5	228.966	112.810	255.248	260.00
8	2-5	146.862	66.842	161.358	174.00
9	3-4	40.561	67.477	78.729	182.00
10	4-5	-98.755	11.969	99.477	195.00
11	7-8	90.000	-77.634	118.857	135.00
12	7-9	-3.544	24.612	24.866	145.00
13	9-10	29.374	-16.740	33.809	106.00
14	6-11	38.038	50.112	62.913	118.20
15	6-12	64.884	32.959	72.775	112.00
16	6-13	109.040	57.428	123.238	145.00
17	9-14	40.806	-0.084	40.806	137.00
18	10-11	9.852	-23.927	25.876	125.00
19	12-13	-7.473	2.337	7.829	126.00
20	13-14	8.231	20.785	22.355	165.00

Table 5. Power losses in line without TCSC**.**

S. No. Line	Bus (i-j)	Real power loss (MW)	Reactive power loss (MVAR)
1	5-6	0.000	156.398
2	4-7	0.000	97.570
3	4-9	0.000	41.787
4	1-2	42.285	129.102
5	2-3	10.214	43.033
6	2-4	21.507	65.258
7	1-5	33.053	136.445
8	2-5	16.900	51.598
9	3-4	5.851	14.933
10	4-5	1.289	4.066
11	7-8	0.000	41.082
12	7-9	0.000	2.121
13	9-10	0.240	0.637
14	6-11	4.950	10.367
15	6-12	6.607	13.751
16	6-13	10.932	21.528
17	9-14	1.978	4.207
18	10-11	0.638	1.495
19	12-13	0.110	0.100
20	13-14	1.498	3.050
-----	Total loss	158.052	838.526

line-k is given by:

$$C_{TCSC}(k) = c \cdot x_C \cdot P_L^2 / Base\_Power$$

Table 6. Power losses in lines with TCSC in line 9.

S. No. Line	Bus (i-j)	Real power loss (MW)	Reactive power loss (MVAR)
1	5-6	0.000	137.816
2	4-7	0.000	90.275
3	4-9	0.000	39.370
4	1-2	42.243	128.973
5	2-3	12.992	54.734
6	2-4	17.756	53.876
7	1-5	30.649	126.521
8	2-5	13.899	42.437
9	3-4	11.303	12.982
10	4-5	1.228	3.875
11	7-8	0.000	34.927
12	7-9	0.000	2.220
13	9-10	0.209	0.556
14	6-11	4.297	8.998
15	6-12	6.447	13.418
16	6-13	10.463	20.605
17	9-14	2.041	4.341
18	10-11	0.449	1.050
19	12-13	0.122	0.111
20	13-14	1.162	2.367
-----	Total loss	155.260	779.450

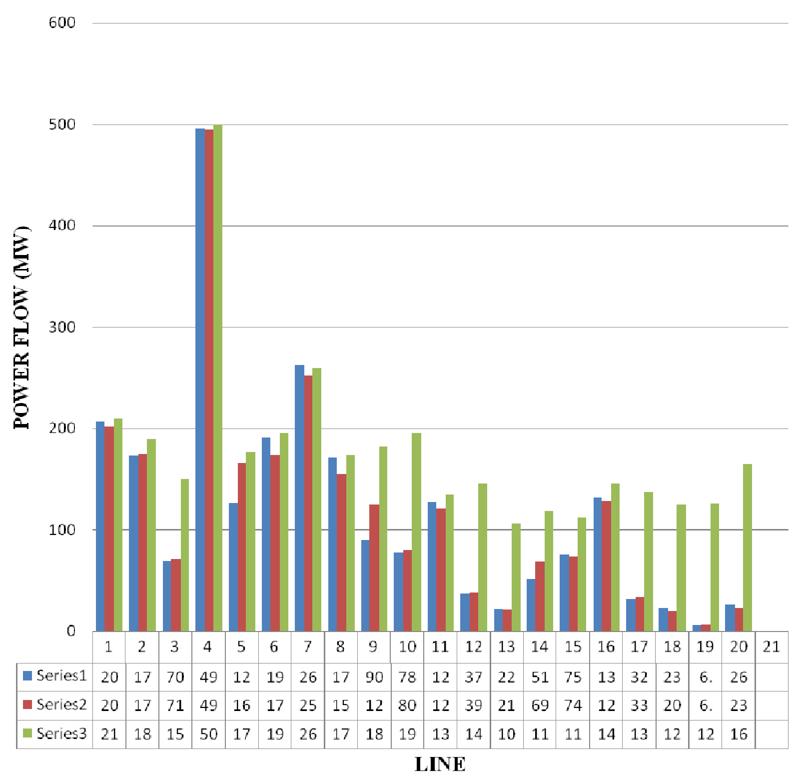

Figure 6. Power flow with TCSC in line 9.series 1: power flow without TCSC series 2: power flow TCSC in line 9 series 3: max power flow limit for lines (line limit).

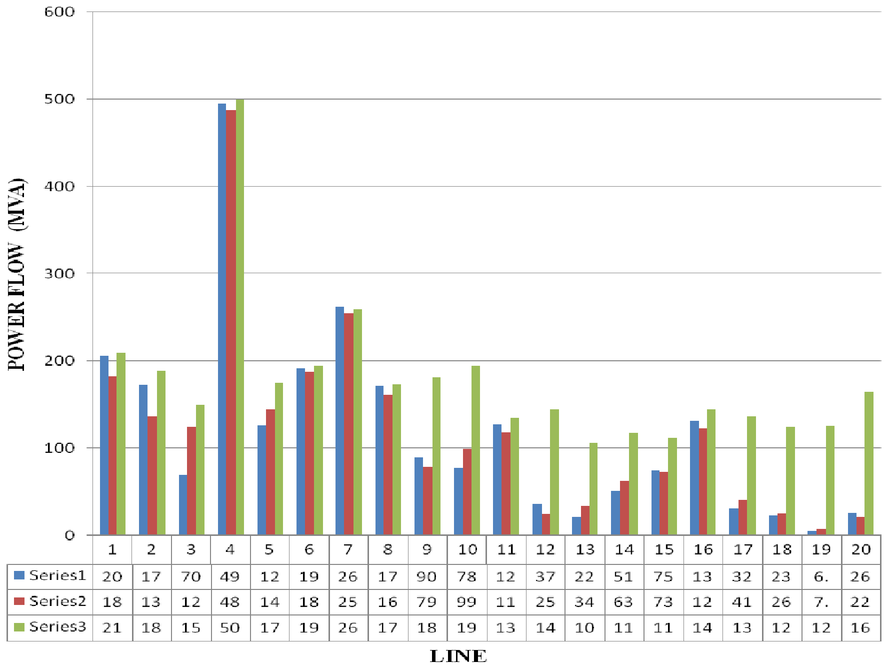

Figure 7. Power flow with TCSC in line 5. series 1: power flow without TCSC Series 2: power flow TCSC in line 9 Series 3: max power flow limit for lines (line limit).

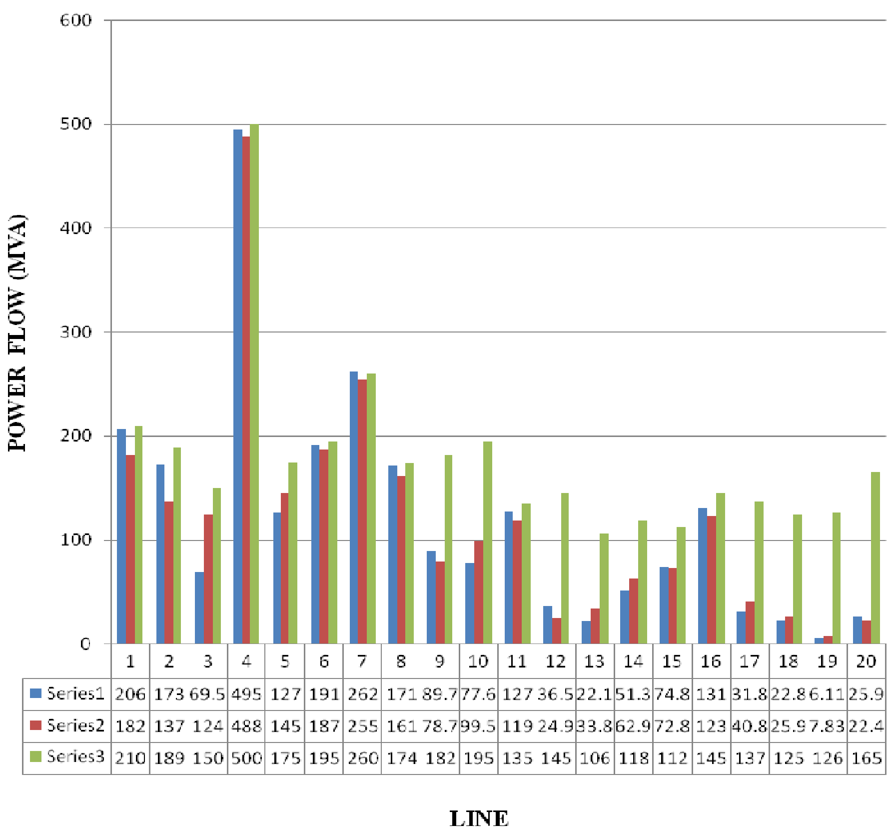

Figure 8. Power flow with TCSC in line 3. series 1: power flow without TCSC series 2: power flow TCSC in line 9 series 3: max power flow limit for lines (line limit).

Table 7. Bid prices of generators.

Generator	Bid prices ($/h)	P_{imin}	P_{imax}
1	$0.11P_1^2 + 5P_1 + 150$	0	1000
2	$0.085P_2^2 + 1.2P_2 + 60$	10	200
3	$0.1225P_3^2 + P_3 + 335$	10	200

Table 8. Total cost of generation.

S. No.	Location of TCSC	Cot of generation ($/hr)
1	Without TCSC	64292.3
2	TCSC in line-3	63045.5
3	TCSC in line-9	63867.5
4	TCSC in line-5	64088.5

Where c is the unit investment cost of FACTS, x_C (k) is the series capacitive reactance, P_L is the power flow in line-k and base power is taken as 100 MVA. The objective function for placement of TCSC will be:

$$\min_{P_i} \sum_i C_i(P_i) + C_{TCSC}$$

Where C_i (P_i) is the cost of power generation.

The prices bid by generators for each 14-bus system are given in Table 7 where P is in MW and $ is a momentary unit which may be scaled by any arbitrary constant without affecting the results. $P_i^{\min}$ and $P_i^{\max}$ are generation power limits of each generator.

Total cost of generation is shown in Table 8. It is observed that placement of TCSC in line -3 is more economical than the placement of TCSC in line-9 and line-5 for congestion management.

Conclusion

Congestion management is an important issue in deregulated power systems. FACTS devices such as TCSC by controlling the power flows in the network can help to reduce the flows in heavily loaded lines. Because of the considerable costs of FACTS devices, it is important to obtain optimal location for placement of these devices. In this report sensitivity of each line is computed and based on sensitivity factor we have determined the optimal location of placement of TCSC in an electricity market. In a system, first two optimal locations of TCSC can be achieved based on the sensitivity factor a_{ij} *and* then optimal location is selected based on minimizing production cost plus device cost. Test results obtained on IEEE 14-bus power systems show that sensitivity factors along with TCSC cost could be effectively used for determining optimal location of TCSC. The optimal solution is determined using optimization tool in MATLAB.

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