Electrical Power and Energy Systems 52 (2013) 68–80

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A new method for secured optimal power flow under normal and network contingencies via optimal location of TCSC

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ARTICLE INFO

Article history:
Received 15 October 2012
Received in revised form 12 March 2013
Accepted 28 March 2013
Available online 22 April 2013

Keywords:
FACTS
TCSC
OPF
SCOPF
Min cut and secured optimal power flow

ABSTRACT

In the deregulated power industry, private power producers are increasing rapidly to meet the increase demand. The purpose of the transmission network is to pool power plants and load centers in order to supply the load at a required reliability, maximum efficiency and at lower cost. As power transfer increases, the power system becomes increasingly more difficult to operate and insecure with unscheduled power flows and higher losses. FACTS devices such as Thyristor Controlled Series Compensator (TCSC) can be very effective to power system security. Proper location of TCSC plays key role in optimal power flow solution and enhancement of system performance without violating the security of the system. This paper applied min cut algorithm to select proper location of TCSC for secured optimal power flow under normal and contingencies operating condition. Proposed method requires a two-step approach. First, the optimal location of the TCSC in the network must be ascertained by min cut algorithm and then, the optimal power flow (OPF) with TCSC under normal and contingencies operating condition is solved. The proposed method was tested and validated for locating TCSC in Six bus, IEEE 14-, IEEE-30 and IEEE-118 bus test systems. Results show that the proposed method is good to select proper location of TCSC for secured OPF.

1. Introduction

With features of the new electricity market and the network structure are becoming more complex, the System Operators are facing many challenges in terms of system operation to obtain economic benefit and security. Various factors such as

- Upgrading of the generation and transmission systems has not been adequate with the increasing in load.
- The creation of electricity markets has led to the trading of significant amounts of electrical energy over long distances.
- The number of unplanned power exchanges increases due to the competition among utilities and contracts concluded directly between producers and consumers.

Made the level of security of power systems weakened. Hence, power system security [1] has become one of the most important issues in the electricity market operation. In these markets, security is measured through "system congestion" levels, which have a direct effect on market transactions and electricity prices, and are represented by means of power transfer limits on main transmission lines between operating areas [2]. Better market and system operating conditions may be achieved when system security and economy are better accounted. Solution of this problem is known as Security Constrained Optimal Power Flow (SCOPF).

The SCOPF [3] is an extension of the OPF problem [4] which is used to obtain an economical operation of the system while considering not only normal operating limits, but also violations that would occur during contingencies. The SCOPF changes the system pre-contingency operating point so that the total operating cost is minimized, and at the same time no security limit is violated if contingencies occur. Although the SCOPF are still challenges related to computations, it is expected that the SCOPF will eventually become a standard tool in the electricity industry [5].

Various approaches to approximate this region in OPF models have been proposed. For example, in [6] has proposed an algorithm for solving SCOPF problem through the application of evolutionary programming (EP). A new robust differential evolution algorithm for SCOPF considering detailed generator model is presented in [7]. Florin Capitanescu and Louis Wehenkel [8] has proposed a new iterative approach to the corrective SCOPF Problem. Ref. [9] has presented a approach to solve an optimal power flow problem with embedded security constraints represented

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http://dx.doi.org/10.1016/j.ijepes.2013.03.025

by a mixture of continuous and discrete control variables, where the major aim is to minimize the total operating cost, taking into account both operating security constraints and system capacity requirements. In [10] has proposed of DC SCOPF approximation to improve iterative AC SCOPF Algorithms. A novel approach to pricing the system security by parallelizing the Security Constrained Optimal Power Flow (SCOPF) based market-clearing model is presented in [11].

Power systems are commonly planned and operated based on the (n_1) security criterion [12]. As the power system becomes more complex, more heavily loaded and the unexpected outages, has created overloads on the existing transmission lines and lead to unstable system. In this case, re-dispatching generation [13] and load shedding [14] to eliminate/alleviate emergency transmission line overloads is an important problem in power system operation but may not be acceptable by both power providers and customers due to their significant effect on the existing power transaction contracts. The use of controllable flexible AC transmission system (FACTS) [15] to improve transfer capability and eliminate/alleviate congestion, while still be able to obtain minimal cost, is one of main current issues. However, it is indicated that the effectiveness of the controls for different purposes mainly depends on the location of control device [16]. Therefore, the real question is "which location should the System Operators place FACTS on in order to achieve a defined goal". Determining the bottleneck of power system plays key role in reducing search space and number of FACTS devices need to be installed. The presence of bottlenecks in the transmission line affects the total supply cost, limiting the cheapest plants and forcing the dispatching of more expensive generators [17]. The above problem can be strongly reduced if FACTS devices are suitably installed in the transmission system with the aim of redistributing real power flows.

Many algorithms have been proposed to enhance the static security via optimal location of FACTS devices. In [18], Differential evolution (DE) algorithm is used to find out the optimal placement and parameter setting of UPFC for enhancing power system security under single line contingencies. In order to evaluate the suitability of a given branch for placing a TCSC, two index called thermal capacity index (TCI) and contingency capacity index (CCI) [19] are used to obtain secured optimal power flow under normal and network contingencies. Ref. [20] has presented principles about installation and operation of FACTS devices to enhance the steady-state security of power system. Momoh et al. [21] has suggested the phase shifters for security enhancement and obtained the parameters using the optimal power flow formulation.

In this paper (TCSC), which is one of the most effective FACTS devices, is selected. The objective of this paper is to obtain secured OPF solution under normal operation and contingency condition through the optimal utilization of TCSC and therefore enhancing the system static security. Utilization of the TCSC during (n_0) and (n_1) overloads is investigated. This is done by opening one of more important lines that have larger effect on remaining of the line and considering the effect of opened line on remaining of the system. If there is congestion in the network, attempt to set the installed TCSC in such a way that the OPF solution obtained without any overloads on the lines under network contingencies is termed as secured OPF. In order to evaluate the suitable location of TCSC, a Min-cut algorithm has been proposed to decide optimal location of TCSC to obtain secured OPF. The proposed method can identify the weakest location of the system and therefore helps the System Operators to operate the system in a more secure and sufficient way. Using this method, the number of branches which need to be investigated to determine the position of TCSC for secured OPF will be significantly decreased.

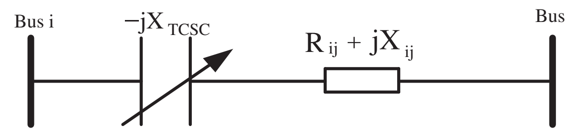

Fig. 1. Model of transmission line with TCSC.

2. Static modeling of TCSC

The effect of TCSC on the network can be seen as a controllable reactance inserted in the related transmission line [22]. 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. In this case study, TCSC only operates as a capacitor. The model of the network with TCSC is shown in Fig. 1. TCSC can be considered as a static reactance – jX_{TCSC} under steady state.

TCSC is integrated in the OPF problem by modifying the line data. 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.

$$X_{New} = X_{ij} - X_{TCSC} \tag{1}$$

$$X_{New} = (1 - L)X_{ij} \tag{2}$$

where $L = X_{TCSC}/X_{ij}$ 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.

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

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

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

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

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

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

3. Problem formulation

The OPF is a constrained optimization problem that requires minimization of an objective function. One of the possible objectives of OPF is the minimization of the power generation cost subject to the satisfaction of the generation and load balance in the transmission network as well as the operational limits and constraints of the generators and the transformers [23]. The OPF is generally expressed in mathematical form as:

$$\min f(x, u) \tag{7}$$

Subject to

$$g(x, u) = 0 \tag{8}$$

$$h(x, u) \leqslant 0 \tag{9}$$

where $f(x,u)$ is the objective function. The equality constraints (8) are the power flow equations, while the inequality constraints (9) are due to various limitations. The limitations include lower and upper limits on generator real and reactive powers limits on voltage magnitudes, line and transformer maximum currents, and sets of possible transformer taps position and shunt admittances. The vector of independent variables u is given by the active powers of the generators, the voltages of the PV nodes and transformer tap settings. The vector of dependent variables x is given by the voltages of PQ nodes, argument of PV nodes voltages and reactive power generation.

3.1. Objective function

The objective function is to minimize the active power generation cost which is expressed as:

$$Min\sum_{i\in N_g} C_i(P_{gi}) \tag{10}$$

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

Subject to

– Power balance equation

$$P_i(V,\delta) + P_{di} - P_{gi} = 0 \quad i = 1,\ldots,N_b \tag{11}$$

$$Q_i(V,\delta) + Q_{di} - Q_{gi} = 0 \quad i = 1,\ldots,N_b \tag{12}$$

– Power generation limit

$$P_{gi}^{\min} \leqslant P_{gi} \leqslant P_{gi}^{\max} \quad i = 1,\ldots,N_g \tag{13}$$

$$Q_{gi}^{\min} \leqslant Q_{gi} \leqslant Q_{gi}^{\max} \quad i = 1,\ldots,N_g \tag{14}$$

– Bus voltage limits

$$V_i^{\min} \leqslant V_i \leqslant V_i^{\max} \quad i = 1,\ldots,N_b \tag{15}$$

– Apparent line flow limit

$$S_l \leqslant S_{l,\max} \quad l = 1,\ldots,N_l \tag{16}$$

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: S_l the apparent power flow in transmission line connecting nodes i and j, and $S_{l,\max}$ is its maximum limit.

4. Optimal location of TCSC

A min-cut algorithm is introduced in this section for placing TCSC at suitable location to obtain secured OPF under normal and contingencies operating condition.

The active power generation cost can achieve optimal by solving OPF without consider line limits by Matpower software but may not be secured i.e. the OPF solution obtained at the cost of overloading the transmission lines. However, the congestion was eliminated if TCSC is placed in the suitable location. In order to reduce search space and improve transfer capability, TCSC need to be installed at the bottleneck location of power system. This is the 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. Therefore, in order to eliminate/alleviate congestion, the transfer capability at the bottleneck should be examined.

Furthermore, 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. Therefore, the placement of TCSC 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/alleviate overload. In order words, preventing congestion using TCSC means redistributes power flow to increase the use of available capacity of the existing lines.

Using the min-cut algorithm to find the minimum cut has been introduced in [24]. In this paper, the min cut algorithm will be used to determine the minimum cut of power system. 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 its smallest. In other words, the power system can satisfy sufficient the power to the loads, but due to the limit of the minimum cut, so maximum possible power flow from source(s) to sink(s) equals the minimum cut value for all the cuts in the network. 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).

4.1. Modeling power network using min cut algorithm

The power network is modeled as a directed graph $G(N,A)$ where power flow is represented as flow in the graph. The set of nodes, N, corresponds to the buses of the power network. The power line between buses n_i, $n_j \in N$ is represented by an arc $a_{ij} \in A$. Each arc is assigned u_{ij}, denoting the maximum allowable power flow through that line, and subsequently over the arc in the network. For the basic min cut algorithm there are two special nodes, the virtual source (s) and the virtual sink (t) which representing the combination of the generator(s) and load(s) 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 nodes s and t, together with G, form the graph $G(N,A)$. Fig. 2 is an example power system which has an equivalent directed graph representation in Fig. 3.

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 steps in the method are summarized as follow:

1. Find any path from the origin node to the destination node. If there are no more such path, exit.
2. Determine 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).

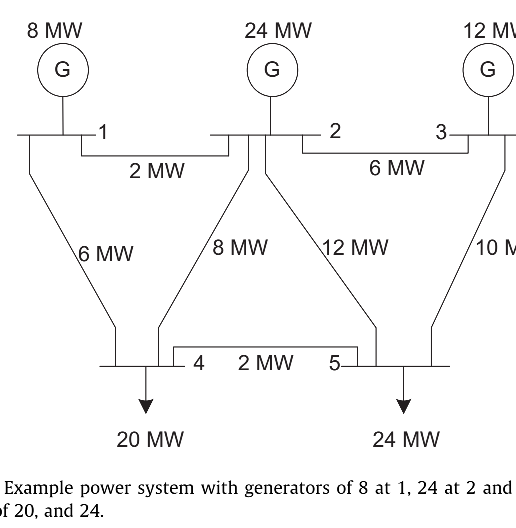

Fig. 2. Example power system with generators of 8 at 1, 24 at 2 and 12 at 3 and loads of 20, and 24.

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.

The algorithm will be used to determine the minimum cut of Fig. 3.

- The arcs along the path s-2–5-t are labeled using 12 units of flow. The bottleneck here is the arc 2–5 as shown in Fig. 3.1.
- The arcs along the path s-3–5-t are labeled using 10 units of flow. The bottleneck here is the arc 3–5. Note that with the simultaneous flow on path s-2–5-t, the total flow on arc 5-t is now 22 units of flow as Fig. 3.2.

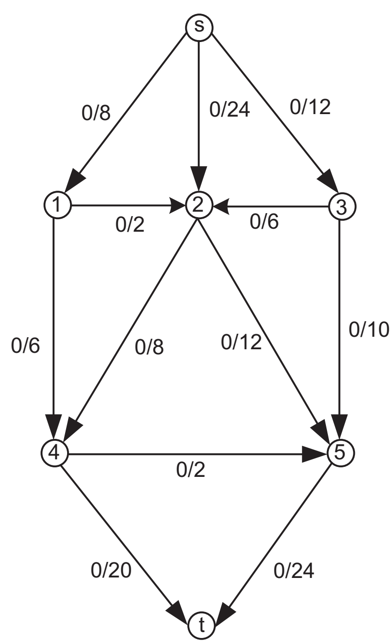

Fig. 3. Power network shown as a directed flow graph with virtual nodes s and t. Edges are labeled with (flow/capacity).

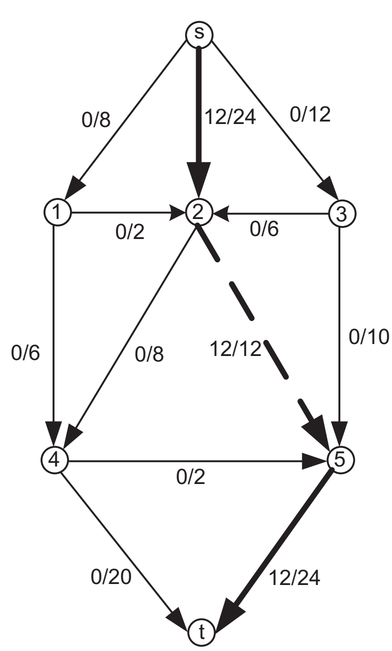

Fig. 3.1. The units of flow along s-2–5-t.

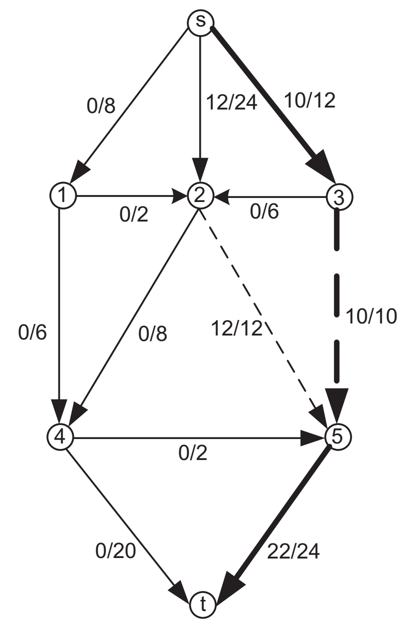

Fig. 3.2. The units of flow along s-3–5-t.

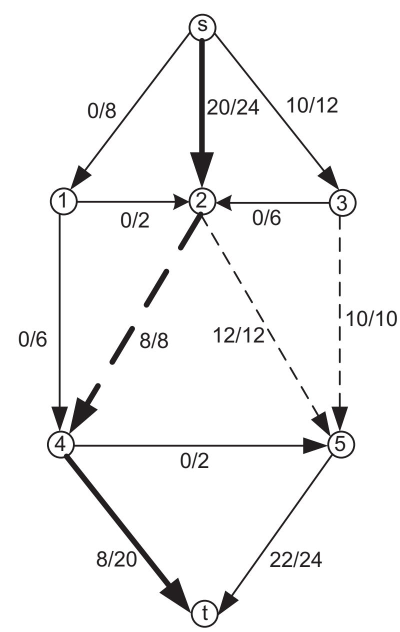

Fig. 3.3. The units of flow along s-2–4-t.

- The arcs along the path s-2–4-t are labeled using 8 units of flow. The bottleneck on this path is arc 2–4 as Fig. 3.3.
- The arcs along the path s-1–4-t are labeled using 6 units of flow. The bottleneck on this path is arc 1–4 as Fig. 3.4.

The algorithm terminates after the last path is found in Fig. 3.4 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 3–5, 2–5, 2–4 and 1–4, and these arcs have all had their flow capacity in the direction from s to t reduced to zero. The final graph is in Fig. 3.4. From the Figure it can be seen that, sum the units of flow on bottleneck arcs (12 + 10 + 8 + 6 = 36) equals sum the units of flow on the arcs out of the source (6 + 20 + 10 = 36) or into the sink (14 + 22 = 36). This is maximum possible power flow from

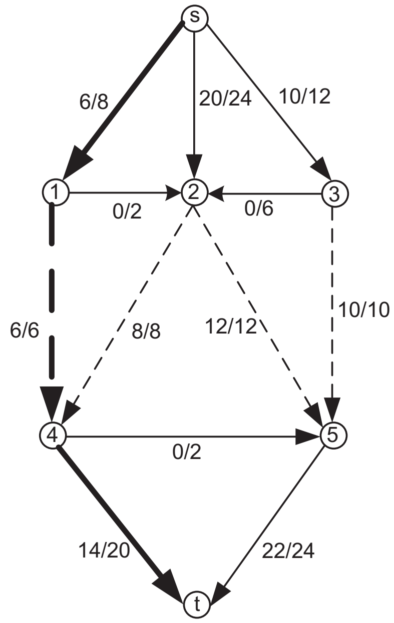

Fig. 3.4. The units of flow along s-1–4-t.

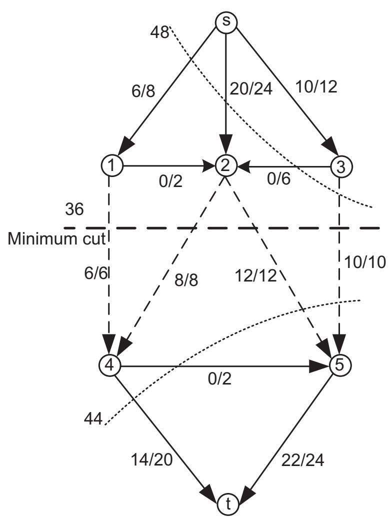

Fig. 3.5. Some possible cuts.

source(s) to sink(s) equals the minimum cut value for all the cuts in the network. Some possible cuts are illustrated in Fig. 3.5. Flow chart determine the minimum cut and flow chart for secured optimal power flow under normal and network contingencies are presented in Figs. 4 and 5 respectively.

5. Case study and discussions

The proposed method for the optimal location of the TCSC to achieve secured optimal power flow has been implemented on Six-bus, IEEE 14-bus, IEEE 30-bus and IEEE 118-bus test systems. A MATPOWER software package version 4.0 [25] was used to obtain optimal power flow with and without consider line limits.

5.1. Six bus system

There are 11 line sections in Six-bus system. The total system load is 210 MW, the network and load data for Six-bus system is shown in [19].

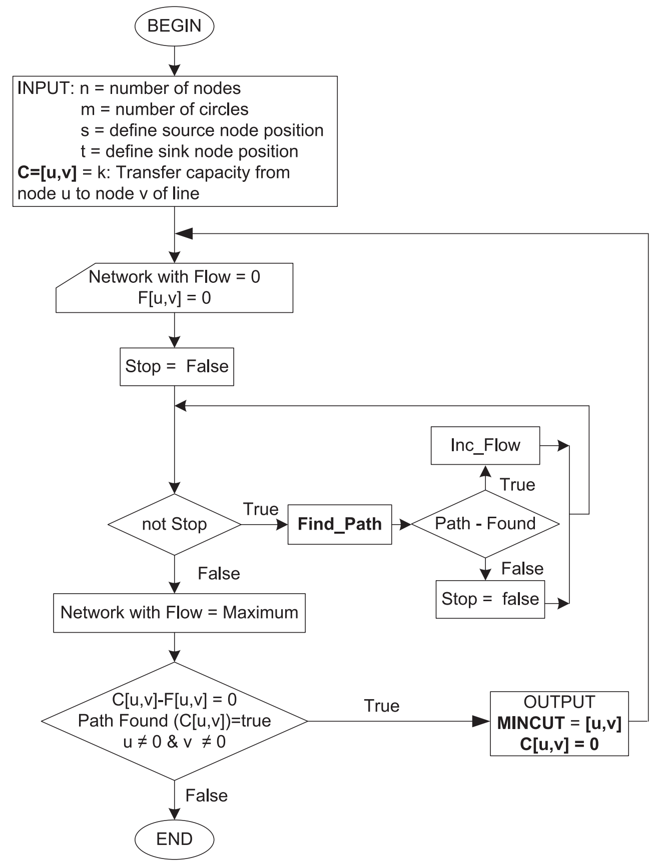

Fig. 4. Flow chart of min cut algorithm.

5.1.1. OPF under normal operation

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

- Case 1: OPF without TCSC, with line limits ignored.
- Case 2: OPF without TCSC.
- Case 3: OPF with TCSC.

From these OPF results in Table 1(column 2), it was observed that, when TCSC was not placed and line limits were not considered (case-1), the total cost of active power generation was obtained optimal 3126.36 $/h. However with this generation schedule, it was found that the real power flow exceeded the line flow limits in line 2–4 and consequently transmission congestion occurred as shown in Table 2(column 3). Clearly the network cannot be operated in this way since security of the network was violated. However, the overload on the transmission line 2–4 was eliminated by OPF solution with consider line limits (case-2). This condition will prevent loads to be served from generators obtained from the cheapest combination of generator outputs as in case-1 and consequently total cost of active power generation was increased from 3126.36 $/h to 3143.97 $/h as in Table 1(column 3). The possibility of operating the power system at the minimal cost while satisfying system security by placing TCSC at proper location to decrease the loading of line 2–4 and increased loading on neighborhood of the overloaded line (case-3). The neighborhood lines are the branches, which were part of a loop that was formed along with the overloaded lines. Therefore, the placement of TCSC on neighborhood of the overloaded line in the minimum cut is a method which rapidly rebalances the power by redirecting the power flow through un-congested transmission line(s) to alleviate

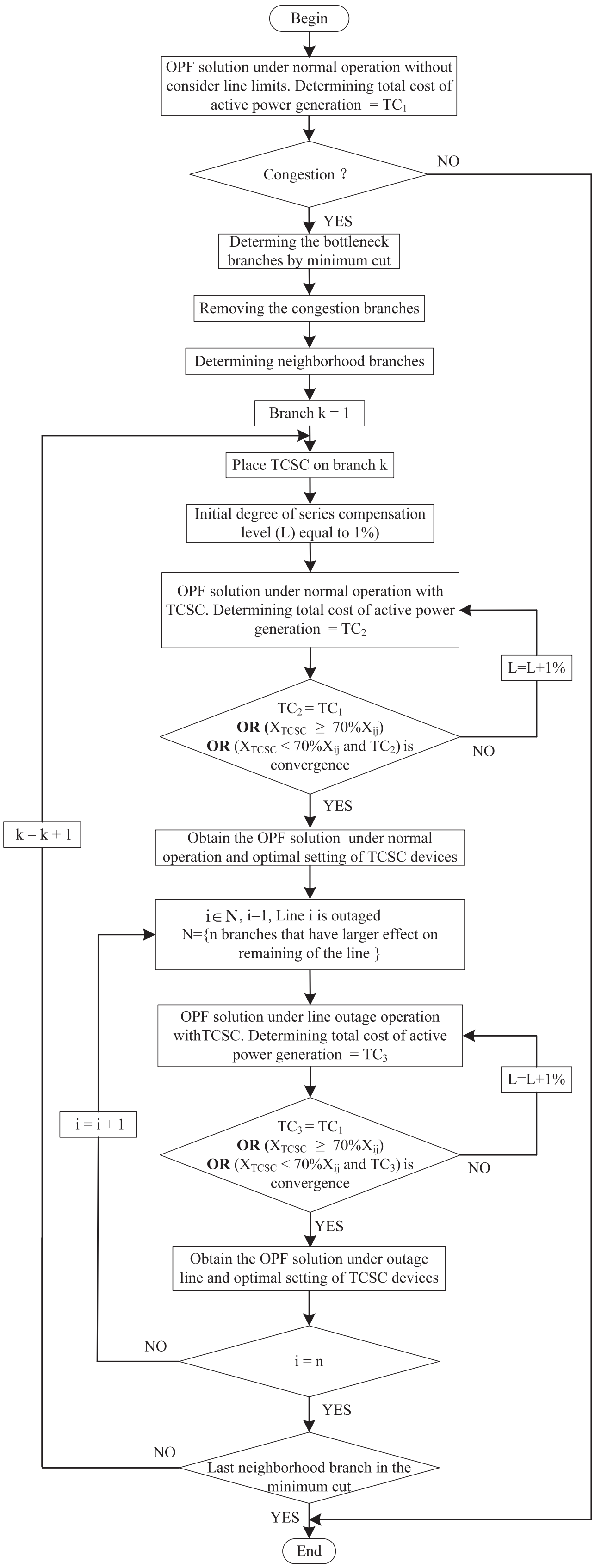

Fig. 5. Flow chart for secured optimal power flow under normal and network contingencies.

overload and provide cheaper power to be transferred from generators to consumers.

Table 1
Optimal generation profile for six bus system.

Gen. No.	Case-1	Case-2
1	50	77.22
2	89.63	69.27
3	77.07	70.42
Total cost of active power generation	**3126.36** ($/h)	**3143.97** ($/h)

Table 2
Optimal power flow profile (in p.u) for six bus system.

Line *i–j*	MVA Limit	Case-1	Case-3 (*L* = 25%) TCSC in line 1–4
1–2	0.4	0.052	0.026
1–4	0.6	0.355	0.414
1–5	0.4	0.256	0.240
2–3	0.4	0.050	0.050
2–4	**0.6**	**0.642**	**0.594**
2–5	0.3	0.242	0.240
2–6	0.9	0.278	0.277
3–5	0.7	0.333	0.332
3–6	0.8	0.775	0.775
4–5	0.2	0.052	0.070
5–6	0.4	0.040	0.039

Table 3
The minimum cut of six bus system.

Line No.	The minimum cut	Lines is considered for placing TCSC
2	1–4	Neighborhood line
5	2–4	Overloaded line
7	2–6	Neighborhood line

Table 4
Optimal generation profile for six bus system.

Gen. No.	Case-3	
	OPF with TCSC in line 1–4 (*L* = 25%)	OPF with TCSC in line 2–6 (*L* = 26%)
1	50	70.78
2	89.62	74.74
3	77.08	71.52
Total cost of active power generation	**3126.37** ($/h)	**3140.25** ($/h)

From Table 3 it can be observed that, the line 1–4 and 2–6 are lines in the minimum cut and are also neighborhood lines of the overloaded line 2–4. Therefore, TCSC can be installed on one of the lines. According to the Table 4 it can see that the line 1–4 is the best location for placement TCSC since it gives minimum total cost of active power generation. The degree of series compensation for improving secured optimal power flow solution was taken as 25%. System power flow result after placing TCSC in line 1–4 is shown in Table 2(column 4). 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 99.03% from the initial 107.11% in the case 1. Line 1–4 is now loaded to 69.06% which is much higher than in the case-1. In the case-1 the loadings of line 1–4 is 59.18%. The TCSC reduced the total reactance of the line 1–4 from 0.2 p.u to 0.15 p.u hence power flow on the line increases. From Table 4(column 2), the total cost of active power generation in case-3 is reduced to 3126.37 $/h over case-2 which override congestion when compared with case-1. Table 5 is constructed for verification purpose, by placing TCSC on each line one at a time and running OPF. As shown in Table 5, the line 1–4 is the best locations for TCSC installation. Comparison between Tables 5 and 3 shows that the

Table 5
Total cost of active power generation ($/h) computed for different locations of the TCSC.

Location TCSC	Total cost of active power generation ($/h)
Line 1–4	3126.37
Line 2–6	3140.25
Line 2–5	3141.71
Line 2–1	3143.44
Line 1–5	3142.82
Line 3–6	3143.14
Line 3–5	3143.09

branches in the minimum cut is proper location for placement of TCSC to minimum total cost active power generation. It can be observed from Table 4 that, the proposed method also captures the best location for the placement of TCSC as compared with the result in [19]. However, the number of branches which need to be investigated to determine the location of TCSC has reduced from 11 branches to 2 branches in the minimum cut as shown in Table 3 which is less than as compared with [19].

5.1.2. OPF under network contingencies

In a power system, if a line is corrupted, its power flow will be shared among other lines of the system. This will lead to possible overloading of some of the lines. Among 11 lines in six-bus System, we selected three more important lines that have larger effect on remaining of the line. Then by opening each of the lines of the system, we consider the effect of opened line on remaining of the system. If there is congestion in the network, then we try to set the installed TCSC in such a way that the OPF solution obtained without any overloads on the lines under network contingencies is termed as secured OPF.

From Table 6, it can be seen that line 2–4 is getting overloaded in most of the case. The secured OPF solution with TCSC placed in lines 1–4 and 2–6 were listed in Tables 7 and 8. According to the Tables 7 and 8, it can see that the total cost of active power generation is less with TCSC placed in line 1–4 as compared over the TCSC placed in line 2–6. Therefore, line 1–4 is the proper location for placement TCSC to obtained secured optimal power flow under normal and contingencies operating condition. From the results given in Table 9, it is noticed that the overloads on the transmission lines 2–4, 2–5 and 3–6 are completely eliminated with TCSC installed in line 1–4.

Table 6
OPF profile (in p.u) for six bus system under 1–5, 2–3 and 4–5 line outage.

Line *i*–*j*	MVA Limit	Outage of line		
		1–5	2–3	4–5
1–2	0.4	0.174	0.053	0.053
1–4	0.6	0.427	0.355	0.358
1–5	0.4	–	0.254	0.268
2–3	0.4	0.123	–	0.050
2–4	0.6	**0.644**	**0.641**	**0.652**
2–5	0.3	**0.336**	0.240	0.254
2–6	0.9	0.320	0.273	0.284
3–5	0.7	0.428	0.335	0.345
3–6	0.8	**0.818**	0.779	0.781
4–5	0.2	0.086	0.051	–
5–6	0.4	0.151	0.041	0.049

Table 7
OPF solution with TCSC in line 1–4 under 1–5, 2–3, 4–5 line outage.

Line outage	1–5 $L = 65\%$	2–3 $L = 25\%$	4–5 $L = 50\%$
Total cost of active power generation ($/h)	3144.67	3126.41	3127.52

Table 8
OPF solution with TCSC in line 2–6 under 1–5, 2–3, 4–5 line outage.

Line outage	1–5 $L = 70\%$	2–3 $L = 70\%$	4–5 $L = 45\%$
Total cost of active power generation ($/h)	3188.66	3137.38	3159.49

Table 9
OPF profile for six bus system for line outage cases with TCSC in line1–4.

Line *i*–*j*	MVA limit	Outage of line		
		1–5	2–3	4–5
1–2	0.4	0.025	0.027	0.043
1–4	0.6	0.599	0.414	0.482
1–5	0.4	–	0.239	0.248
2–3	0.4	0.114	–	0.117
2–4	0.6	**0.483**	**0.593**	**0.512**
2–5	0.3	**0.284**	0.238	0.264
2–6	0.9	0.244	0.271	0.291
3–5	0.7	0.424	0.335	0.350
3–6	0.8	**0.800**	0.780	0.781
4–5	0.2	0.126	0.067	–
5–6	0.4	0.096	0.041	0.053

Table 10
Optimal generation profile for IEEE-14 bus system.

Gen. No.	Case-1	Case-2	Case-3 OPF with TCSC in line 1–5 ($L = 58.28\%$)
1	100	77.54	100
2	50	50	50
3	31.29	44.46	31.33
6	45	45	45
8	36.71	45	36.81
Total cost of active power generation	**6097.82** ($/h)	**6576.09** ($/h)	**6102.97** ($/h)

5.2. IEEE 14-bus test system

There are 20 line sections in IEEE 14-bus system. The total system load is 259 MW, the network and load data for IEEE 14-bus shown in [25,26]. The cost coefficient values are given in Appendix A.

5.2.1. OPF under normal operation

From these OPF results in Table 10, it was observed that, the total cost of active power generation in case-1 was reduced by 7.27% over case-2. However, with this generation schedule, it can see that, line 1–2 was overloaded as shown in Table 11(column 3) and the OPF solution obtained at this point was optimal but not secured. The overload on the transmission line 1–2 was however eliminated or alleviated and secured OPF solution can obtain by placing TCSC at proper location.

From Table 12 it can be observed that, the line 1–5 is line in the minimum cut and is also neighborhood line of the overloaded line 1–2. Therefore, the suitable location to install TCSC is in line 1–5. The degree of series compensation for improving secured optimal power flow solution was taken as 58.28%. System power flow result after placing TCSC in line 1–5 is shown in Table 11(column 4). It can be observed from Table 11(column 4) that congestion has been relieved. The loading of the lines 1–2 has now reduced

Table 11
Optimal power flow profile (in p.u) for IEEE-14 bus system.

Line *i*–*j*	MVA Limit	Case-1	Case 3 (TCSC in line 1–5) (*L* = 58.28%)
1–2	0.5	**0.6650**	**0.4942**
1–5	0.6	0.3350	0.5058
2–3	0.5	0.4478	0.3992
2–4	0.5	0.2934	0.2343
2–5	0.4	0.1992	0.1195
3–4	0.7	0.1924	0.2204
4–5	0.8	0.3991	0.4803
4–7	0.4	0.0367	0.0403
||APF||	–	No OL[a]	No OL[a]

[a] No overloaded line.

Table 12
The minimum cut of IEEE-14 bus system.

Line No.	The minimum cut
1	1–2
2	1–5

to 98.84% from the initial 133% in the case without TCSC (case-1). Line 1–5 is now loaded to 84.3% which is much higher than in the case-1. The TCSC reduced the total reactance of the line 1–5 from 0.22304 p.u to 0.09304 p.u hence power flow on the line increases. According to the Table 10(column 4), the total cost of active power generation in case-3 is reduced by 7.19% over case-2 which override congestion when compared with case-1.

5.2.2. OPF under network contingencies

(1) Outage of line 2–3.

System power flow by opening line 2–3 is shown in Table 13. From Table 13(column 3), it is found that by opening line 2–3, line 1–2 has been congested. The secured OPF solution was achieved by control parameter of TCSC in line 1–5 with an optimal setting of 26.9%. The total branch reactance with TCSC in line 1–5 was reduced from 0.22304 p.u to 0.16304 p.u, thereby pumping more power through this line. The increase in power flows though the line 1–5 with TCSC was from 0.4294 p.u to 0.5067 p.u and consequently congestion has been relieved as in Table 14 (column 3).

Table 13
OPF profile (in p.u) for IEEE-14 bus system under 2–3, 2–4, 2–5 line outage.

Line *i*–*j*	MVA Limit	Outage of line		
		2–3	2–4	2–5
1–2	0.5	**0.5706**	**0.5841**	**0.5928**
1–5	0.6	0.4294	0.4159	0.4072
2–3	0.5	–	**0.5335**	0.4902
2–4	0.5	0.4978	–	0.3795
2–5	0.4	0.3500	0.3277	–
3–4	0.7	0.6262	0.1097	0.1514
4–5	0.8	0.6221	0.5897	0.2773
4–7	0.4	0.0483	0.0486	0.0349
||APF||	–	No OL[a]	No OL[a]	No OL[a]

Table 14
OPF profile for IEEE-14 bus system for line outage cases with TCSC in line1–5.

Line *i*–*j*	MVA Limit	Outage of line		
		2–3	2–4	2–5
1–2	0.5	**0.4933**	**0.4555**	**0.4927**
1–5	0.6	0.5067	0.5445	0.5073
2–3	0.5	–	**0.4955**	0.4583
2–4	0.5	0.4640	–	0.3132
2–5	0.4	0.3081	0.2394	–
3–4	0.7	0.6264	0.1464	0.1825
4–5	0.8	0.6537	0.6252	0.3681
4–7	0.4	0.0491	0.0499	0.0381
||APF||	–	No OL[a]	No OL[a]	No OL[a]

[a] No overloaded line.

Table 15
OPF solution with TCSC in line 1–5 under 2–3, 2–4, 2–5 line outage.

Line outage	2–3 *L* = 26.90%	2–4 *L* = 44.83%	2–5 *L* = 40.35%
Total cost of active power generation ($/h)	6224.31	6119.46	6106.23

(2) Outage of line 2–4.

From Table 13(column 4), it can be observed that by opening line 2–4, line 1–2 and 2–3 has been congested. The secured OPF solution was achieved by control parameter of TCSC in line 1–5 with an optimal setting of 44.83%. The total branch reactance with TCSC in line 1–5 was reduced from 0.22304 p.u to 0.12304 p.u, therefore increasing the power flow transfer capability in the line 1–5 from 0.4159 p.u to 0.5445 p.u. and consequently congestion has been relieved as in Table 14 (column 4).

(3) Outage of line 2–5.

System power flow by opening line 2–5 is shown in Table 13. From Table 13(column 5), it is found that by opening line 2–5, line 1–2 has been congested. The secured OPF solution was achieved by control parameter of TCSC in line 1–5 with an optimal setting of 40.35%. The total branch reactance with TCSC in line 1–5 was reduced from 0.22304 p.u to 0.13304 p.u, thereby pumping more power through this line. The increase in power flows though the line 1–5 with TCSC was from 0.4072 p.u to 0.5073 p.u and consequently congestion has been relieved as in Table 14 (column 5).

From Table 15 it was observed that the total real power generation cost increases under line outages. However, the congestion was eliminated in some cases via optimal utilization of TCSC by proposed method therefore enhancing the system static security and OPF solution under line outages.

5.3. IEEE 30-bus test system

There are 41 line sections in IEEE 30-bus system. The total system load is 189.2 MW, the network and load data for IEEE 30-bus shown in [25,26]. The cost coefficient values are given in Appendix A.

It was observed from Table 16 that the total cost of active power generation in case-1 was reduced by 5.32% over case-2. However transmission congestion occurred in line 6–8 and 21–22 as shown in Table 17(column 3). The bold values represent the overloaded line 6–8 and 21–22 and the OPF solution obtained at this point is optimal but not secured. Placing TCSC at suitable location by using the minimum cut can eliminate these overloads on line 6–8 and 21–22.

From Table 18 it can be observed that, the minimum cut passes through tie line (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 neighborhood lines of the overloaded lines 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 10–22 was shown in Table 17(column 4). The degree of series compensation for improving secured optimal power flow solution was taken as

Table 16
Optimal generation profile for IEEE-30 bus system.

Gen. No.	Case-1	Case-2	Case-3 TCSC in line 8–28 (L = 60%) TCSC in line 10–22 (L = 46.66%)
1	46.17	21.61	46.26
2	80.00	80.00	80.00
13	0.00	0.00	0.00
22	50.00	36.78	50.00
23	0.00	13.11	0.00
27	16.28	41.23	16.22
Total cost of active power generation	**1700.07** ($/h)	**1795.75** ($/h)	**1700.42** ($/h)

Table 17
Optimal power flow profile (in p.u) for IEEE-30 bus system.

Line i–j	MVA Limit	Case-1	Case-3/ TCSC in line 8–28 (L = 60%), and line 10–22 (L = 46.66%)
1–2	1.3	0.1970	0.1982
1–3	1.3	0.2675	0.2678
2–4	0.65	0.2806	0.2808
3–4	1.3	0.2401	0.2404
2–5	1.3	0.1885	0.1885
2–6	0.65	0.3131	0.3131
4–6	0.9	0.2226	0.2211
5–7	0.7	0.1902	0.1902
6–7	1.3	0.0654	0.0657
6–8	0.32	**0.3569**	**0.3162**
6–9	0.65	0.0967	0.0974
6–10	0.32	0.0556	0.0560
9–11	0.65	0.0000	0.0000
9–10	0.65	0.0973	0.0980
4–12	0.65	0.2547	0.2554
12–13	0.65	0.3050	0.3019
12–14	0.32	0.0585	0.0588
12–15	0.32	0.0965	0.0976
12–16	0.32	0.0595	0.0586
14–15	0.16	0.0116	0.0111
16–17	0.16	0.0609	0.0612
15–18	0.16	0.0457	0.0446
18–19	0.16	0.0331	0.0330
19–20	0.32	0.1066	0.1080
10–20	0.32	0.1307	0.1321
10–17	0.32	0.1380	0.1395
10–21	0.32	0.1394	0.1126
10–22	0.32	0.1117	0.1481
21–22	0.32	**0.3491**	**0.3195**
||APF||	–	No OL[a]	No OL[a]

Table 18
The minimum cut of IEEE-30 bus system.

Line No.	The minimum cut	Lines is considered for placing TCSC
38	2 7– 30	Not neighborhood line
37	27–29	Not neighborhood line
10	6–8	Overloaded line
40	8–28	**Neighborhood line**
16	13–12	Not neighborhood line
35	25–27	Not neighborhood line
28	10–22	**Neighborhood line**
29	21–22	Overloaded line

60% and 46.66% respectively. It can be observed from Table 17 (column 4) that congestion has been relieved. The loading of the lines 6–8 has now reduced to 98.81% from the initial 111.53% and lines 21–22 has now reduced to 99.84% from the initial 109.09% in the case-1. Line 8–28 and 10–22 is now loaded to 30.68% and 46.28%

Table 19
OPF profile (in p.u) for IEEE-30 bus system under line outage cases.

Line i–j	MVA Limit	Outage of line				
		1–2	2–6	2–4	21–10	4–6
1–2	1.3	–	0.1043	0.0933	0.1988	0.2422
1–3	1.3	0.4361	0.3444	0.3639	0.2690	0.2068
2–4	0.65	0.1917	0.4168	–	0.2828	0.1821
3–4	1.3	0.4047	0.3143	0.3331	0.2415	0.1812
2–5	1.3	0.1576	0.2664	0.2420	0.1904	0.2346
2–6	0.65	0.2441	–	0.4317	0.3168	0.4144
4–6	0.9	0.2819	0.4093	0.0926	0.2304	–
5–7	0.7	0.1613	0.2648	0.2413	0.1928	0.2350
6–7	1.3	0.0868	0.0599	0.0520	0.0594	0.0375
6–8	0.32	**0.3536**	**0.3517**	**0.3542**	**0.3563**	**0.3509**
6–9	0.65	0.0926	0.1016	0.1052	0.0871	0.0975
6–10	0.32	0.0533	0.0585	0.0605	0.0499	0.0562
9–11	0.65	0.0000	0	0.000	0.0000	0.0000
9–10	0.65	0.0932	0.1024	0.1059	0.0874	0.0983
4–12	0.65	0.2578	0.2715	0.2512	0.2526	0.2892
12–13	0.65	0.3101	0.3287	0.3318	0.3135	0.2493
12–14	0.32	0.0586	0.0592	0.0575	0.0583	0.0619
12–15	0.32	0.0966	0.0991	0.0925	0.0955	0.1107
12–16	0.32	0.0593	0.0597	0.0630	0.0700	0.0553
14–15	0.16	0.0117	0.0108	0.0131	0.0134	0.0065
16–17	0.16	0.0596	0.0575	0.0664	0.0641	0.0425
15–18	0.16	0.0463	0.0480	0.0461	0.0551	0.0506
18–19	0.16	0.0326	0.0327	0.0354	0.0382	0.0286
19–20	0.32	0.1052	0.1032	0.1089	0.0999	0.0944
10–20	0.32	0.1293	0.1271	0.1330	0.1233	0.1185
10–17	0.32	0.1362	0.1324	0.1428	0.1297	0.1162
10–21	0.32	0.1431	0.1536	0.1453	–	0.1630
10–22	0.32	0.1139	0.1201	0.1152	0.2043	0.1256
21–22	0.32	**0.3528**	**0.3628**	**0.3548**	**0.2085**	**0.3714**
||APF||	–	NoOL[a]	No OL[a]	No OL[a]	No OL[a]	No OL[a]

[a] No overloaded line.

Table 20
OPF profile (in p.u) for IEEE-30 bus system under line outage cases with TCSC in line 8–28 and line 10–22.

Line i–j	MVA limit	Outage of line				
		1–2	2–6	2–4	21–10	4–6
1–2	1.3	–	0.1077	0.0957	0.1989	0.2453
1–3	1.3	0.4371	0.3448	0.3642	0.2690	0.2074
2–4	0.65	0.1922	0.4173	–	0.2828	0.1827
3–4	1.3	0.4058	0.3148	0.3335	0.2415	0.1819
2–5	1.3	0.1577	0.2665	0.2419	0.1904	0.2344
2–6	0.65	0.2444	–	0.4318	0.3166	0.4141
4–6	0.9	0.2807	0.4082	0.0902	0.2295	–
5–7	0.7	0.1615	0.2648	0.2412	0.1927	0.2348
6–7	1.3	0.0865	0.0609	0.0530	0.0595	0.0386
6–8	0.32	**0.3167**	**0.3182**	**0.3168**	**0.3198**	**0.3169**
6–9	0.65	0.0922	0.1027	0.1056	0.0875	0.0967
6–10	0.32	0.0530	0.0592	0.0608	0.0502	0.0557
9–11	0.65	0.0000	0.0000	0.0000	0.0000	0.0000
9–10	0.65	0.0928	0.1035	0.1064	0.0878	0.0976
4–12	0.65	0.2571	0.2713	0.2524	0.2528	0.2902
12–13	0.65	0.3016	0.3195	0.3306	0.3127	0.2433
12–14	0.32	0.0587	0.0593	0.0579	0.0584	0.0623
12–15	0.32	0.0973	0.1000	0.0939	0.0958	0.1129
12–16	0.32	0.0577	0.0575	0.0629	0.0698	0.0531
14–15	0.16	0.0110	0.0099	0.0125	0.0133	0.0055
16–17	0.16	0.0596	0.0576	0.0672	0.0640	0.0427
15–18	0.16	0.0447	0.0457	0.0452	0.0550	0.0483
18–19	0.16	0.0323	0.0323	0.0358	0.0380	0.0280
19–20	0.32	0.1069	0.1056	0.1106	0.0999	0.0972
10–20	0.32	0.1311	0.1297	0.1347	0.1234	0.1213
10–17	0.32	0.1381	0.1352	0.1445	0.1296	0.1193
10–21	0.32	0.1114	0.1165	0.1139	–	0.1215
10–22	0.32	0.1576	0.1837	0.1596	0.2035	0.1995
21–22	0.32	**0.3176**	**0.3152**	**0.3189**	**0.2085**	**0.3146**
15–23	0.16	0.0294	0.0278	0.0317	0.0427	0.0241
||APF||	–	NoOL[a]	No OL[a]	No OL[a]	No OL[a]	No OL[a]

[a] No overloaded line.

Table 21
OPF solution with TCSC in line 8–28 and line 10–22 under line outage cases.

Outage of line	1–2	2–4	2–6	4–6	21–10
TCSC in line 8–28	*L* = 55%	*L* = 55%	*L* = 50%	*L* = 50%	*L* = 55%
TCSC in line 10–22	*L* = 53.3%	*L* = 53.3%	*L* = 66.6%	*L* = 66.6%	*L* = 0%
Total cost of active power generation	1702.69 ($/h)	1707.17 ($/h)	1709.50 ($/h)	1703.41 ($/h)	1702.4 ($/h)

Table 22
OPF solution for IEEE 118-bus system.

#	Normal operating condition		For 69–75 line outage	
	Without TCSC	With TCSC in line 69–70 *L* = 33.07%	Without TCSC	With TCSC in line 69–70 *L* = 42.51%
Total cost of active power generation	**129660.69** ($/h)	**129660.85** ($/h)	**129873.65** ($/h)	**129874.01** ($/h)
Overloaded lines	69–75, 69–77	No overloads	69–77, 76–77, 76–118	No overloads

respectively which is much higher than in the case-1. The TCSC reduced the total reactance of the line 8–28 and 10–22 from 0.2 p.u to 0.08 p.u and from 0.15 p.u to 0.08 p.u respectively hence power flow on the lines increases. According to Table 16, the total cost of active power generation in case-3 is reduced by 5.30% over case-2 which not occur congestion when compared with case-1.

From Table 19, it can be seen that line 6–8 and 21–22 were getting overloaded in most of the line outage cases except line 21–10 outage. When the line 21–10 was outages, the line 6–8 only gets overloaded. The line overloading was presented in bold face. However these overloads were eliminated or alleviated by placing TCSC in the line 8–28 and 10–22 respectively. From Table 20, it was observed that the overloads on the transmission lines were eliminated by placing TCSC in line 8–28 and10–22 for most of the line outage cases.

Furthermore, the secured OPF solution with TCSC placed in line 8–28 and 10–22 for 1–2, 2–6, 2–4, 20–10 and 4–6 line outages were listed in Table 21. The secured OPF solution was obtained by placing TCSC in line 8–28 and 10–22 with an optimal setting of 55% and 53.3% under 1–2 line outage, 55% and 53.3% for 2–4 line outage, 50% and 66.6% under 2–6 line outage, 50% and 66.6% for 4–6 line outage and 55% and 0% for 21–10 line outage.

5.4. IEEE 118-bus test system

The network and load data for IEEE 118-bus are given in [25,26] and Appendix A.

From Table 22 it can be observed that, the OPF solution under normal operating conditions without consider line limits is obtained at the cost of overloading the line 69–75 and line 69–77. The overload on the transmission lines were however eliminated and secured OPF solution can obtain by placing TCSC at proper location. As per the procedure mentioned in the previous sections the line 69–70 is line in the minimum cut and is also neighborhood line of the overloaded lines 69–75, 69–77. Therefore, this line is selected to install TCSC. The degree of series compensation for improving secured optimal power flow solution was taken as 33.07%. According to the Table 22 it can see that, the OPF solution with TCSC is obtained without any overloads.

Furthermore, the OPF solution under 69–75 line outage is obtained at the cost overloading the lines 69–77, 76–77 and 76–118. However, all the overloads were also eliminated by placing TCSC in the line 69–70 with an optimal setting of 42.51% as shown in Table 22.

Overall results show that the proposed method is capable of finding the best location for TCSC installation under normal and network contingencies. Placing TCSC in the bottleneck location gives better results in terms of OPF solution and also capable of eliminating the overloads on the transmission lines for several contingencies considered in the study, therefore enhancing the system static security.

6. Conclusion

Enhancement of secured optimal power flow under normal and contingencies operating condition using FACTS devices is an important issue in deregulated power systems. TCSC by controlling the power flows in the network can help to reduce the flows in heavily loaded lines, remove overload, enhanced system performance. Suitable location of TCSC can be very effective to system performance. Therefore, it is important to obtain optimal location for placement of these devices.

This paper applied the minimum cut methodology for proper location of TCSC. Using this method, the search scope is limited hence the number of branches which need to be investigated to determine the location of FACTS has been significantly decreased. Only some lines in the minimum cut need to be examined in detail to assess the best location. The simulation results that were presented in this paper demonstrate the effectiveness of the proposed method.

Acknowledgements

The authors would like to thank the helpful comments and suggestions from the editors and the anonymous reviewers, which have considerably enhanced the quality of paper. The support for this research under Chinese National Science Foundation Grant (No. 51277059) is gratefully acknowledged.

Appendix A.

See Tables A1 and A2.

Table A1
Cost coefficients.

Gen. No.	*a* ($/MW^2 h)	*b* ($/MW h)	*c* ($/h)
IEEE-14 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
IEEE-30 bus system			
1	0.02	10	0
2	0.0175	6	0
22	0.0625	5	0
27	0.00834	12	0
23	0.025	15	0
13	0.025	15	0

Table A2
Transmission line data for IEEE 118-bus system.

Line No.	From Bus	To Bus	Circuit ID	R (p.u.)	X (p.u.)	B (p.u.)	Flow limit (MVA)
1	1	2	1	0.0303	0.0999	0.0254	70
2	1	3	1	0.0129	0.0424	0.01082	70
3	4	5	1	0.00176	0.00798	0.0021	130
4	3	5	1	0.0241	0.108	0.0284	70
5	5	6	1	0.0119	0.054	0.01426	95
6	6	7	1	0.00459	0.0208	0.0055	30
7	8	9	1	0.00244	0.0305	1.162	500
8	8	5	1	0	0.0267	0	500
9	9	10	1	0.00258	0.0322	1.23	500
10	4	11	1	0.0209	0.0688	0.01748	70
11	5	11	1	0.0203	0.0682	0.01738	70
12	11	12	1	0.00595	0.0196	0.00502	45
13	2	12	1	0.0187	0.0616	0.01572	30
14	3	12	1	0.0484	0.16	0.0406	45
15	7	12	1	0.00862	0.034	0.00874	45
16	11	13	1	0.02225	0.0731	0.01876	70
17	12	14	1	0.0215	0.0707	0.01816	45
18	13	15	1	0.0744	0.2444	0.06268	45
19	14	15	1	0.0595	0.195	0.0502	45
20	12	16	1	0.0212	0.0834	0.0214	45
21	15	17	1	0.0132	0.0437	0.0444	130
22	16	17	1	0.0454	0.1801	0.0466	30
23	17	18	1	0.0123	0.0505	0.01298	90
24	18	19	1	0.01119	0.0493	0.01142	30
25	19	20	1	0.0252	0.117	0.0298	30
26	15	19	1	0.012	0.0394	0.0101	30
27	20	21	1	0.0183	0.0849	0.0216	30
28	21	22	1	0.0209	0.097	0.0246	70
29	22	23	1	0.0342	0.159	0.0404	70
30	23	24	1	0.0135	0.0492	0.0498	70
31	23	25	1	0.0156	0.08	0.0864	350
32	26	25	1	0	0.0382	0	130
33	25	27	1	0.0318	0.163	0.1764	350
34	27	28	1	0.01913	0.0855	0.0216	70
35	28	29	1	0.0237	0.0943	0.0238	45
36	30	17	1	0	0.0388	0	350
37	8	30	1	0.00431	0.0504	0.514	130
38	26	30	1	0.00799	0.086	0.908	350
39	17	31	1	0.0474	0.1563	0.0399	30
40	29	31	1	0.0108	0.0331	0.0083	30
41	23	32	1	0.0317	0.1153	0.1173	95
42	31	32	1	0.0298	0.0985	0.0251	45
43	27	32	1	0.0229	0.0755	0.01926	30
44	15	33	1	0.038	0.1244	0.03194	30
45	19	34	1	0.0752	0.247	0.0632	30
46	35	36	1	0.00224	0.0102	0.00268	70
47	35	37	1	0.011	0.0497	0.01318	45
48	33	37	1	0.0415	0.142	0.0366	45
49	34	36	1	0.00871	0.0268	0.00568	130
50	34	37	1	0.00256	0.0094	0.00984	350
51	38	37	1	0	0.0375	0	350
52	37	39	1	0.0321	0.106	0.027	70
53	37	40	1	0.0593	0.168	0.042	70
54	30	38	1	0.00464	0.054	0.422	95
55	39	40	1	0.0184	0.0605	0.01552	30
56	40	41	1	0.0145	0.0487	0.01222	45
57	40	42	1	0.0555	0.183	0.0466	30
58	41	42	1	0.041	0.135	0.0344	45
59	43	44	1	0.0608	0.2454	0.06068	30
60	34	43	1	0.0413	0.1681	0.04226	30
61	44	45	1	0.0224	0.0901	0.0224	45
62	45	46	1	0.04	0.1356	0.0332	70
63	46	47	1	0.038	0.127	0.0316	70
64	46	48	1	0.0601	0.189	0.0472	45
65	47	49	1	0.0191	0.0625	0.01604	45
66	42	49	1	0.0715	0.323	0.086	70
67	42	49	2	0.0715	0.323	0.086	70
68	45	49	1	0.0684	0.186	0.0444	70
69	48	49	1	0.0179	0.0505	0.01258	70
70	49	50	1	0.0267	0.0752	0.01874	70
71	49	51	1	0.0486	0.137	0.0342	70
72	51	52	1	0.0203	0.0588	0.01396	30
73	52	53	1	0.0405	0.1635	0.04058	45
74	53	54	1	0.0263	0.122	0.031	70

Table A2 (*continued*)

Line No.	From Bus	To Bus	Circuit ID	*R* (p.u.)	*X* (p.u.)	*B* (p.u.)	Flow limit (MVA)
75	49	54	1	0.073	0.289	0.0738	70
76	49	54	2	0.0869	0.291	0.073	70
77	54	55	1	0.0169	0.0707	0.0202	70
78	54	56	1	0.00275	0.00955	0.00732	30
79	55	56	1	0.00488	0.0151	0.00374	30
80	56	57	1	0.0343	0.0966	0.0242	45
81	50	57	1	0.0474	0.134	0.0332	70
82	56	58	1	0.0343	0.0966	0.0242	30
83	51	58	1	0.0255	0.0719	0.01788	45
84	54	59	1	0.0503	0.2293	0.0598	45
85	56	59	1	0.0825	0.251	0.0569	45
86	56	59	2	0.0803	0.239	0.0536	45
87	55	59	1	0.04739	0.2158	0.05646	45
88	59	60	1	0.0317	0.145	0.0376	70
89	59	61	1	0.0328	0.15	0.0388	70
90	60	61	1	0.00264	0.0135	0.01456	130
91	60	62	1	0.0123	0.0561	0.01468	30
92	61	62	1	0.00824	0.0376	0.0098	45
93	63	59	1	0	0.0386	0	350
94	63	64	1	0.00172	0.02	0.216	350
95	64	61	1	0	0.0268	0	70
96	38	65	1	0.00901	0.0986	1.046	350
97	64	65	1	0.00269	0.0302	0.38	350
98	49	66	1	0.018	0.0919	0.0248	130
99	49	66	2	0.018	0.0919	0.0248	130
100	62	66	1	0.0482	0.218	0.0578	70
101	62	67	1	0.0258	0.117	0.031	70
102	65	66	1	0	0.037	0	95
103	66	67	1	0.0224	0.1015	0.02682	95
104	65	68	1	0.00138	0.016	0.638	95
105	47	69	1	0.0844	0.2778	0.07092	70
106	49	69	1	0.0985	0.324	0.0828	70
107	68	69	1	0	0.037	0	500
108	69	70	1	0.03	0.127	0.122	130
109	24	70	1	0.00221	0.4115	0.10198	30
110	70	71	1	0.00882	0.0355	0.00878	45
111	24	72	1	0.0488	0.196	0.0488	30
112	71	72	1	0.0446	0.18	0.04444	30
113	71	73	1	0.00866	0.0454	0.01178	30
114	70	74	1	0.0401	0.1323	0.03368	45
115	70	75	1	0.0428	0.141	0.036	30
116	69	75	1	0.0405	0.122	0.124	95
117	74	75	1	0.0123	0.0406	0.01034	130
118	76	77	1	0.0444	0.148	0.0368	45
119	69	77	1	0.0309	0.101	0.1038	70
120	75	77	1	0.0601	0.1999	0.04978	45
121	77	78	1	0.00376	0.0124	0.01264	70
122	78	79	1	0.00546	0.0244	0.00648	45
123	77	80	1	0.017	0.0485	0.0472	95
124	77	80	2	0.0294	0.105	0.0228	95
125	79	80	1	0.0156	0.0704	0.0187	95
126	68	81	1	0.00175	0.0202	0.808	95
127	81	80	1	0	0.037	0	95
128	77	82	1	0.0298	0.0853	0.08174	45
129	82	83	1	0.0112	0.03665	0.03796	45
130	83	84	1	0.0625	0.132	0.0258	45
131	83	85	1	0.043	0.148	0.0348	45
132	84	85	1	0.0302	0.0641	0.01234	45
133	85	86	1	0.035	0.123	0.0276	45
134	86	87	1	0.02828	0.2074	0.0445	45
135	85	88	1	0.02	0.102	0.0276	70
136	85	89	1	0.0239	0.173	0.047	95
137	88	89	1	0.0139	0.0712	0.01934	130
138	89	90	1	0.0518	0.188	0.0528	130
139	89	90	2	0.0238	0.0997	0.106	130
140	90	91	1	0.0254	0.0836	0.0214	45
141	89	92	1	0.0099	0.0505	0.0548	350
142	89	92	2	0.0393	0.1581	0.0414	350
143	91	92	1	0.0387	0.1272	0.03268	45
144	92	93	1	0.0258	0.0848	0.0218	70
145	92	94	1	0.0481	0.158	0.0406	70
146	93	94	1	0.0223	0.0732	0.01876	70
147	94	95	1	0.0132	0.0434	0.0111	70
148	80	96	1	0.0356	0.182	0.0494	70
149	82	96	1	0.0162	0.053	0.0544	70

(*continued on next page*)

Table A2 (*continued*)

Line No.	From Bus	To Bus	Circuit ID	*R* (p.u.)	*X* (p.u.)	*B* (p.u.)	Flow limit (MVA)
150	94	96	1	0.0269	0.0869	0.023	70
151	80	97	1	0.0183	0.0934	0.0254	70
152	80	98	1	0.0238	0.108	0.0286	70
153	80	99	1	0.0454	0.206	0.0546	70
154	92	100	1	0.0648	0.295	0.0472	70
155	94	100	1	0.0178	0.058	0.0604	70
156	95	96	1	0.0171	0.0547	0.01474	45
157	96	97	1	0.0173	0.0885	0.024	70
158	98	100	1	0.0397	0.179	0.0476	45
159	99	100	1	0.018	0.0813	0.0216	70
160	100	101	1	0.0277	0.1262	0.0328	30
161	92	102	1	0.0123	0.0559	0.01464	70
162	101	102	1	0.0246	0.112	0.0294	45
163	100	103	1	0.016	0.0525	0.0536	95
164	100	104	1	0.0451	0.204	0.0541	70
165	103	104	1	0.0466	0.1584	0.0407	70
166	103	105	1	0.0535	0.1625	0.0408	70
167	100	106	1	0.0605	0.229	0.062	70
168	104	105	1	0.00994	0.0378	0.00986	70
169	105	106	1	0.014	0.0547	0.01434	45
170	105	107	1	0.053	0.183	0.0472	45
171	105	108	1	0.0261	0.0703	0.01844	45
172	106	107	1	0.053	0.183	0.0472	70
173	108	109	1	0.0105	0.0288	0.0076	30
174	103	110	1	0.03906	0.1813	0.0461	70
175	109	110	1	0.0278	0.0762	0.0202	70
176	110	111	1	0.022	0.0755	0.02	70
177	110	112	1	0.0247	0.064	0.062	70
178	17	113	1	0.00913	0.0301	0.00768	45
179	32	113	1	0.0615	0.203	0.0518	45
180	32	114	1	0.0135	0.0612	0.01628	45
181	27	115	1	0.0164	0.0741	0.01972	350
182	114	115	1	0.0023	0.0104	0.00276	95
183	68	116	1	0.00034	0.00405	0.164	500
184	12	117	1	0.0329	0.14	0.0358	70
185	75	118	1	0.0145	0.0481	0.01198	70
186	76	118	1	0.0164	0.0544	0.01356	30

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