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Optimal Placement of TCSC to Improve the Performance of Modern Power System

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Abstract: *Optimal Placement and parameter setting of flexible AC Transmission systems (FACTs) devices can increase loadability, improve stability, reduced active and reactive power losses in transmission line. In this paper, sensitivity based analysis has been proposed to determine optimal location and size of Thyristor Controlled Series Capacitor (TCSC) to improve the overall (voltage stability, power transfer capability and reduce losses) performance of power system. The effect of TCSC on the network is included as a variable reactance. Further, the suitable location of the TCSC is identified using the real power loss minimization based sensitivity-index, total reactive power loss minimization based sensitivity index and real power flows minimization based sensitivity index. Simulation has been performed on a bench mark 5-bus and IEEE-30 bus systems. From the simulation results it is observed that real power loss and real power flow minimization based sensitivity index methods are more effective as compared to the reactive power loss reduction-based sensitivity index method to obtain the optimal location of TCSC. Further, results obtained for 5-bus system and IEEE 30-bus systems showed the steadiness of the proposed sensitivity-based approaches.*

Keywords: *FACTS, TCSC, Optimal Placement, Sensitivity Based Approach, Loss Minimization, Voltage Profile Improvement.*

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I. Introduction

Recently, power system is forced to operate close to the transmission system thermal and stability limits. Various factors, such as environmental, right of way and cost constraints, limit the expansion of the transmission networks. The thyristor-controlled series compensator (TCSC) can enhance the power security by effectively controlling the line flow in the network. Further, it helps in reducing the flow in heavily loaded lines, resulting increased system load ability, less system loss and improve security of the system. However, high cost, losses, appropriate size and location are some major issues with the use of TCSC. Therefore, in reference [1-2], the real power flow PI sensitivity was considered for the optimal location of TCSC.

Thyristor controlled series compensators (TCSC), Thyristor controlled phase shifters (TCPS) and unified power flow controller (UPFC) were discussed considering linearized DC network model [3] to study and analyzed the optimal active power flow. A new comprehensive load flow model considering TCSC presented in [4]. In this model, the state variable is the TCSC's firing angle, which combines with the nodal voltage magnitudes and the angle of the entire network in a single frame of reference for a unified iterative solution through a newton-raphson method. Simulation studies of the TCSC in a power system were carried out considering three cases such as incorporating only the dynamics of the TCSC, considering transient processes of the TCSC, and without considering the transient processes of the TCSC [5]. Optimal placement and sizing of SVC and TCSC for voltage security enhancement was discussed in [6-7]. Congestion management in high voltage transmission lines using thyristor-controlled series capacitors (TCSC) was studied in [8]. Further, it was shown that FACTS devices can be an alternative to reduce the flows in heavily loaded lines which led to increase loadability. Performance of TCSC and SVC on voltage stability limit improvement and loss minimization under most critical line outage condition was analyzed [9]. Further, amount of increased reactive power generation and line losses were taken as indicator of stressed condition of a power system. TCSC Power flow control capability was evaluated in [10]. This paper utilizes the steady state model of thyristor-controlled series capacitor and a unified power flow controller for series voltage compensation, and evaluation of power flow control. Performance analysis of TCSC device in power system network was discussed in [11-12].

After literature review it is observed that the FACTS controllers, such as Static Var Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) can enhance the power system security and its performance by effectively controlling the line power flows. It is important to optimally place these controllers because of their considerable cost. Out of different types of FACTS controllers, TCSC seems to be more effective to change the power flows in lines which may lead to improvement in power system security, load ability and reduction in system losses. Therefore, in this work, to improve the performance of power system, a sensitivity-based approach has been proposed for finding out the optimal placement of TCSC. In addition to PI sensitivity, real power loss sensitivity and reactive power loss sensitivity have also been considered for the optimal location of TCSC.

This paper organized as follows; in section 2 real power, reactive power sensitivity based approaches pertaining to have been discussed of the case study area. Properties of various components of the micro grid are dealt within section 3. Output power production in the case study by various sources are discussed is done in section 4, and conclusions are drawn in section 5.

II. Sensitivity Based Approaches

In this work, the following approaches have been considered to find out the optimal location of TCSC. The proposed criterion of optimal placement of TCSC has been implemented on a benchmark 5-bus system for which network data is available in open literature [13] and other system corresponds to the standard IEEE-30 bus system in reference [14].

2.1 Real Power Flow Performance Index Sensitivity

As real power flow Performance Index (PI) is a good indicator of real power security, reduction in PI with respect to the location of TCSC will enhance the system control security. The sensitivity of PI with respect to the control parameters of TCSC has been used as a measure to locate this controller in the power system. The relative security of the system loading under normal and each of the contingency cases can be line real power flow performance index [1-2] as given below.

$$PI = \sum_{m=1}^{NL} \frac{w_m}{2n} \left(\frac{P_{lm}}{P_{lm}^{\max}} \right) \tag{1}$$

Where P_{lm} is the real line power flow and $P_{lm}^{\max}$ is the rated capacity of line l_m, n is an exponent and w_m is a real non-negative weighting coefficient, which may be used to reflect the relative importance of line, N_L is the total number of lines in the network. In this study, the value of exponent has been taken as 2 and w_m =1.0.

The control parameters considered for TCSC is the effective line reactance X_{ij}. PI sensitivity factors with respect to the control parameters of the TCSC can be defined as,

$$P_i^s = \frac{\partial PI}{\partial X_{i,j}} \quad = \text{PI sensitivity with respect to } X_{i,j} \tag{2}$$

2.1.1 Reduction in real power flows

It is based on the sensitivity of real power flow with respect to control variable of TCSC i.e. X_{ij}. Where X_{ij} is net line series reactance with TCSC placed between buses I and j and C_{ij} is the loss sensitivity with respect to control parameter of X_{ij}. The loss sensitivity with respect to X_{ij} [15] can be computed as:

$$c_{ij} = \frac{\partial P_{ij}}{\partial X_{ij}} = [-V_i^2 + V_i V_j \cos\delta_{ij}] \frac{2 * r_{ij}^2 * x_{ij}^2}{\left(r_{ij}^2 + x_{ij}^2\right)^2} + (V_i V_j \sin\delta_{ij}) * \frac{r_{ij}^2 - x_{ij}^2}{\left(r_{ij}^2 + x_{ij}^2\right)^2} \tag{3}$$

2.2 Total System Real Power Loss Sensitivity

The power flow in the transmission line mainly depends on the difference of voltage angles of terminal buses. The Power flow can be controlled by adjusting any of the bus voltage angles, it is attractive for electrical utilities to have a way of permitting more efficient use of the transmission lines by controlling the power flows. Until a few years ago, the only means of carrying out this function where electromechanical devices such as switched inductors or capacitor banks and phase shifting transformers. However, specific problems related to these devices make them not very efficient in some situations.

The Thyristor controlled series capacitor has been considered from a static point of view to reduce the total system real power loss. It is important to ascertain the location for Placement of this facts device because of its considerable cost. Hence, a method based on real power loss sensitivity approach has been suggested for optimal placement of the TCSC controller. The real power loss and its sensitivity can be given by,

$$P_{loss} = \sum_{k \in nl} G_k \left(V_i^2 + V_j^2 - 2V_i V_j \cos\theta_{ij} \right) \tag{4}$$

Where k is line between buses i and j, Vi and V_j are voltage magnitude at bus i and j, G_k is conductance of line k., θ_{ij} is the voltage angle difference between bus i and bus j.

$$P_i^s = \left.\frac{\partial P_{loss}}{\partial X_{i,j}}\right| = P_{loss}\ sensitivity\ with\ respect\ to\ X_{i,j} \qquad (5)$$

1.2.1 Reduction in Total system Real Power Losses

It is based on the sensitivity of the total system real power loss (ΣP_L) with respect to control variable of TCSC i.e. X_{ij}. X_{ij} is the net line series reactance with TCSC placed between buses i and j and $_{bij}$ is the Real power loss sensitivity with respect to X_{ij} [16-17]can be computed as:

$$b_{i\,j} = \frac{\partial P_{Lk}}{\partial X_{ij}} = [V_i^2 + V_j^2 - 2V_iV_j \cos\delta_{ij}]\frac{-2 * r_{ij}^2 * x_{ij}^2}{\left(r_{ij}^2 + x_{ij}^2\right)^2} \qquad (6)$$

2.3 Total system Reactive Power Loss Sensitivity

For the optimal Placement of TCSC, a method based on sensitivity of the total system reactive power loss with respect to the control variable of TCSC. For TCSC placement between buses i and j we considered the net line series reactance as a control parameter. Reactive power loss and its sensitivity with respect to control parameter of TCSC placed between buses i and j can be written as:

$$Q_{loss} = \sum_{k \in nl} -(V_i^2 + v_j^2)(B_k + B_{sh}) + 2V_iV_jB_k \cos\theta_{ij}) \qquad (7)$$

Where, B_k is susceptance of line k and B_{sh} is half of the shunt susceptance.

$$Q_l^s = \left.\frac{\partial Q_{loss}}{\partial X_{i,j}}\right| = P_{loss}\ sensitivity\ with\ respect\ to\ X_{i,j} \qquad (8)$$

2.3.1 Reduction of total system Reactive Power Loss

Defined the sensitivity a_{ij} of the total system reactive power loss (ΣQ_{LK}) on a series compensated line-k with respect to control variable parameters of TCSC i.e. x_{ij} [63]. Where x_{ij} is the net line series reactance with TCSC placed between bus i and j and $_{aij}$ is the loss sensitivity with respect to X_{ij} [61],[62] [16-17] placed in line k or bus-i and bus-j can be computed as :

$$a_{i\,j} = \frac{\partial Q_{Lk}}{\partial X_{ij}} = [V_i^2 + V_j^2 - 2V_iV_j \cos\delta_{ij}]\frac{r_{ij}^2 - x_{ij}^2}{\left(r_{ij}^2 + x_{ij}^2\right)^2} \qquad (9)$$

The loss sensitivity for each line can be calculated using above equation by substituting $X_{TCSC}= X_c =0$. If a_{ii} value is more positive then sensitivity of the line will be more. TCSC can be placed in a line having more positive sensitivity index.

III. Solution Algorithm

1). Conduct load flow analysis using NR Method without TCSC and determine real power flow performance index, total system real power losses (P_l), and reactive power losses (Q_l) in the base case condition.

2). Simulate various single line outage contingencies in load flow program. Find out and rank critical contingencies according to their severity.

3). these critical contingencies are the sensitive line of a power system as their absence (outage) creates overloading in the power system.

4). these critical contingencies (Lines) may be considered as possible location for placement of TCSC.

5). Starting from the most sever line, TCSC is placed in one line at a time and its effect on power system in terms of PI sensitivity, P_{loss} sensivity and Q_{loss} sensitivity is evaluated using equation (2), (4), and (6) to select the optimal location of TCSC.

6). The line having highest positive sensitivity with respect to real power flow performance index, P_l and Q_l is selected as the optimal location of the TCSC.

IV. Simulation Results and Discussion

The real power flow PI sensitivity, real power loss sensitivity and reactivity power loss sensitivity-based criteria for selecting the optimal location of TCSC has been implemented on a benchmark 5-bus system [13] and on IEEE 30-bus system [14]. In these systems, the rating of all the lines is considered as 1.5 p.u. [57]. Voltage deviation is considered +/- 5% to avoid voltage collapse during faulty condition. In general, if the load requirement increases, the voltage at the corresponding buses may drop below 0.95 pu. and consequently, an additional voltage support is provided by TCSC, and its optimal location is determined by Newton-Raphson load flow method in MATLAB Environment. The simulation results are discussed in following sections.

4.1. 5-Bus System

To demonstrate the impact of TCSC on power system security, the bench mark 5-bus system contains two generators and seven transmission lines have been considered. Details related to 5-bus system has been shown in [13]. Bus-1 has been taken reference bus. Results of load flow are shown in table 1 and 2. Further, values of sensitivity indices are shown in table 2.

Table 1. Results of load flow analysis for 5-bus system

Bus No.	V(pu)	Angle(rad)	Angle(degrees)
1	1.06	0	0
2	1	-2.061	-0.036
3	0.997	-4.637	-0.08099
4	0.984	-4.957	-0.08658
5	0.972	-5.765	-0.1007

From table 2, it is observed that the total real power losses and reactive power losses are 0.0613 p.u. and -0.1076 p.u., respectively.

Table 2. Load flows, real and reactive power loss sensitivities indices in 5-bus system without TCSC.

Line	Bus (i-j)	a_{ij}	b_{ij}	c_{ij}	P_{ij}	P_l	Q_l
1	1-2	-0.9943	-0.7458	-17.2668	0.8933	0.0249	0.0109
2	1-3	-0.1518	-0.1139	-1.81478	0.4179	0.0152	-0.0069
3	2-3	-0.048	-0.0359	-1.21907	0.2447	0.0036	-0.0287
4	2-4	-0.0615	-0.0461	-1.39239	0.2771	0.0046	-0.0255
5	2-5	-0.243	-0.1822	-4.2658	0.5466	0.0122	0.0073
6	3-4	-0.03157	-0.02367	-6.12502	0.1939	0.0004	-0.0182
7	4-5	-0.0044	-0.0032	-0.28016	0.066	0.0004	-0.0465
Total active & Reactive Power losses						**0.0613**	**-0.1076**

Sensitivity analysis is carried out considering the value of a_{ij}, b_{ij}, and c_{ij} as shown in table 2. The description of sensitivity analysis is given below:

✓ Based on $\mathbf{a_{ij}}$ values, the line in descending order of sensitivity are: line 4-5, 3-4, 2-3, 2-4, 1-3, 2-5.
✓ Based on $\mathbf{b_{ij}}$ values, the lines in descending order of sensitivity are: line 4-5, 3-4, 2-3,2-4, 1-3, 2-5.
✓ Based on $\mathbf{c_{ij}}$ values, the lines in descending order of sensitivity are: line 3-4, 2-5, 1-3, 2-4, 2-3, 4-5.

On the basis of sensitivity ranking TCSC is placed in the sensitive lines with 80% compensation and the total system reactive power loss is calculated by using three sensitivity methods. Total system reactive power losses without TCSC and when TCSC placed in the lines 4-5, 3-4, 2-3, 2-4, 1-3, 2-5 and 1-2 based on sensitivity index a_{ij} are shown in table 3.

Table 3. Total system reactive power losses with and without TCSC

Line	Bus (i-j)	Q_l (without TCSC)	Q_l (TCSC in Line 4-5)	Q_l (TCSC in Line 3-4)	Q_l (TCSC in Line 2-3)	Q_l (TCSC in Line 2-4)	Q_l (TCSC in Line1-3)	Q_l (TCSC in Line 2-5)	Q_l (TCSC in Line 1-2)
1	1-2	1.0868	1.0134	1.0346	1.5788	1.5463	-0.7047	-0.7047	1.3227
2	1-3	-0.6922	-0.49	-0.5593	-1.225	-1.236	-2.4269	-2.4269	-1.1606
3	2-3	-2.8708	-2.714	-2.7639	-3.2176	-3.43	-3.8579	-3.8579	-3.2453
4	2-4	-2.5545	-2.3296	-2.6786	-3.121	-3.0185	-3.5759	-3.5759	-3.0794

5	2-5	0.7287	0.1199	0.6464	0.3239	0.1391	-0.092	-0.092	-1.7967
6	3-4	-1.823	-1.7869	-1.9149	-1.6278	-1.8453	-1.507	-1.507	-1.8892
7	4-5	-4.6525	-4.7188	-4.6359	-4.4894	-4.3833	-4.3862	-4.3862	-4.5588
Sum: Q_l		**-10.7775**	**-10.906**	**-10.8716**	**-11.7781**	**-12.2277**	**-16.5506**	**-14.4073**	**-5.2711**

The total system real power losses when TCSC is placed in lines 4-5, 3-4, 2-3, 2-4, 1-2, 2-5 and 1-3 based on the sensitivity index a_{ij} are given in table 4.

Table 4. Real power losses with TCSC in sensitive lines in 5-bus system

Bus (i-j)	P_l (without TCSC)	P_l (TCSC in Line 4-5)	P_l (TCSC in Line 3-4)	P_l (TCSC in Line 2-3)	P_l (TCSC in Line 2-4)	P_l (TCSC in Line 1-2)	P_l (TCSC in Line 2-5)	P_l (TCSC in Line1-3)
1-2	0.8933	0.8829	0.8859	0.9301	0.9273	1.3193	0.9256	0.5241
1-3	0.4179	0.4287	0.4254	0.3827	0.3858	0.1802	0.3886	0.8063
2-3	0.2447	0.2616	0.2564	0.3457	0.1944	0.3533	0.198	0.0799
2-4	0.2771	0.2985	0.2646	0.2334	0.392	0.3639	0.218	0.145
2-5	0.5466	0.4982	0.5403	0.5252	0.5152	0.5897	0.6839	0.4803
3-4	0.1939	0.2204	0.2122	0.2573	0.1142	0.0687	0.1206	0.3884
4-5	0.066	0.1131	0.0721	0.0868	.00965	0.0246	0.0644	0.1306
SUM P_l	**2.6395**	**2.7034**	**2.6569**	**2.7612**	**2.6254**	**2.8997**	**2.5991**	**2.5546**

From table 4, it is seen that real power loss minimization-based sensitivity method is more effective for finding optimal location of TCSC for enhancing the power system performance.

Table 5. Real power flow with TCSC in sensitive lines in 5-bus systems

Line	Bus (i-j)	P(TCSC in Line1-3)	P (TCSC in Line 2-5)	P (TCSC in Line 2-4)
1	1-2	0.5241	0.9256	0.9273
2	1-3	0.8063	0.3886	0.3858
3	2-3	0.0799	0.198	0.1944
4	2-4	0.145	0.218	0.392
5	2-5	0.4803	0.6839	0.5152
6	3-4	0.3884	0.1206	0.1142
7	4-5	0.1306	0.0644	0.0965
SUM		2.5546	2.5991	2.6254

Tables 3, 4, and 5 shows that the reactive power losses have been reduced significantly after placing TCSC in lines 1-3 , 2-5 and 2-4. The maximum reduction in reactive power loss is with TCSC in line 1-3 using the sensitivity indices a_{ij} and c_{ij}. Using reactive power loss sensitivity method, there is hardly any change in total reactive power losses as well as real power flows in the lines. While maximum change has been observed when TCSCs are placed based on real power loss minimization method and real power flow minimization method. Hence optimal location for TCSC is line 1-3 which is giving maximum decrease in real power flows as well as maximum decrease in total system reactive power loss. The results given in table 5 reveals that TCSC placement in lines 1-3, 2-5 and 2-4 is increasing the load ability of the lines and also decreasing the total reactive power loss of the system. Table 4 shows the real power flows in the transmission lines when TCSC is placed in lines 4-5, 3-4, 2-3,2-4, 2-5, 1-2 and 1-3 based on the sensitivity index 'a_{ij}.

After placing TCSC in line 1-3, the real power flow of lines 1-2, 2-3, 2-4, 2-5 was decreased. Similarly, when TCSC was placed in line 2-5, real power transfers in lines 1-3, 2-3, 2-4, 3-4, 4-5 was decreased. After placing TCSC in line 2-4, the real power transfer of lines 1-3, 2-5, 3-4, 4-5 and 2-3 was decreased which enhanced available transfer capability of the lines. Effect of change in % compensation (TCSC in line 2-5) on real power flows and reactive power losses in the critical line i.e. line 5 is more sensitive. Therefore, optimal location for TCSC placement is in line 5 which reduces reactive power losses and real power flows. However, size of TCSC should be selected considering the power transfer limits of the lines to avoid transmission lines congestion.

4.2. IEEE 30-Bus System

IEEE-30 bus power system comprised of 6 generator buses, 24 load buses, and 41 transmission lines. Bus-1 has been taken as the reference bus. The system data corresponding to generators and the line data are given in [14]. IEEE 30 bus simulation results of load flow along with sensitivity indices are given in table 6.

Table 6. Load flows, real and reactive power loss sensitivities indices in IEEE 30-bus system without TCSC

line	a_{ij}	b_{ij}	c_{ij}	P_{ij}	P_l	Q_l
1-2	-2.2747	-1.7098	-26.8143	177.7779	0.0546	0.1052
1-3	-0.5514	-0.2862	-4.3332	83.2206	0.0281	0.0709
2-4	-0.1564	-0.115	-2.4561	45.7119	0.0111	-0.0052
3-4	-0.0004	-0.3627	-18.1341	78.0124	0.0077	0.0134
2-5	-0.5665	-0.2859	-4.0059	82.9904	0.03	0.0818
2-6	-0.2834	-0.2096	-3.1859	61.9122	0.0205	0.0226
4-6	-0.4303	-0.2696	-14.5515	70.1255	0.006	0.0118
5-7	-0.0239	-0.0225	0.7172	-14.2048	0.0015	-0.0169
6-7	-0.1112	-0.081	-4.1009	37.5231	0.0037	-0.006
6-8	-0.0732	-0.0455	-6.2928	29.5283	0.001	-0.0056
6-9	-0.1041	0	-1.3021	27.6928	0	0.0159
6-10	-0.0257	0	-0.2758	15.8227	0	0.0128
9-11	-0.0222	0	1.46E-15	0.00E+00	0	0.0046
9-10	-0.0736	0	-2.5175	27.6928	0	0.0081
4-12	-0.1886	0	-1.6063	44.1214	0	0.0468
12-13	-0.0095	0	-1.28E-14	0.00E+00	0	0.0013
12-14	-0.0038	-0.0047	-0.2866	7.8563	0.0007	0.0015
12-15	-0.0194	-0.0265	-1.3039	17.8574	0.0022	0.0043
12-16	-0.0035	-0.0044	-0.3615	7.2077	0.0005	0.0011
14-15	0	-0.0002	-0.0527	1.5818	0.0001	0.0001
16-17	-0.001	-0.001	-0.1879	3.6543	0.0001	0.0003
15-18	-0.0022	-0.0028	-0.2534	6.0143	0.0004	0.0008
18-19	-0.0005	-0.0006	-0.1961	2.7752	0.0001	0.0001
19-20	-0.003	-0.004	0.9474	-6.7298	0.0002	0.0003
10-20	-0.0057	-0.0064	-0.4233	9.0275	0.0008	0.0018
10-17	-0.0033	-0.003	-0.7288	5.3718	0.0001	0.0004
10-21	-0.0203	-0.0242	-2.2297	15.7331	0.0011	0.0024
10-22	-0.0044	-0.0056	-0.5272	7.5831	0.0005	0.0011
21-22	0	0	0.9079	-1.8768	0	0
15-23	-0.0019	-0.0024	-0.257	5.0014	0.0003	0.0006
22-24	-0.0015	-0.0034	-0.2944	5.6539	0.0004	0.0007
23-24	-0.0003	-0.0004	-0.0718	1.7701	0.0001	0.0001
24-25	-0.0002	-0.0003	0.0093	-1.3248	0.0001	0.0001
25-26	-0.0007	-0.0016	-0.0932	3.5445	0.0004	0.0007
25-27	-0.0014	-0.002	0.1987	-4.8772	0.0003	0.0005

28-27	-0.0314	0	-0.4445	-18.1835	0	0.0131
27-29	-0.0022	-0.0033	-0.133	6.1894	0.0009	0.0016
27-30	-0.0028	-0.0041	-0.1032	7.0913	0.0016	0.003
29-30	-0.0007	-0.0011	-0.0693	3.7035	0.0003	0.0006
8-28	0	0	0.0288	-0.5751	0	-0.0437
6-28	-0.0302	-0.0185	-2.7809	18.8187	0.0006	-0.1309
Total real & reactive power losses					**0.176**	**0.2221**

From the load flow results, it is observed that the total reactive power losses are 0.2221 p.u. and the total system real power losses are 0.176 p.u.
Sensitivity analysis based on a_{ij}, b_{ij} and c_{ij} values is as below:

✓ Based on **a_{ij}** values, the lines in descending order of sensitivity are: line 2-5, 1-3, 4-6, 2-6, 14-12, 2-4.

✓ Based on **b_{ij}** values, the lines in descending order of sensitivity are: line 2-5, 1-3, 4-6, 2-6, 14-12, 2-4

✓ Based on **c_{ij}** values, the lines in descending order of sensitivity are: line 19-20, 21-22, 25-27, 8-28, 24-25, 9-11, 12-13, and 14-15.

On the basis of sensitivity ranking TCSC is placed in the sensitive lines with 80% compensation and the total system reactive power loss is calculated by using three sensitivity methods.

Table 7. Total system reactive power losses with and without TCSC in IEEE 30-bus system

bus (i-j)	**Q_l without TCSC**	**Q_l (TCSC in Line (2-5)**	**Q_l (TCSC in Line (1-3)**	**Q_l (TCSC in Line (4-6)**	**Q_l (TCSC in Line (2-6)**	**Q_l (TCSC in Line (14-12)**	**Q_l (TCSC in Line (2-4)**
1-2	0.1052	0.1195	0.03	0.0989	0.1343	0.1053	0.133
1-3	0.0709	0.054	0.0147	0.0801	0.0433	0.071	0.0408
2-4	-0.0052	-0.0184	-0.0261	0.0019	-0.0232	-0.0051	-0.0172
3-4	0.0134	0.0102	0.0489	0.0152	0.0081	0.0135	0.0076
2-5	0.0818	0.0103	0.0616	0.0744	0.054	0.0817	0.0637
2-6	0.0226	-0.0023	-0.0046	0.0119	0.0009	0.0226	-0.002
4-6	0.0118	0.003	0.0284	-0.0034	-0.0011	0.0116	0.0269
5-7	-0.0169	-0.0163	-0.0131	-0.0156	-0.0101	-0.0169	-0.0135
6-7	-0.006	-0.0147	-0.0013	-0.0044	0.0022	-0.006	-0.0018
6-8	-0.0056	-0.0054	-0.0054	-0.0054	-0.0049	-0.0056	-0.0053
6-9	0.0159	0.0176	0.0152	0.018	0.0185	0.0158	0.0153
6-10	0.0128	0.0136	0.0121	0.0144	0.014	0.0127	0.0121
9-11	0.0046	0.0062	0.005	0.0046	0.0068	0.0046	0.0051
9-10	0.0081	0.0085	0.0077	0.009	0.0088	0.008	0.0078
4-12	0.0468	0.0445	0.0495	0.0417	0.0433	0.0475	0.0492
12-13	0.0013	0.0021	0.0017	0.0012	0.0023	0.0013	0.0017
12-14	0.0015	0.0015	0.0016	0.0015	0.0015	0.0005	0.0016
12-15	0.0043	0.0042	0.0045	0.0038	0.0042	0.0037	0.0045
12-16	0.0011	0.0011	0.0013	0.0009	0.001	0.0011	0.0013
14-15	0.0001	0.0001	0.0001	0	0.0001	0.0003	0.0001
16-17	0.0003	0.0002	0.0004	0.0002	0.0002	0.0003	0.0004
15-18	0.0008	0.0008	0.0009	0.0006	0.0007	0.0009	0.0009
18-19	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001

19-20	0.0003	0.0004	0.0003	0.0004	0.0004	0.0003	0.0003
10-20	0.0018	0.0019	0.0017	0.002	0.0019	0.0017	0.0017
10-17	0.0004	0.0004	0.0003	0.0005	0.0004	0.0004	0.0003
10-21	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024
10-22	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011
21-22	0	0	0	0	0	0	0
15-23	0.0006	0.0006	0.0007	0.0005	0.0006	0.0007	0.0007
22-24	0.0007	0.0007	0.0006	0.0007	0.0007	0.0006	0.0007
23-24	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	0.0002
24-25	0.0001	0.0002	0.0001	0.0002	0.0002	0.0001	0.0001
25-26	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007
25-27	0.0005	0.0005	0.0004	0.0006	0.0005	0.0005	0.0004
28-27	0.0131	0.0132	0.0128	0.0137	0.0134	0.013	0.0128
27-29	0.0016	0.0016	0.0016	0.0016	0.0017	0.0016	0.0016
27-30	0.003	0.0031	0.0031	0.003	0.0031	0.003	0.0031
29-30	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
8-28	-0.0437	-0.0429	-0.0436	-0.0436	-0.0427	-0.0437	-0.0436
6-28	-0.1309	-0.1284	-0.1305	-0.1305	-0.1275	-0.1309	-0.1304
TOTAL	**0.2221**	**0.0966**	**0.0857**	**0.2036**	**0.1626**	**0.2211**	**0.185**

The total system reactive power losses when TCSC placed in the lines 2-5, 3-4, 1-3, 4-6, 2-6, 14-12 and 2-4 based on the sensitivity index $\mathbf{a_{ij}}$ are shown in table 7.

Table 8. Real power losses with TCSC in IEEE 30-bus system

bus (i-j)	**P_l without TCSC**	**P_l (TCSC in Line (2-5)**	**P_l (TCSC in Line (1-3)**	**P_l (TCSC in Line (4-6)**	**P_l (TCSC in Line (2-6)**	**P_l (TCSC in Line (14-12)**	**P_l (TCSC in Line (2-4)**
1-2	177.7779	186.1116	131.2025	174.3297	192.7482	177.7857	192.0793
1-3	83.2206	76.2938	131.5795	86.7829	71.7749	83.2574	70.7984
2-4	45.7119	34.4515	24.5659	50.6553	27.894	45.7551	79.5113
3-4	78.0124	71.5019	122.0381	81.3442	67.2461	78.0468	66.3295
2-5	82.9904	117.2243	75.9823	80.5129	72.4854	82.9791	76.7612
2-6	61.9122	46.8153	46.0022	56.2105	104.2334	61.8875	47.7164
4-6	70.1255	53.9426	90.8741	81.2963	44.05	69.843	88.5932
5-7	-14.2048	16.7033	-20.7317	-16.5072	-24.0381	-14.2152	-20.0042
6-7	37.5231	6.3135	44.3488	39.9263	47.8594	37.534	43.588
6-8	29.5283	29.5283	29.4979	29.6453	29.591	29.5107	29.5066
6-9	27.6928	28.3309	26.874	29.3842	28.7358	27.5515	26.956
6-10	15.8227	16.1604	15.3479	16.789	16.3815	15.7419	15.3939
9-11	0	0	0	0	0	0	0
9-10	27.6928	28.3309	26.874	29.3842	28.7358	27.5515	26.956
4-12	44.1214	43.1056	45.7168	40.9235	42.4034	44.4788	45.562
12-13	0	0	0	0	0	0	0
12-14	7.8563	7.7752	8.017	7.5417	7.7155	10.5763	8.0007
12-15	17.8574	17.4325	18.5426	16.4881	17.1357	15.7272	18.4763
12-16	7.2077	6.698	7.9572	5.6936	6.3523	6.9753	7.8849

14-15	1.5818	1.5007	1.7399	1.2714	1.4414	4.2526	1.7239
16-17	3.6543	3.147	4.3954	2.1524	2.8028	3.4238	4.324
15-18	6.0143	5.7493	6.4124	5.2111	5.5704	6.2909	6.3733
18-19	2.7752	2.5119	3.1688	1.9794	2.3342	3.0489	3.1301
19-20	-6.7298	-6.9926	-6.3375	-7.5238	-7.1701	-6.457	-6.376
10-20	9.0275	9.2945	8.6293	9.8351	9.4748	8.7504	8.6685
10-17	5.3718	5.8784	4.6332	6.8727	6.2228	5.6017	4.7044
10-21	15.7331	15.8553	15.6382	15.9445	15.9168	15.6271	15.6489
10-22	7.5831	7.6631	7.5212	7.721	7.703	7.5141	7.5282
21-22	-1.8768	-1.7572	-1.9714	-1.6669	-1.6965	-1.9821	-1.9609
15-23	5.0014	4.7632	5.4324	4.1489	4.5889	5.2641	5.3906
22-24	5.6539	5.852	5.4976	6.0007	5.9523	5.48	5.515
23-24	1.7701	1.5313	2.1978	0.9219	1.357	2.031	2.1564
24-25	-1.3248	-1.3694	-1.0537	-1.8288	-1.445	-1.2372	-1.0778
25-26	3.5445	3.5452	3.5447	3.5445	3.5453	3.5445	3.5447
25-27	-4.8772	-4.9259	-4.6043	-5.3863	-5.0034	-4.7889	-4.6285
28-27	-18.1835	-18.2372	-17.9094	-18.6975	-18.3169	-18.0945	-17.9339
27-29	6.1894	6.1914	6.1899	6.1893	6.192	6.1894	6.1899
27-30	7.0913	7.0939	7.0919	7.0912	7.0946	7.0913	7.092
29-30	3.7035	3.7042	3.7037	3.7035	3.7043	3.7036	3.7037
8-28	-0.5751	-0.5759	-0.611	-0.4627	-0.5252	-0.5926	-0.6036
6-28	18.8187	18.8746	18.58	19.2237	18.9062	18.7467	18.5975
TOTAL	**870.7953**	**856.0174**	**896.5782**	**876.6458**	**849.954**	**874.3944**	**895.8199**

From table 8, it is seen that real power losses are minimum when TCSC is placed in line 2-6. Hence, real power flow minimization based on sensitivity method is more effective for finding optimal location of TCSC for enhancing the power system performance.

V. Conclusions

Sensitivity based analysis has been carried out to find out the optimal location of TCSC to improve the performance of power system in terms of security, load ability and real & reactive power losses. It is observed that real power loss minimization based on sensitivity index method and real power flow minimization-based sensitivity index method are more effective as compared to the reactive power loss reduction-based sensitivity index method to obtain the optimal location of TCSC. Further, results obtained for 5-bus system and IEEE 30-bus systems showed the consistency of the proposed sensitivity-based approaches.

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