TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.5, May 2014, pp. 3649 ~ 3661
DOI: http://dx.doi.org/10.11591/telkomnika.v12i5.4423

Optimal Location of Thyristor-controlled-series-capacitor using Min Cut Algorithm

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Abstract

Existence of many different Operators in the new electricity has brought many challenges in the system operation and control to obtain minimum generation cost and security. With the growing demand of electricity in the competitive electricity market environment, one or more transmission lines could be overloaded, therefore causing congestion. The congestion can be eliminated/alleviated by improving transfer capability of the network. Thyristor controlled series compensators (TCSC), with its ability to directly control the power flow can be very effective to improve the operation of transmission network. This paper describes an approach for determining the most suitable locations for installing TCSC devices in order to eliminate line overloads and minimize generation costs. The proposed approach is based on the minimum cut methodology that reduces the search space and using benefit index to decide on the best locations for the TCSC. The 5-bus, IEEE 14-bus and 30-bus test systems are used to demonstrate the proposed approach. Results show that the proposed method is capable of finding the best location for TCSC installation to minimize total costs.

Keywords*: congestion, FACTS, TCSC, min cut, benefit index*

1. Introduction

The restructuring of the electricity industry has brought many social welfare benefits. However, it is also facing many challenges related to power system security. Various factors such as environmental and economic constraints have limited the expansion of the transmission networks. Meanwhile, the creation of electricity markets has led to the trading of significant amounts of electrical energy over long distances, and the number of unplanned power exchanges increases due to the competition among utilities and contracts concluded directly between producers and consumers has made the level of security of power systems weakened. In these markets, security is measured through “system congestion” levels [1]. Congestion occurs when the transmitted power exceeds the capacity or transfer limit of the transmission line [2, 3]. Congestion leads to inefficient use of the system, increasing total generation costs and effecting direct on market transactions and electricity prices (prices in some areas will increase and in others decrease). Congestion therefore distorts the market [4]. Hence, congestion management is a challenging task for Independent System Operator (ISO) for maintaining stability, security and reliability [5].

In order to eliminate/alleviate congestion, managing dispatch (generation re-dispatching [6] and load shedding [7]) are easy to implement and maybe still necessary in the worst situation but may not be acceptable by both power providers and customers due to their significant effect on the existing power transaction contracts. Hence, the use of controllable flexible AC transmission system (FACTS) [8] to improve transfer capability of existing power systems and eliminate/alleviate congestion, while still be able to obtain minimal cost, is one of main interests in current issues. TCSC can provide benefits in increasing system transfer capability and power flow control flexibility and rapidity, however, the current challenge is now to obtain the optimal installation of (FACTS) devices.

It is indicated that the effectiveness of the controls for different purposes mainly depends on the location of control device [9]. The proper location of FACTS devices is a key to obtain minimum generation cost. Therefore, Operators are facing the problem of where TCSC

Received September 19, 2013; Revised December 15, 2013; Accepted January 4, 2014

should be installed in order to achieve require goal? This is one of difficult problems due to a large size of search space for a practical system. However, it can be solved if bottleneck of power system is determined. Determining the system bottleneck plays key role in reducing search space and number of FACTS devices need to be installed. The bottleneck is location that demonstrates maximum possible power flow from source(s) to sink(s). When the system load is increased, the bottleneck is the first location where congestion occurs [10]. Furthermore, the existence of bottlenecks in the transmission line affects the total supply cost, limiting the cheapest plants and forcing the dispatching of more expensive generators [11]. Therefore, it needs to be eliminated by placing TCSC devices on suitable location in the transmission system to redistribute real power flows.

In fact, the distribution of power flow is independent from capacity loading of line but it is rely on impedance. This leads to the result that the bottleneck can be overloaded though the capacity loading of bottleneck is higher than the power demand. Hence, the placement of FACTS on the branch bottleneck to modify the line impedance is a method which rapidly rebalances the power by redirecting the power flow across this branch to eliminate overload.

Various methods have been proposed to achieve these different objectives via optimal location of FACTS devices. But mostly, these works are commonly focused on the following methods and techniques.

Population based intelligent techniques to find optimal solutions, such as Genetic Algorithm [12], Evolutionary Programming [13], and Particle Swarm Optimization [14], combines PSO and GA [15], TS/SA method [16], and Gravitational Search Algorithm (GSA) [17] have been used to determine the optimal setting of FACTS parameters, minimizing the total generator fuel cost within power flower security limits.

Sensitivity based approach was used to find the optimal location of FACTS devices in power network. The sensitivity index is used to rank the system branches according to their suitability for installing a TCSC. Once the locations are determined, an optimization problem of finding the best settings for the installed TCSC is formulated and solved [18]. Such an approach is used in [19], where LMP difference and congestion rent contribution are utilized for optimal location of TCSC to reduce the congestion cost. An overload sensitivity factor (power flow index) is used for optimal location of series FACTS devices for static congestion management [20]. In [21], optimal placement of TCSC for reducing congestion cost has been presented by using a performance index, which incorporates two factors. One is the sensitivity matrix of the TCSC with respect to the congested line and the other is the shadow price corresponding to the congested line. A method based on the sensitivity of the reduction of total system VAR power loss and real power performance index to determine the optimal location of TCSC for congestion management is presented in [22].

M.A. Khaburi has been used the partition method to limit the search space [23]. The power system was divided into two different areas. The area, where a lot of generators are focused, is called source area while the area, where a lot of loads are focused, is called sink area. These areas are connected by the lines. Compensated equipments are installed on the branches between the two areas to find the optimal solution according to the objective function.

In this paper, utilization of the TCSC to eliminate congestion and minimum generation cost is investigated. In order to completely eliminate congestion but no need generation rescheduling, System Operator can use one, two or many TCSC devices. However, it needs to be considered performance gained from investment in TCSC devices so that can choose an effective solution. In order to evaluate the suitability of a given branch for placing a TCSC, an index called the benefit index (BI) is introduced for each branch. This index is obtained from the difference between the minimum generation cost with and without TCSC. Base on the index, the best location for the TCSC devices is decided.

This paper has applied the minimum cut methodology for determining bottleneck of power system to reduce search space as well as using benefit index for determining the most suitable locations for installing TCSC devices. The basic idea of the algorithm is to find the cut that has the minimum cut value over all possible cuts in the network. That is the cut which contains bottleneck branches with sum of capacity through it's smallest. Therefore, if the minimum cut is identified, the branch that has the ability to contribute to adjust impedance will be recognized and only that branch is able to install TCSC to help the congested branch.

Hence, searching space will be reduced from n branch to m branch. (m is the branches that minimum cut passes through).

The study results on 5-bus, IEEE 14-bus and IEEE 30-bus power system have proved the effectiveness of the proposed method.

2. Problem Formulation

2.1. Static Modeling of TCSC

The effect of TCSC on the network can be seen as a controllable reactance inserted in the related transmission line [16]. Series capacitive compensation works by reducing the effective series impedance of the transmission line by canceling part of the inductive reactance. Hence the power transferred is increased. The model of the network with TCSC is shown in Figure 1.

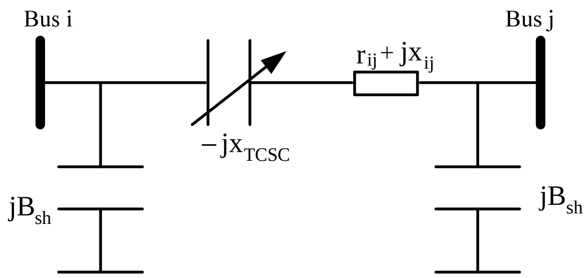

Figure 1. Model of Transmission Line with TCSC

The maximum compensation by TCSC is limited to 70% of the reactance of the un-compensated line where TCSC is located. A new line reactance (X_{new}) is given as follows:

$$X_{New} = X_{ij} - X_{TCSC} \quad (1)$$

$$X_{New} = (1- k)X_{ij} \quad (2)$$

Where $k = X_{TCSC}/X_{ij}$ is the degree of series compensation and X_{ij} is the line reactance between bus-i and bus-j.

The power flow equations of the line with a new reactance can be derived as follows:

$$P_{ij} = V_i^2 G_{ij} - V_i V_j (G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij}) \quad (3)$$

$$Q_{ij} = -V_i^2 B_{ij} - V_i V_j (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}) \quad (4)$$

$$P_{ji} = V_j^2 G_{ij} - V_i V_j (G_{ij} \cos\delta_{ij} - B_{ij} \sin\delta_{ij}) \quad (5)$$

$$Q_{ji} = -V_j^2 B_{ij} + V_i V_j (G_{ij} \sin\delta_{ij} + B_{ij} \cos\delta_{ij}) \quad (6)$$

Where δ_{ij} is the voltage angle difference between bus i and bus j.

$$G_{ij} = \frac{R_{ij}}{R_{ij}^2 + X_{New}^2} \quad \text{and} \quad B_{ij} = \frac{X_{New}}{R_{ij}^2 + X_{New}^2} \quad (7)$$

2.2. Objective Function

The objective function for determining the locations and control settings of TCSC to minimize the active power generation cost is formulated as follows:

$$\text{Min} \sum_{i \in N_g} C_i(P_{gi}) + C_{TCSC} \tag{8}$$

Where $C_i(P_{gi}) = aP_{gi}^2 + bP_{gi} + c$ is the bid curve of i^{th} generator; a, b and c are cost coefficients for the generator.

Subject to:

a) Power balance equation:

$$P_i(V,\delta) + P_{di} - P_{gi} = 0 \quad i = 1,..., N_b \tag{9}$$

$$Q_i(V,\delta) + Q_{di} - Q_{gi} = 0 \quad i = 1,..., N_b \tag{10}$$

b) Power generation limit:

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \quad i = 1,....., N_g \tag{11}$$

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \quad i = 1,....., N_g \tag{12}$$

c) Bus voltage limits:

$$V_i^{min} \le V_i \le V_i^{max} \quad i = 1,.....,N_b \tag{13}$$

d) Apparent line flow limit:

$$S_l \le S_{l,max} \quad l = 1,....., N_l \tag{14}$$

$$0 \le X_{TCSCi} \le X_{TCSCi}^{max} \quad i = 1,.....,N_{TCSC} \tag{15}$$

Where P_{gi}, Q_{gi} are the active and reactive power generation at bus-i: P_{di}, Q_{di} the active and reactive power demand at bus i: V_i the voltage magnitude at bus i: $V_{i,min}$ and $V_{i,max}$ the minimum and maximum voltage limits; $P_{gi,min}$ and $P_{gi,max}$ are the minimum and maximum limits of real power generation: N_b the total number of buses, N_g is the total number of generation buses: N_{TCSC} is the set of TCSC indices: S_l the apparent power flow in transmission line connecting nodes *i* and *j*, and S_l,max is its maximum limit.

2.3. Cost Function

The TCSC cost in line-k is given by [24]:

$$C_{TCSC}^k = C.X_c^k.P_L^2.\text{Base\_power} \tag{16}$$

Where C is the unit investment cost of TCSC, X_c^k is the series capacitive reactance and P_L is the power flow in line-k.

$$C_{TCSC}^t = \frac{\alpha.C_{TCSC}^k}{8760}(\$/h) \quad \text{and} \quad \alpha = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{17}$$

α = the capital recovery factor (CRF);
r = the interest rate;
n = the capital recovery plan.

It is assumed that the investment cost of the TCSC is 150$/kVar. Considering the interest rate r =0.05, the capital recovery period n =10 years, the capital recovery factor can be computed, i.e., α = 0.1295.

2.4. Benefit Index

The benefit index (BI) for the investment in FACTS devices can be calculated as follow:

$$BI = \frac{\text{Generation cost after redispatch without TCSC - Generation cost after redispatch with TCSC}}{\text{Cost investment of TCSC}} \quad (18)$$

This index is calculated for each location of TCSC and used to evaluate the suitability of a given branch for placing a TCSC. The branch that gives a maximum benefit index is the main proper location of TCSC.

3. Proposed Method

3.1. Min Cut Algorithm

The best location of TCSC plays key role in controlling of the system power flows to eliminate congestion. The problem can be solved if minimum cut of power system is determined. There are several methods to find minimum cut for any network having a single origin node and single destination node. One of the usual approaches to solve this problem is to use its close relationship to the maximum flow problem. The famous Max-Flow/Min-Cut-Theorem by Ford and Fulkerson (1956) [25] showed the duality of the maximum flow and the so-called minimum s-t-cut. There, s and t are two vertices that are the source and the sink in the flow problem and have to be separated by the cut, that is, they have to lie in different parts of the partition.

a. Max-Flow

Max flow is the maximum possible flow from origin to destination equals the minimum cut values for all cuts in the network.

b. Minimum Cut

The minimum cut problem is to find the cut across the network that has the minimum cut value over all possible cuts.

3.2. Modeling Power Network Using Min Cut Algorithm

The power system is modeled as a directed network *G(N,A)* where it is defined by a set *N* of *n* nodes and a set *A* of *m* directed arcs. Each arc $a_{ij} \in A$ has a capacity u_{ij} that shows the maximum amount that can flow between node i and j. The min cut algorithm is added two nodes, the virtual source and the virtual sink, representing the combination of the generators and loads, respectively. Each line out of the virtual source has a maximum flow that matches the generation of the connected node, and each line into the virtual sink represents the load demanded by the connected node. The modeling of an example power system depicted in Figure 2 is shown in Figure 3.

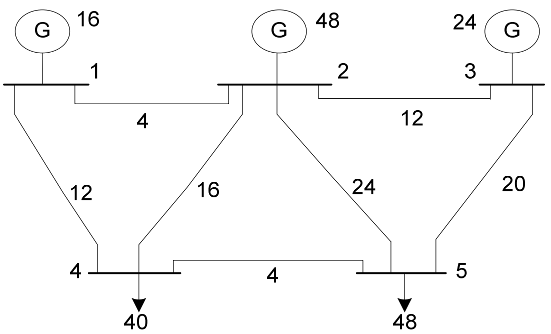

Figure 2. Example Power System with Generators of 16 at 1, 48 at 2 and 24 at 3 and Loads of 40 and 48

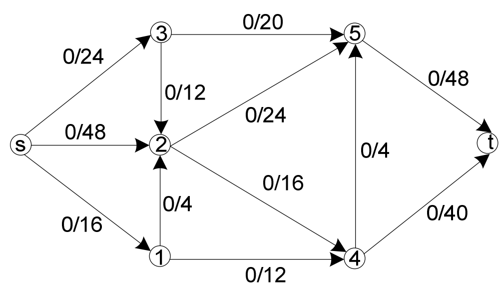

Figure 3. Power Network Shown as a Directed Flow Graph with Virtual Nodes s and t. Edges are Labeled with (flow/capacity).

The algorithm works by successively assigning flow $f(a_{ij})$ to arcs along a directed path from s to t until no more flow can be added. The details for determining the minimum cut of power system is presented in Reference [10, 25].

a) The steps in the method are:

1. Find any path from the origin node to the destination node. If there are no more such path, exit.
2. Detemine f, the maximum flow along this path, which will be equal to the smallest flow capacity on any arc in the path (the bottleneck arc).
3. Subtract f from the remaining flow capacity according to the direction from the origin node to the destination node for each arc in the path.
4. Go to Step 1

b) The algorithm will be used to determine the minimum cut of the 5-bus system in Figure 2

1. The arcs along the path s - 1 - 4 - t are labeled using 12 units of flow. The bottleneck here is the arc 1 – 4 as shown in Figure 4
2. The arcs along the path s - 2 - 4 - t are labeled using 16 units of flow. The bottleneck here is the arc 2 – 4. Note that with the simultaneous flow on path s - 1 - 4 - t, the total flow on arc 4 – t is now 28 units of flow as Figure 5
3. The arcs along the path s - 2 - 5 - t are labeled using 24 units of flow. The bottleneck on this path is arc 2 – 5 as Figure 6
4. The arcs along the path s - 3 - 5 - t are labeled using 20 units of flow. The bottleneck on this path is arc 3 – 5 as Figure 7

The algorithm terminates after the last path is found in Figure 7 because there are no more available paths to be found between s and t. This is obvious since all paths must pass through the set of arcs 1-4, 2-4, 2-5 and 3-5, and these arcs have all had their flow capacity in the direction from s to t reduced to zero. The final graph is in Figure 7. From the Figure it can be seen that, sum the units of flow on bottleneck arcs (12 + 16 + 24 + 20 = 72) equals sum the units of flow on the arcs out of the source (12+40+20=72) or into the sink (28+44=72). This is maximum possible power flow from source(s) to sink(s) equals the minimum cut value for all the cuts in the network. Some possible cuts are illustrated in Figure 8. Flow chart for determination optimal location of TCSC in congestion management is presented in Figure 9

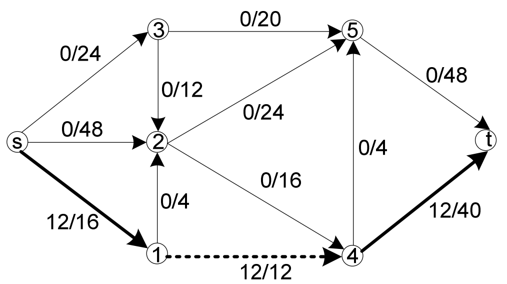

Figure 4. The Units of Flow along s-1-4-t

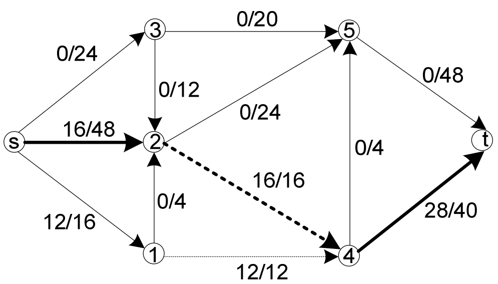

Figure 5. The Units of Flow along s-2-4-t

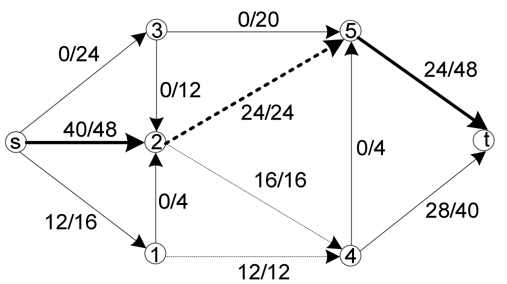

Figure 6. The Units of Flow along s-2-5-t

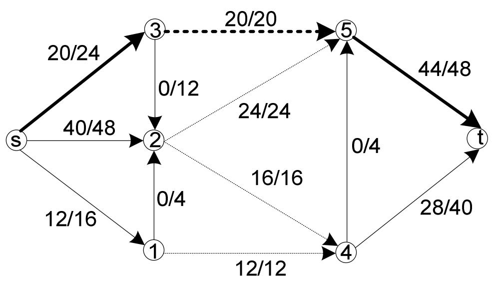

Figure 7. The Units of Flow along s-3-5-t

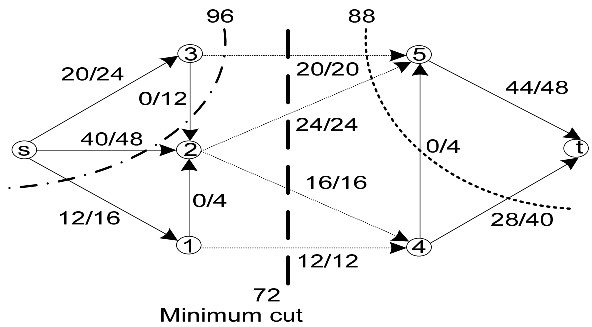

Figure 8. Some Possible Cuts

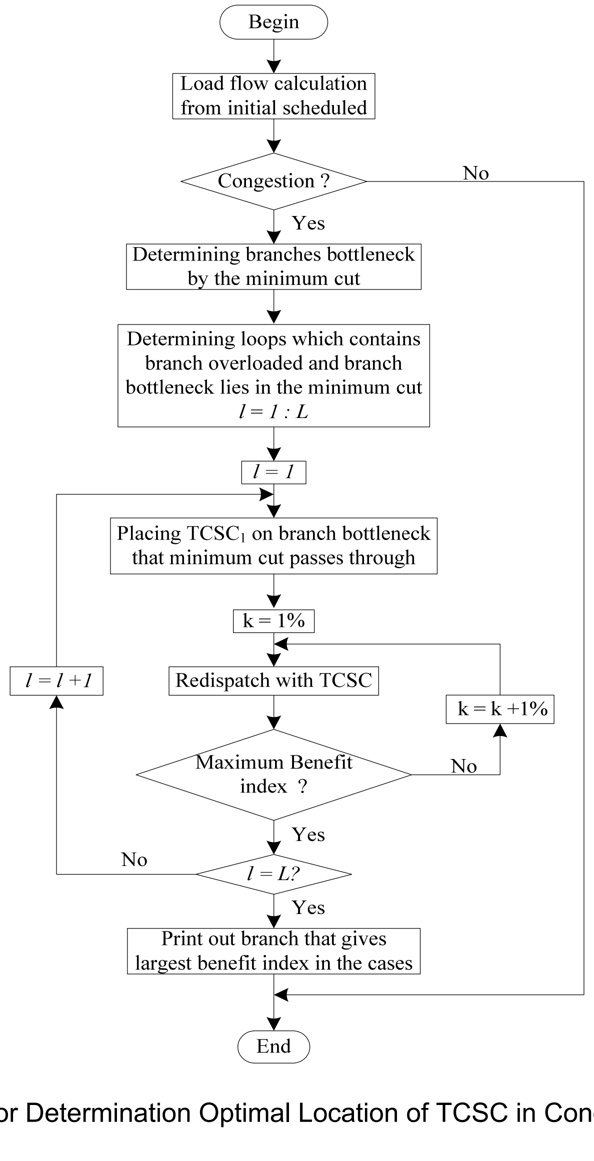

Figure 9. Flow Chart for Determination Optimal Location of TCSC in Congestion Management

4. Results and Discussions

The proposed method for the optimal location of the TCSC for congestion management has been implemented on 5-bus, IEEE 14-bus and IEEE 30-bus test systems. MATPOWER [26], a toolbox of MATLAB, has been used for the simulations.

4.1. The 5-Bus System

The network and data of the 5-bus system are given in Appendix

In order to verify the proposed approach and illustrate the impacts of TCSC, three cases for test systems were investigated:

Case 1: Generation initial schedule, minimum generation cost.

Case 2: Generation redispatching without TCSC.

Case 3: Generation redispatching with TCSC.

Table 1. Re-dispatch with TCSC in line 2-5 Objective Function Minimum Generation for the 5 bus System

Ge	P scheduled	Re-dispatch without TCSC	Re-dispatch with TCSC	Total absolute redispatch without TCSC	Total absolute redispatch with TCSC	Generation cost before redispatch	Generation cost after re-dispatch without TCSC	Generation cost after re-dispatch with TCSC
1	48	85.3	48	74.1	0.0	2811.38 ($/hr)	3033.86 ($/hr)	2811.39 ($/hr)
2	116.2	79.4	116.2					
3	72	72	72					

From Table 1(Column 2), it was observed that generation power of Generator 2 is more than compare with Generator 1 and 3 due to Generator 2 is the cheapest Generator. With this generation schedule, total cost of active power generation was obtained optimal 2811.38($/hr) (Case 1) as Table 1 (Column 7) but not secured due to congestion occurred in lines 2-4 as shown in Table 2 (Column 3). The network cannot be operated in this way since security of the network was violated. However, the congestion on the line 2–4 was eliminated by generation re-dispatching but may not be obtain minimal cost. The branch 2-4 is one of branch bottleneck of power system that prevents loads to be served from cheapest generators.

To satisfy sufficient the power to the loads, some cheap generators have to reduce their dispatch and some expensive generators in the congested zone have to increase their dispatch and consequently total cost of active power generation was increased from 2811.38 $/h to 3033.86 $/h (Case 2) as Table 1 (column 8). The possibility of operating the power system at the minimal cost while satisfying system security by placing TCSC at proper location with an optimal setting size of TCSC to increase the use of available capacity of the existing lines. In order to archive require goal, the TCSC need to be installed on branch that the minimum cut passes through and lies in loop which contains branch overload. From Table 3, it can been see that, line 2-5, 1-4 and 3-5 are lines that the minimum cut passes through and are also lines in loops 1 (1-2-4-1), loop 2(2-5-4-2) and loop 3(2-3-5-4-2) which contains branch overloaded 2-4 respectively. Therefore, to eliminate/alleviate congestion, TCSC can be installed on one of the lines. Once the locations are determined, an optimization problem of finding the best settings for the installed TCSC is formulated and solved. As there are a lot of locations that can install on TCSC to eliminate congestion, it needs base on benefit gained from investment in TCSC so that can decide best location of TCSC. The branch that gives the largest benefit index is the main location of TCSC.

Table 2. Line Loadings from Load Flow with Initial Scheduled and Re-dispatch with TCSC in Line 2-5

Line no	i - j	Loading % with initial scheduled	Loading % re-dispatch with TCSC
1	1 – 2	18.41	19.10
2	2 – 4	**107.45**	99.05
3	1 – 4	40.9	39.25
4	2 – 3	22.4	30.90
5	2 – 5	41.44	58.84
6	3 – 5	50.39	41.38
7	4 – 5	15.01	23.51

Table 3.The Minimum of the 5-bus System

Line no	The minimum cut
1	2 - 5
2	2 - 4
3	1 – 4
4	3 – 5

Table 4. Benefit Index Computed for Different Branches in the Minimum Cut

Line no	i-j	Loop i	BI
1	1-4	1-2-4-1	7.79
3	2-5	2-5-4-2	**9.22**
4	3-5	2-3-5-4-2	3.90

Table 5. Benefit Index Computed for Different Locations of the TCSC

Line no	i-j	BI
1	1-4	7.79
3	2-5	**9.22**
4	3-5	3.90
5	1-2	-56.2
6	2-3	-8.32
7	4-5	0.84

As shown in Table 4, the line 2-5 is the best location for placement TCSC since it gives the largest benefit index. The value of control parameter of TCSC is taken as -0.064pu. System power flow result after placing TCSC in line 2-5 is shown in Table 2. It can be observed from Table 2 (Column 4) that congestion has been relieved. The loading of the lines 2-4 has now reduced to 99.05% from the initial scheduled 107.45%. Line 2-5 is now loaded to 58.84% which is much higher than in initial scheduled. The TCSC reduced the series impedance of the line 2-5 hence power flow on the line increases. According to the table 1, the re-dispatched amount to remove congestion in the presence of the TCSC on line 2-5 is 0.0 MW compared to 74.1MW in the case re-dispatch without TCSC, generation cost is only 2811.39 $/hr (Case 3) compared to 3033.86$/hr for the case re-dispatch without TCSC. So, the annual saving is 1.94(million$). Table 5 is constructed for verification purpose, by placing TCSC on each line one at a time and running OPF. According to Table 5, line 2-5 is the best location for TCSC installation to eliminate congestion and minimize generation cost followed by line 1-4 and 3-5. The other lines are gives a benefit index less than one or zero. Hence, it is not advisable to make the investment since the savings in the generation costs cannot pay for the investment. From Table 3 it can be observed that the number of branches which need to be investigated to determine the location of TCSC has reduced from 7 branches to 3 branches in the minimum cut.

4.2. IEEE 14-Bus Test System

There are 20 line sections in IEEE 14-bus system. The network and load data for IEEE 14-bus are shown in [19].

From Table 7 (Column 3) it can be seen that, one part of the system is congested. Generator 1 is the cheapest generator and is served by two transmission lines (1-2 and 1-5) with a total capacity of 110MW. The two lines are not equally loaded due to the difference in impedance and the result is that line 1-2 is loaded to 132.86% of its capacity while line 1-5 is only loaded to 55.95% of its capacity. Placing TCSC at suitable location via the minimum cut of power system can eliminate the overload on line 1-2.

Table 6. Re-dispatch with TCSC in line 1-5 Objective Function Minimum Generation for IEEE-14 Bus System

Ge	P scheduled	Re-dispatch without TCSC	Re-dispatch with TCSC	Total absolute redispatch without TCSC	Total absolute redispatch with TCSC	Generation cost before redispatch	Generation cost after re-dispatch without TCSC	Generation cost after re-dispatch with TCSC
1	100	76.71	97.09	46.58	7.56	5944.21 ($/hr)	6448.28 ($/hr)	6000.25 ($/hr)
2	50	50	50					
3	29.71	42.29	33.49					
6	45	45	45					
8	34.29	45	33.42					

Table 7. Line Loadings from Load Flow with Initial Scheduled and Re-dispatch with TCSC in Line 1-5

Line no	i - j	Loading % with initial scheduled	Loading % re-dispatch with TCSC
1	1 – 2	**132.86**	**99.28**
2	1 – 5	55.95	78.48
3	2 – 3	73.73	66.6
4	2 – 4	75.1	61.85
5	2 – 5	51.12	32.65
6	3 – 4	67.5	69.16
7	4 – 5	51.62	59.31
8	4 – 7	5.85	5.02
9	4 – 9	28.15	28.25
10	5 – 6	10.24	11.28
11	6 – 11	44.6	45.84
12	6 – 12	41.3	41.5
13	6 – 13	65.06	65.6
14	7 – 8	57.15	55.7
15	7 – 9	63.88	62.82
16	9 – 10	6.75	5.2
17	9 – 14	22.4	21.73
18	10 – 11	38.25	39.8
19	12 – 13	10.8	11
20	13 – 14	40.9	41.9

Table 8. The Minimum of IEEE 14-bus System

Line no	The minimum cut
1	2 - 5
2	2 - 4

Table 9. Benefit Index Computed for Different Locations of the TCSC

Line no	i-j	BI
2	1-5	**8.28**
6	3- 4	**3.62**
3	2-3	-2.32
7	4-5	0.16
1	1-2	-10.38
10	5-6	0.14
4	2-4	-6.9
14	7-8	0.09
8	4-7	0.6
15	7-9	-0.25

From Table 8 it can be observed that, line 1-5 is the line that the minimum cut passes through and is also line in loop (1-2-5-1). Therefore, suitable position of TCSC is at line 1-5. The value of control parameter of TCSC for computing maximum benefit index is taken as -0.11pu. System power flow result after placing TCSC in line 1-5 is shown in Table 7 (Column 4). It can be observed from this Table, congestion has been relieved. The loading of the lines 1-2 has now reduced to 99.28%. Line 1-5 is now loaded to 78.48% which is much higher than from the initial scheduled. According to the Table 6, the re-dispatched amount to remove congestion in the presence of the TCSC on line 1-5 is only 7.56MW compared to 46.58MW in the case without TCSC, generation cost is only 6000.25$/hr compared to 6448.28$/hr for the case without TCSC. So, the annual saving is 3.92(million$). From Table 9 it can see the line 1-5 is the best location for placement TCSC since it gives the largest benefit index.

Observation of Table 9 shows that the proposed method also captures the best location for the placement of TCSC in comparison with the result in [19]. However, the number of branches which need to be investigated to determine the location of TCSC has reduced from 20 branches to 2 branches in the minimum cut as shown in Table 8 which is less than as compared with [19].

4.3. IEEE 30-Bus Test System

IEEE 30-bus system has 41 line sections. The network and load data for IEEE 30-bus shown in [26], the cost coefficients for IEEE 30-bus is given in Appendix

The load flow of IEEE 30-bus system is shown in Table 11 (Column 3 and 7). From the load flow, it was found that line 6–8 and line 21–22 was overloaded. To avoid overloading, it needs to place TCSC at suitable location. It can be observed from Table 12 that, the minimum cut passes through tie lines (27-30, 27-29, 6-8, 8-28, 21-22, 13-22, 25-27 and 10-22). In which line 8-28 and 10-22 are lines in loops (6-8-28-6) and (10-22-21-10) which contains branch overloaded 6-8 and 21-22, respectively. Therefore, the lines 8-28 and 10-22 were considered for placing TCSC. System power flow result after placing TCSC in line 8-28 and line 10-22 is shown in Table 11 (Column 4 and 8). The value of control parameter of TCSC for computing maximum benefit index is taken as -0.13pu and -0.07pu respectively. It can be observed from Table 11 (Column 4 and 8) that congestion has been relieved and generation cost is shown in Table 10. According to the Table 10, the re-dispatched amount to remove congestion in the presence of the TCSC on line 8-28 and line 10-22 is only 0.15MW compared to 76.08MW in the case without TCSC, generation cost is only 1700.47$/hr compared to 1796.13$/hr for the case without TCSC. So, the annual saving is 0.84(million$), the benefit index obtained is 4.38. From Table 12 it can be observed that, the number of branch which needs to be investigated to determine the location of TCSC has significantly reduced.

Table 10. Re-dispatch with TCSC in Line 8-28 and 10-22 Objective Function Minimum Generation for IEEE-30 Bus System

Ge	P scheduled	Re-dispatch without TCSC	Re-dispatch with TCSC	Total absolute redispatch without TCSC	Total absolute redispatch with TCSC	Generation cost before redispatch	Generation cost after re-dispatch without TCSC	Generation cost after re-dispatch with TCSC
1	46.17	21.53	46.26	76.08	0.15	1700.07 ($/hr)	1796.13 ($/hr)	1700.47 ($/hr)
2	80	80	80					
22	0.0	0.02	0.0					
27	50	36.73	50					
23	0.0	13.18	0.0					
13	16.28	41.25	16.22					

Table 11. Line Loadings from Load Flow with Initial Scheduled and Re-dispatch with Two TCSC in Line 8-28 and 10-22 for IEEE-30 Bus System

Line no	i - j	Loading % with initial scheduled	Loading % re-dispatch with TCSC	Line no	i - j	Loading % with initial scheduled	Loading % with initial scheduled
1	1 – 2	15.66	15.83	21	16 – 17	38	38.19
2	1 – 3	20.56	20.66	22	15 – 18	28.5	27.81
3	2 – 4	43.15	43.29	23	18 – 19	20.62	20.60
4	3 – 4	18.46	18.49	24	19 – 20	33.28	33.74
5	2 – 5	14.5	14.71	25	10 – 20	40.81	41.28
6	2 – 6	48.15	48.27	26	10 – 17	43.09	43.57
7	4 – 6	24.72	24.56	27	10 – 21	43.31	35.16
8	5 – 7	27.17	27.39	28	10 – 22	34.59	46.26
9	6 – 7	5.03	5.64	29	**21 – 22**	**108.68**	**99.81**
10	**6 – 8**	**111.53**	**97.15**	30	15 – 23	19.43	17.63
11	6 – 9	14.7	14.98	31	22 – 24	76.31	74.42
12	6 – 10	17.06	17.5	32	23 – 24	46.68	44.66
13	9 – 11	0	0	33	24 – 25	19.68	19.19
14	9 – 10	14.86	15.08	34	25 – 26	26.56	26.59
15	4 – 12	38.30	39.3	35	25 – 27	46.43	46.08
16	12 – 13	45.23	46.4	36	28 – 27	15.75	16.50
17	12 – 14	18.28	18.37	37	27 – 29	39.81	39.85
18	12 – 15	30.15	30.51	38	27 – 30	45.5	45.54
19	12 – 16	18.56	18.32	39	29 – 30	23.25	23.3
20	14 – 15	7.18	6.89	40	8 – 28	23.9	36.96
				41	6 – 28	28.06	35.43

Overall results show that the proposed method is capable of finding the best location for TCSC installation. Using the minimum cut of power system that reduces significantly search space as well as using benefit index to evaluate the suitability of a given branch for placing a TCSC is on of effective methods to optimal location of TCSC in congestion management and to minimize total costs.

Table 12. The Minimum of IEEE 30-bus System

Line no	The minimum cut
38	2 7– 30
37	27 – 29
10	6 – 8
40	8 – 28
29	21 – 22
16	13 – 12
35	25 – 27
28	10 – 22

5. Conclusion

In deregulated power systems, System Operators face the challenge of finding effective ways of managing transmission congestion to obtain minimum total costs. The TCSC by controlling the power flows in the network can help to reduce the flows in heavily loaded lines. Therefore, it has been considered one of the effective methods in order to solve above issue. This paper has applied minimum cut methodology that reduces the search space and then, base on the benefit index to decide proper location of TCSC.

The study results on 5-bus, IEEE 14-bus and IEEE 30-bus system have proved the effectiveness of the proposed method. This method is capable of finding the best location for TCSC installation to minimize total costs. Using this method, the search scope is limited hence the number of branches which need to be investigated to determine the location of TCSC has been significantly decreased.

6. Appendix

The 5-bus system one-line diagram is shown in Figure 2. System line data is shown in Table A, B. Bus-1 has been taken as a reference bus. The line flow limit is set to 100 MVA, Load-4 (P_4 = 160MW, Q_4 = 15MVAR), Load-5 (P_5 = 75MW, Q_5 = 15MVAR).

Table A. 5-bus System Line Data

i-j	R (pu)	X (pu)
1-2	0.0023	0.12
2-4	0.0012	0.08
1-4	0.063	0.24
2-3	0.0011	0.14
2-5	0.0012	0.12
3-5	0.0017	0.16
4-5	0.0021	0.24

Table B. Generator Data

Gen no	a($/MW2h)	b($/MWh)	c ($/h)
The 5-bus system			
1	0.11	6	150
2	0.0065	1.2	60
3	0.1125	1	335
IEEE-30 bus system			
1	0.0252	16	0
2	0.1400	14	0
3	0.5000	8	0
6	0.0667	26	0
8	0.2000	24	0

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