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Application of min cut algorithm for optimal location of FACTS devices considering system loadability and cost of installation

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ABSTRACT

Due to the growth of electricity demands and transactions in power markets, existing power networks need to be improved in order to increase their loadability. Series FACTS devices such as Thyristor controlled series compensators (TCSC) can be installed on transmission lines to enhance the system loadability through changing line reactance. The proper location and the best setting of TCSC is a key for achieving maximum system loadability and optimal installation cost of TCSC devices. This paper has applied the minimum cut methodology on the power system to determine the most suitable locations for the installed TCSC as well as using Kirchhoff's law of current to establish clearly formulation for determining the best setting of TCSC devices. Simulations are performed on IEEE 6-bus, IEEE 30-bus and IEEE 118-bus systems. The results obtained show that the proposed method is capable of finding the location, quantity and size of TCSC in such effective way for enhancing system loadability and minimum installation cost of TCSC devices. Using this method, search space and the number of TCSC devices required will be significantly decreased.

Introduction

Growing demand for electricity and deregulation of electricity markets have led to heavy stress on power networks. Therefore, existing power networks need to be improved in order to increase their loadability. System maximum loadability can be simulated by increasing the system load until the network or equipment constraints, such as thermal and voltage security limits, are reached [1]. This is one of the most challenging tasks and difficult to deal with in the new electricity markets of the Independent System Operator. In order to solve this problem without building more transmission lines, installation of Flexible AC transmission system (FACTS) devices can be a better alternative.

FACTS can provide benefits in increasing system transmission capacity and power flow control flexibility and rapidity [2,3], however, the current challenge is now to obtain the optimal cost of installation of (FACTS) devices. Studies that investigate the deployment of FACTS must address the following questions [4]

- Which type of FACTS devices should be used?
- How many should be used?
- What is their best allocation?
- What should be their parameter settings?
- What is their installation cost?

In which, it is indicated that the effectiveness of the controls for different purposes mainly depends on the location of control device [5]. The proper location of FACTS devices is a key to maximum system loadability (MSL) and optimal cost of installation of FACTS devices. Therefore, Operators are facing the problem of where FACTS 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 [6]. 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. Therefore, in order to enhance system loadability (SL), 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

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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.

Most of those studies for optimal allocation of FACTS devices are commonly focused on the following methods and techniques.

Population based intelligent techniques, such as Genetic Algorithm [7,8], Evolutionary Programming [9,10], Particle Swarm Optimization [11], Differential Evolution [12] and Back Propagation Neural Network [13] were proposed to determine maximum loadability of the transmission system using FACTS devices. The hybrid immune algorithms were utilized to increase system loadability by optimizing the locations for UPFC installation [14]. Investigating the loadability of power systems via optimal static VAR compensator (SVC) placement by messy genetic-algorithm optimization scheme was proposed in [15]. In Ref. [16], an ordinal optimization (OO) STATCOM installation strategy was presented to enhance transmission system loading margin.

Sensitivity based approach was used to locate Thyristor Controlled Series Compensator and Unified Power Flow Controller for enhancing the power system loadability, considering voltage and angle sensitivities with respect to changes in the system load [17]. In [18], the performance indices of real power flows was used to find the optimal FACTS devices installation locations. 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] were used to obtain secured optimal power flow under normal and network contingencies. In [20], by using a mixed integer optimization technique, the demand responses and the SVC and TCSC controllers were optimally coordinated with the conventional generators to manage the network congestion under a restructured market environment. Mixed Integer Linear and Nonlinear Programming based Optimal Power Flow methods were used to determine the maximum loadability using FACTS devices in pool and hybrid electricity markets [21].

This paper has applied the minimum cut methodology on the power system to determine location as well as using Kirchhoff's law of current to establish clearly formulation for determining the best setting of FACTS devices. In this study, (TCSC), which is one of the most effective FACTS devices, is selected due to the cost of installation of TCSC is less than as compared with UPFC and STATCOM [22,23]. Proper use of TCSC devices to control loop power flows is on of effective methods to eliminate overload and unwanted loop flows [24,25]. The objective of this paper is to achieve MSL and optimal cost of installation of TCSC devices via optimal location and size of TCSC, while satisfying the power system constraints. In order to obtain the above goal, the location for TCSC installation needs to satisfy criteria follows

- Branch bottleneck that the minimum cut passes through and lies in loops which contains branch overloaded.
- The branch has ability to increase the largest transmission power after setting a value of TCSC.
- The branch that is able to carry great power flow to limit number of TCSC that need to be installed.

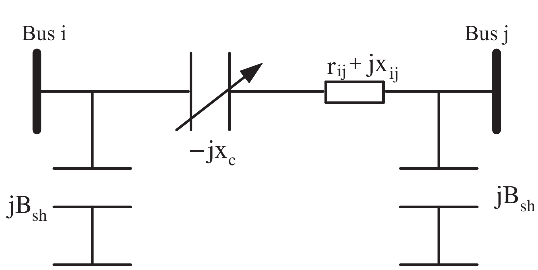

Fig. 1. Model of transmission line with TCSC.

Computer simulations were done for IEEE 6-, 30- and 118-bus systems. It is observed that SL cannot be increased beyond a limit after placing certain number of TCSC devices and the maximum value of SL that can be achieved without violating the constraints is known as maximum system loadability.

Problem formulation

A TCSC can be inserted in series with the transmission line to adjust the line impedance and thereby controls the power flow to increase loadability. Let $x_{ij,c}$ be a regulated reactance of the TCSC installed on transmission line and it is assumed that TCSC only operates as a capacitor. The maximum compensation by TCSC is limited to 70% of the reactance of the un-compensated line where TCSC is located. The model of the network with TCSC is shown in Fig. 1.

Real and reactive power flows of a compensated line can be expressed as [1].

$$P_{ij}^{c} = V_i^2 g'_{ij} - V_i V_j \left(g'_{ij} \cos \delta_{ij} + b'_{ij} \sin \delta_{ij} \right) \tag{1}$$

$$Q_{ij}^{c} = -V_i^2 \left(b'_{ij} + b_{sh} \right) - V_i V_j \left[g'_{ij} \sin \delta_{ij} - b'_{ij} \cos \delta_{ij} \right] \tag{2}$$

where $g'_{ij} = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} + x_{ij,c})^2}$ and $b'_{ij} = \frac{-(x_{ij} - x_{ij,c})}{r_{ij}^2 + (x_{ij} + x_{ij,c})^2}$ are the conductance and susceptance with a TCSC on the line *i*–*j*, δ_{ij} is the phase angle difference between buses *i* and *j*.

The objective function which determines the locations and control settings of TCSC for system loadability enhancement is formulated as follows:

Max λ

Subject to

– Power balance equation

$$\sum_{\forall j} P_{ij,c} + (1 + \lambda) P_{Dio} = P_{Gio} + P_{Gi} \tag{3}$$

$$\sum_{\forall j} Q_{ij,c} + (1 + \lambda) Q_{Dio} = Q_{Gio} + Q_{Gi} \tag{4}$$

– Power generation limit

$$0 \leqslant P_{Gio} + P_{Gi} \leqslant P_{Gi}^{\max} \tag{5}$$

$$0 \leqslant Q_{Gio} + Q_{Gi} \leqslant Q_{Gi}^{\max} \tag{6}$$

– Bus voltage limits

$$V_i^{\min} \leqslant V_i \leqslant V_i^{\max} \tag{7}$$

– Line thermal limit

$$|S_{ij}| = \sqrt{P_{ij,c}^2 + Q_{ij,c}^2} \leqslant S_{ij}^{\max} \tag{8}$$

where P_{Gio}, P_{Dio} and Q_{Gio}, Q_{Dio} are the real and reactive power injections of generator and load at bus under base case condition ($\lambda = 0$). P_{Gi} and Q_{Gi} are the additional real and reactive power generations for providing increased system load.

After solving the problem, the maximum additional loading of the system $\lambda^{*}.\sum P_{\mathrm{Dio}}$ can be obtained.

Optimal placement of TCSC

Min cut algorithm

The best location and setting of TCSC plays key role in controlling of the system power flows to increase SL. The problem can be solved if minimum cut of power system is determined. That is the cut which contains bottleneck branches with sum of capacity through it is 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 and improve SL. Hence, searching space will be reduced from n branch to m branch (m is the branches that minimum cut passes through).

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) [26] 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 as Fig. 2. Maximum amount can flow between node i and j is called capacity of arc C_{ij}

- **Max-Flow**

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

- **Minimum Cut**

A cut is any set of directed links containing at least one link in every path from origin node to destination node. This means if the links in the cut are removed the flow from the origin to destination is completely cut off. The cut value is the sum of the flow capacities in the origin to node direction over all the links. The minimum cut problem is to find the cut across the network that has the minimum cut value over all possible cuts.

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 Fig. 3 is shown in Fig. 4. Flow chart for achieving MSL and optimal installation cost of TCSC devices is presented in Fig. 5

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:
  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).
  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 details for determining the minimum of power system is presented in Refs. [6,26].

Optimal setting of TCSC

In order to determine the best possible setting of TCSC for achieving MSL, the following calculation problems have to be solved.

An illustrative example which shows how to determine size of the TCSC devices to alleviate overloads after increasing load is described.

Consider a 4-bus system shown in Fig. 6, it is assumed that the minimum cut passes through branches 1–3, 1–4 and 2–4. In such case, branch 1–4 is overloaded after increasing load, the branches 1–3 and 2–4 are considered to install TCSC.

- Consider the loop1 (1–4–3–1) in Fig. 6, Kirchhoff's law 2 is written as follow:

$$(\dot{I}_{13}\dot{Z}_{13} - \dot{I}_{34}\dot{Z}_{34-}\dot{I}_{41}\dot{Z}_{41}) = 0 \tag{9}$$

In order to eliminate/alleviate overload on branch 1–4, the TCSC needs to be installed on branch 1–3 to modify impedance branch 1–3 (Z_{13}) and consequently the power flow (ΔI) across this branch according to direct as Fig. 6. Therefore, Kirchhoff's law 2 can be written

$$\begin{aligned}&(\dot{I}_{13} + \Delta\dot{I})(\dot{Z}_{13} - \dot{Z}_{TCSC}) - (\dot{I}_{34} - \Delta\dot{I})Z_{34} - (\dot{I}_{41} - \Delta\dot{I})\dot{Z}_{41} = 0\\ &\quad\Rightarrow (\dot{I}_{13}\dot{Z}_{13} - \dot{I}_{34}\dot{Z}_{34} - \dot{I}_{41}\dot{Z}_{41}) + \Delta\dot{I}(\dot{Z}_{13} + \dot{Z}_{34} + \dot{Z}_{41})\\ &\quad - (\dot{I}_{13} + \Delta\dot{I})Z_{TCSC} = 0\end{aligned} \tag{10}$$

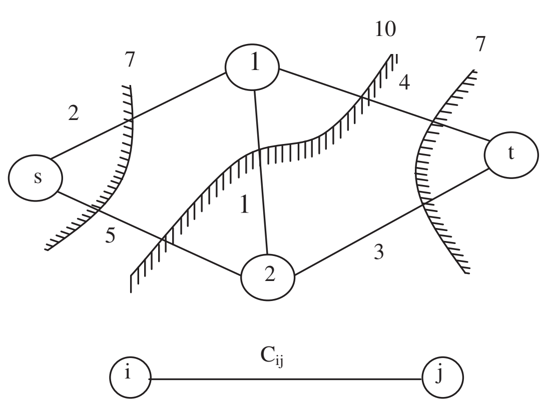

Fig. 2. Modeling of a network with some cuts.

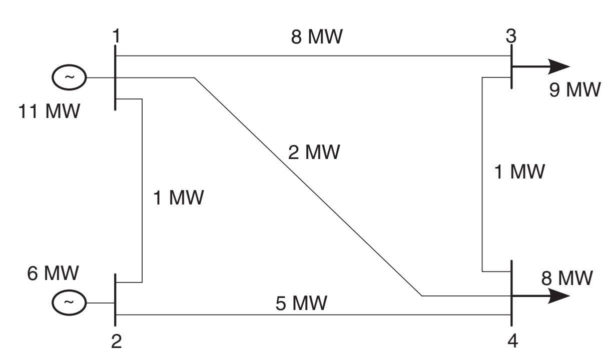

Fig. 3. Example power system with generators of 11 at 1 and 6 at 2 and loads of 9 and 8.

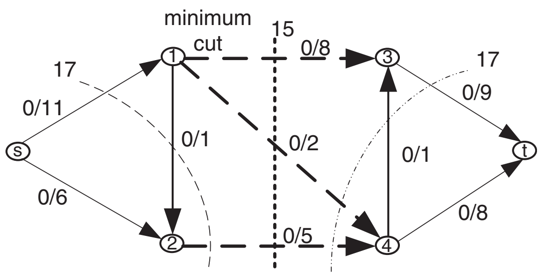

Fig. 4. The modeling of an example power system.

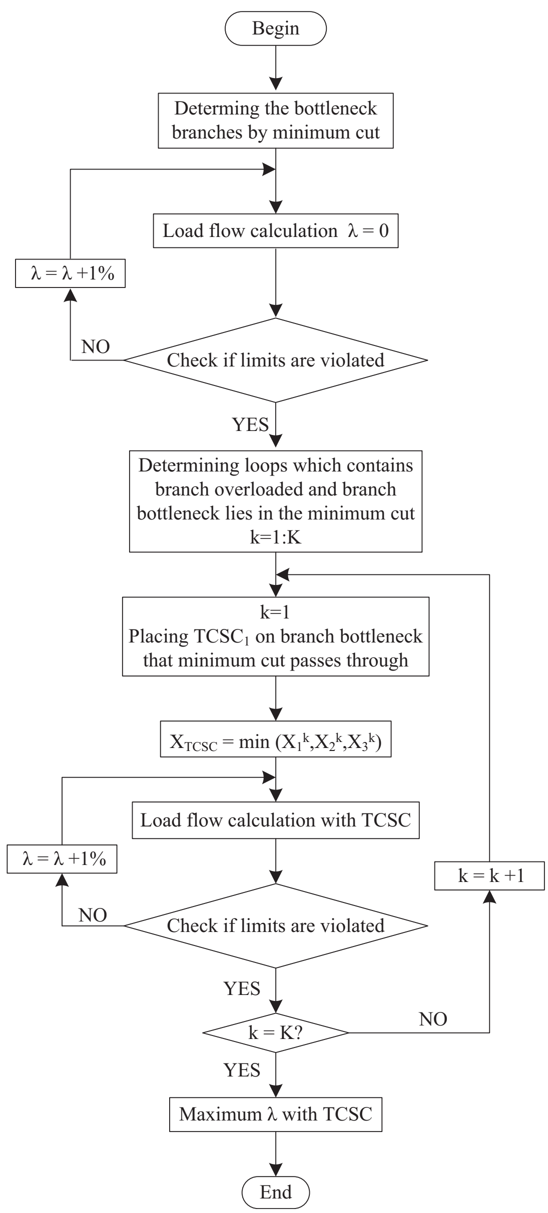

Fig. 5. Flow chart for achieving MSL and optimal installation cost of TCSC devices.

From Eqs. (9) and (10) we have

$$\Rightarrow Z_{\mathrm{TCSC}} = \frac{\Delta \dot{I}(\dot{Z}_{13} + \dot{Z}_{34} + \dot{Z}_{41})}{\dot{I}_{13} + \Delta \dot{I}} = \frac{\Delta \dot{I} \dot{Z}_{\mathrm{loop1}}}{\dot{I}_{13} + \Delta \dot{I}} \tag{11}$$

where the TCSC acts as the capacitive compensation and resistance is more less than compare with reactance of transmission line

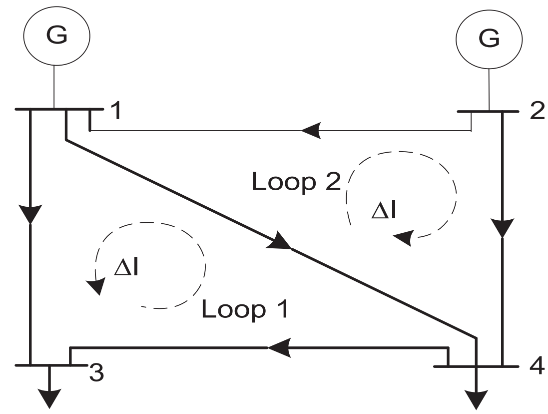

Fig. 6. The 4-bus system.

($R_n \ll X_n$). Therefore, it can be seen as $X_{\mathrm{TCSC}} \approx Z_{\mathrm{TCSC}}$. Eq. (11) can be rewritten

$$X_{\mathrm{TCSC}} = -\left[\left(\frac{\Delta I \dot{Z}_{\mathrm{loop1}}}{I_{13} + \Delta I}\right)\right] = -\left[\left(\frac{\Delta S \dot{Z}_{\mathrm{loop1}}}{S_{13} + \Delta S}\right)\right] \tag{12}$$

Similarly, considering the loop2 (1–4–2–1) as Fig. 6, the TCSC is installed on branch 2–4. We have

$$X_{\mathrm{TCSC}} = -\left[\left(\frac{\Delta I \dot{Z}_{\mathrm{loop2}}}{I_{24} + \Delta I}\right)\right] = -\left[\left(\frac{\Delta S \dot{Z}_{\mathrm{loop2}}}{S_{24} + \Delta S}\right)\right] \tag{13}$$

When power system has many loops which contains branch overloaded and branch in the minimum cut, the general equation for determining size of TCSC is presented as follows

$$\Rightarrow X^k_{\mathrm{TCSC}} = -\left[\left(\frac{\Delta I \dot{Z}_{\mathrm{loop}\,i}}{I_k + \Delta I}\right)\right] = -\left[\left(\frac{\Delta S \dot{Z}_{\mathrm{loop}\,i}}{S_k + \Delta S}\right)\right] \tag{14}$$

where

k: is branch which TCSC is located.
Loop i: loop ith contains branch overloaded and branch k in the minimum cut.
ΔS (ΔI): power flow on branch overloaded needs to be reduced.
$S_k(I_k)$: power flow on branch k before installing TCSC.
$\dot{Z}_{\mathrm{loop}\,i}$: impedance of loop i.

From formulation (14) it can be seen that, size of TCSC is dependent on impedance of the loop, therefore, to can best possible setting of TCSC, the loop with small Z_{loop} is considered to install the first.

In addition, to avoid causes that can lead to overload of branches after installing TCSC as well as overcompensation state, size of TCSC is chosen as follows:

$$X_{\mathrm{TCSC}} = \min X_1, X_2, X_3 \tag{$*$}$$

where

$X_1 = X_{\mathrm{TCSC}}$ is calculated acording to Eq. (14)
X_2: is size of series capacitive compensation which can lead to overload of branches
$X_{\mathrm{TCSC}} \leqslant X_2$
X_3: is size of series capacitive compensation which does not lead to overcompensation state
$0 \leqslant X_{\mathrm{TCSC}} = X_3 \leqslant 70\% X_{ij}$.

This case shows that, instead of load decreasing, properly installed and controlled TCSC devices can effectively eliminate line overloads for achieving MSL.

Cost function

According to [11], optimal installation cost of TCSC devices is determined as follows

$$IC = C \times S \times 1000 \quad (15)$$

where IC is the optimal installation cost of TCSC devices in US$ and C is the cost of installation of TCSC devices in US$/KVAR. According to Siemens database and reported in [22,23], the costs of installation of TCSC devices are given by (16)

$$C_{TCSC} = 0.0015S^2 - 0.7130S + 153.75 \quad (16)$$

where S is the operating range of the FACTS devices in MVAR

$$S = |Q_2| - |Q_1| \quad (17)$$

where Q_2 is the reactive power flow in the line after installing FACTS device in MVAR and Q_1 is the reactive power flow in the line before installing FACTS device in MVAR.

Case study and discussions

The proposed method for the optimal location and size of the TCSC to achieve MSL and optimal installation cost of TCSC devices is implemented on IEEE 6-bus, IEEE 30-bus and IEEE 118-bus. The network and load data for IEEE 6, 30 and 118-bus are given in [11]. Newton Raphson method was used to calculate power flow in these simulations.

IEEE-6 bus system

The 6-bus test system consists of three generator buses at buses 1, 2 and 3. Buses 4, 5 and 6 are load buses. The system has 11 transmission lines with a capacity of 230 kV. The 6-bus test system, which is considered for the purpose of case study, is shown in Fig. 7. The total system load is 210 MW and 210 MVAR.

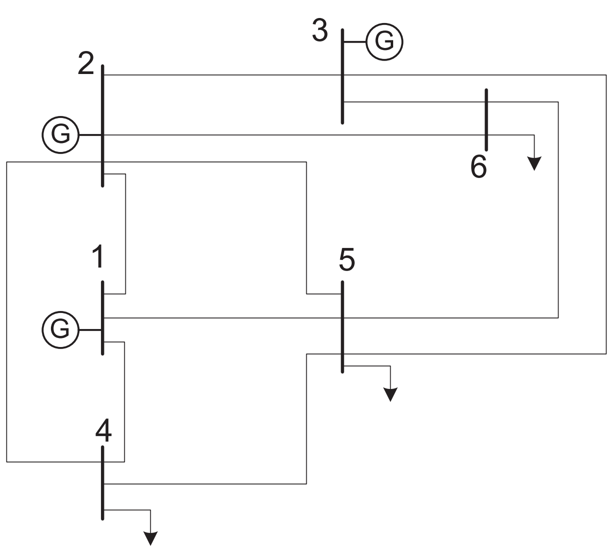

Fig. 7. Six-bus test system.

It can been see from Table 1 that, the minimum cut passes through lines 2–5, 1–4, 2–6, 1–5, 2–4 and 3–6. In which, lines 1–5, 2–4 and 3–6 is congested after MSL is obtained at $\lambda = 0.15$ (MSL = 115%) as shown in Table 2 (Columns 4 and 5). This impeded system loadability. Clearly the network cannot be operated in this way since security of the network is violated. The existing power networks can increase their loadability while still satisfying system security by placing TCSC at proper locations to decrease the loading of lines 1–5, 2–4 and 3–6 and increased loading on the lines where TCSC is located.

From Table 3 it can be observed that, the lines 2–5, 1–4 and 2–6 are lines in loops1(2–5–1–2), 2(1–4–2–1) and 3(2–6–3–2) which contains branch overloaded 1–5, 2–4 and 3–6, respectively. Therefore, to eliminate congestion, TCSC devices can be installed on the lines with an optimal setting size of TCSC as formulation (∗).

System power flow result after placing TCSC devices in line 1–5, 2–4 and 3–6 are showed in Table 2 and Fig. 8. It can be observed from Table 2 (Columns 6 and 7) that congestion has been relieved. The loading of the lines 1–5, 2–4 and 3–6 have now reduced from 103.94% to 100%, 106.12% to 98.68% and 101.47% to 100% respectively. Lines 2–5, 1–4 and 2–6 is now loaded to 98.84%, 100% and

Table 1
The minimum cut for IEEE 6-bus system.

Line no.	The lines that minimum cut passes through
1	2–5
2	1–4
3	2–6
4	1–5
5	2–4
6	3–6

Table 3
The loops which contains branch overloaded and branch in the minimum cut for IEEE 6-bus system.

Line no.	The lines that minimum cut passes through	Loop *i*th
1	2–5	2–5–1–2
2	1–4	1–4–2–1
3	2–6	2–6–3–2

Table 2
The real and reactive power flow in the line *i–j* at $\lambda = 0.15$ (MSL = 115%) before and after installing TCSC devices, optimal setting and optimal cost of installation of TCSC devices (IC) and MSL in IEEE 6 bus system.

Line no.	From *i–j*	Limit (MVA)	P_{ijb} (MW)	Q_{ijb} (MVAR)	P_{ija} (MW)	Q_{ija} (MVAR)	Setting for TCSC (p.u.)	IC ($\times 10^6$ US$)
1	1–2	40	30.53	−6.11	30.21	−5.97		0.356 (MSL = 115%)
2	1–4	60	47.17	33.67	49.26	34.35	−0.0416	
3	1–5	40	34.51	23.19	32.72	22.08		
4	2–3	40	1.02	−2.79	2.78	−3.55		
5	2–4	60	40.66	49	36.24	47.87		
6	2–5	30	14.8	20.12	20.87	21.06	−0.0642	
7	2–6	90	27.93	24.5	28.86	25.21	−0.0097	
8	3–5	70	34.25	22.58	33.08	20.78		
9	3–6	80	53.2	61.32	51.28	59.09		
10	4–5	20	4.07	−2.54	3.35	−2.6		
11	5–6	40	3.23	−6.31	3.23	−5.79		

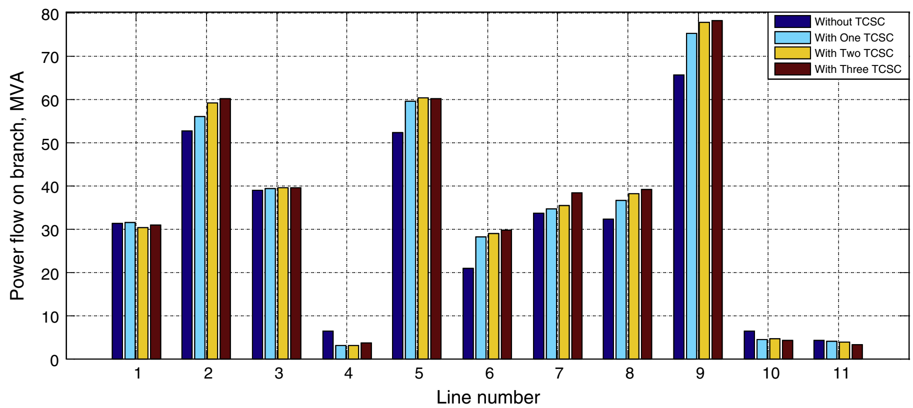

Fig. 8. The power flow on branch after placing TCSC devices in six bus system.

42.58% which is much higher than in initial scheduled. The TCSC reduced the series impedance of the lines 2–5, 1–4 and 2–6 hence power flow on the lines increases. The value of control parameter of TCSC is taken as Table 2 (Column 8). This value satisfies the allowed limits, which do not lead to overload of branches after installing TCSC as well as overcompensation state. From Table 4 (Column 7) it can also be seen that the all buses voltage within voltage security limits. Observation of Table 5 and Fig. 9 shows that, the proposed method also captures the best location for the placement of TCSC to achieve MSL as result in [11]. However, the number of branch which needs to be investigated to determine the location of TCSC has reduced from 11 branches to 3 branches

Table 4
Power flow of base case at $\lambda = 0$, at $\lambda = 0.15$ with FACTS devices.

Bus	Base case ($\lambda = 0$)					$\lambda = 0.15$, MSL = 115% with FACTS				
	Vol.	P_G	Q_G	P_L	Q_L	Vol.	P_G	Q_G	P_L	Q_L
1	1.020	109.51	40.39	–	–	1.020	112.41	50.46	–	–
2	1.000	49.92	75.02		–	1.000	52.71	97.17	–	–
3	1.000	59.28	71.35	–	–	1.000	87.13	76.32	–	–
4	0.981			70	70	0.974			80.5	80.5
5	0.965			70	70	0.958			80.5	80.5
6	0.972			70	70	0.962			80.5	80.5
Sum		218.71	186.76	210	210		252.25	223.95	241.5	241.5

Table 5
MSL and the optimal installation cost (IC) of FACTS devices obtained by proposed method and [11] algorithm in IEEE-6 bus system.

FACTS devices	Results obtained in proposed method			Results reported in [11]		
	MSL (%)	N	IC ($\times 10^6$ US$)	MSL (%)	N	IC ($\times 10^6$ US$)
TCSC	115	3	0.356	115	5	0.368

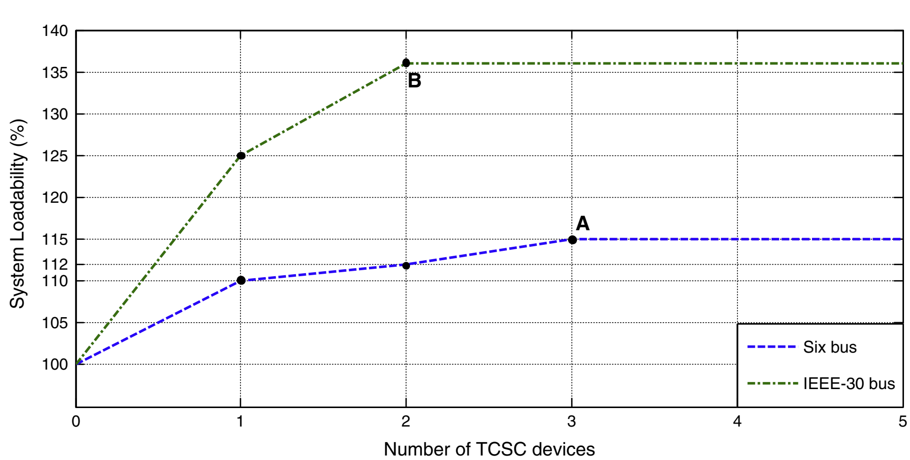

Fig. 9. System loadability curve for TCSC device in six bus and IEEE-30 bus system.

in the minimum cut. Hence, the minimum number of TCSC required and optimal installation cost of TCSC devices obtained in this work is less than as compared with result reported in [11].

IEEE 30-bus test system

There are 41 line sections in IEEE 30-bus system. The total system load is 189.2 MW and 107.2 MVAR.

It was observed from Table 6 that lines 8–28 and 21–22 is congested after MSL is obtained at $\lambda^* = 0.36$ (MSL = 136%). However transmission congestion can eliminate by placing TCSC at suitable location via the minimum cut.

From Table 7 it can be observed 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 6–8 and 10–22 are lines in loops (6–8–28–6) and (10–22–21–10) which contains branch overloaded 8–28 and 21–22, respectively. Therefore, to eliminate congestion, TCSC devices can be installed on the lines with an optimal setting size of TCSC as formulation (∗).

System power flow result after placing TCSC in line 6–8 and 10–22 was shown in Table 6 and Fig. 10. The degree of series compensation for achieving MSL was taken as −0.017 p.u. and −0.089 p.u. respectively. This value satisfies the allowed limits, which do not lead to overload of branches after installing TCSC as well as overcompensation state. It can be observed from Table 6 (Columns 6 and 7) that congestion has been relieved. The loading of the lines 8–28 has now reduced from 110.84% to 98.58% and lines 21–22 has now reduced from 119.53% to 100%. Lines 6–8 and 10–22 is now loaded to 85.44% and 67.80% respectively which is much higher than in the case without TCSC. The TCSC reduced the total reactance of the lines 6–8 and 10–22 from 0.06 p.u. to 0.043 p.u. and from 0.15 p.u. to 0.061 p.u. respectively hence power flow on the lines increases.

The comparison of the results for IEEE-30 bus system obtained by proposed method and Ref. [11] is shown in Table 8 and Fig. 9. From the results, it is observed that the minimum number of TCSC required and installation cost of TCSC devices obtained by proposed method is less than the result obtained by Ref. [11] while MSL is achieved nearly same value.

Table 7
The minimum cut for IEEE 30-bus system.

Line no.	The lines that minimum cut passes through
1	27–30
2	27–29
3	6–8
4	8–28
5	13–12
6	25–27
7	10–22
8	21–22

Table 6
The real and reactive power flow in the line *i–j* at $\lambda = 0.36$ (MSL = 136%) before and after installing TCSC devices, optimal setting and optimal cost of installation of TCSC devices (IC) and MSL in IEEE 30 bus system.

Line no.	From *i–j*	Limit (MVA)	P_{ijb} (MW)	Q_{ijb} (MVAR)	P_{ija} (MW)	Q_{ija} (MVAR)	Setting for TCSC (p.u.)	IC ($\times 10^6$ US$)
1	1–2	130	24.29	−9.38	25.47	−9.75		0.474 (MSL = 136%)
2	1–3	130	24.83	6.47	24.85	6.18		
3	2–4	65	24.35	8.47	23.94	8.21		
4	3–4	130	21.19	5.54	21.22	5.26		
5	2–5	130	19.92	7.7	19.66	7.52		
6	2–6	65	29.99	15.57	29.42	11.19		
7	4–6	90	30.72	15.39	29.92	14.79		
8	5–7	70	19.69	8.7	19.43	8.55		
9	6–7	130	12.02	5.21	12.27	5.35		
10	6–8	32	18.72	17.52	20.05	18.59	−0.017	
11	6–9	65	7.95	−5.05	7.35	−5.92		
12	6–10	32	4.54	−2.89	4.20	−3.39		
13	9–11	65	0.00	0.00	0.00	0.00		
14	9–10	65	7.95	−5.25	7.35	−6.13		
15	4–12	65	3.96	−3.0	4.39	−2.9		
16	12–13	65	40.00	16.83	37.6	16.41		
17	12–14	32	7.08	1.31	6.86	1.4		
18	12–15	32	11.76	−1.34	10.88	−1.11		
19	12–16	32	9.72	0.82	8.85	0.44		
20	14–15	16	1.49	1.04	1.71	0.94		
21	16–17	16	4.83	−1.78	3.97	−2.13		
22	15–18	16	10.73	1.85	10.26	−1.55		
23	18–19	16	6.19	0.37	5.73	0.1		
24	19–20	32	6.96	4.33	7.41	4.6		
25	10–20	32	10.08	5.63	10.55	5.92		
26	10–17	32	7.66	9.97	8.52	10.32		
27	10–21	32	6.31	15.65	0.04	−14.13		
28	10–22	32	7.16	11.54	15.84	14.83	−0.089	
29	21–22	32	26.65	27.44	21.52	23.73		
30	15–23	16	12.08	8.25	12.69	7.61		
31	22–24	16	1.06	8.38	0.14	−8.93		
32	23–24	16	7.14	2.66	7.73	2.34		
33	24–25	16	4	−1.49	4.55	−1.82		
34	25–26	16	4.89	3.23	4.89	3.23		
35	25–27	16	8.98	1.92	9.54	1.61		
36	28–27	65	6.12	12.71	6.76	12.27		
37	27–29	16	8.57	2.43	8.57	2.43		
38	27–30	16	9.9	2.46	9.9	2.46		
39	29–30	16	5.1	0.89	5.1	0.89		
40	8–28	32	24.97	25.19	21.43	23.15		
41	6–28	32	16.72	11.68	14.75	10.98		

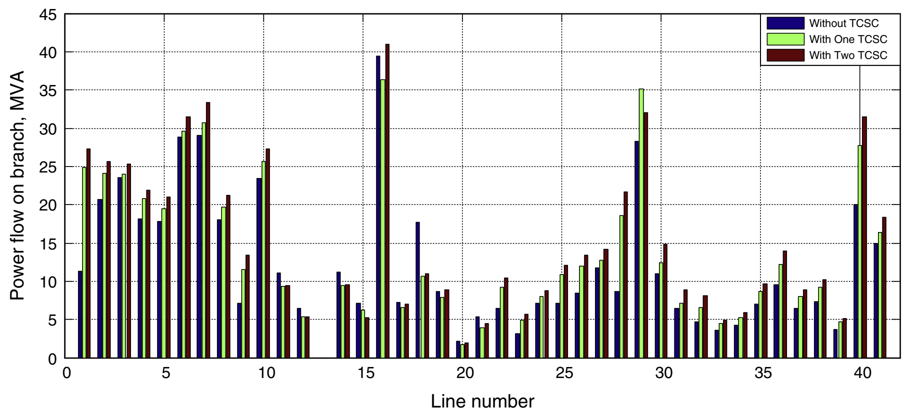

Fig. 10. The power flow on branch after placing TCSC devices in IEEE-30 bus system.

Table 8
MSL and the optimal installation cost (IC) of FACTS devices obtained by proposed method and [11] algorithm in IEEE 30-bus system.

FACTS devices	Results obtained in proposed method			Results reported in [11]		
	MSL (%)	*N*	IC ($\times 10^6$ US$)	MSL (%)	*N*	IC ($\times 10^6$ US$)
TCSC	136	2	0.474	138	8	3.57

Table 9
MSL and the optimal installation cost (IC) of FACTS devices obtained by proposed method and [11] algorithm in IEEE 118-bus system.

FACTS devices	Results obtained in proposed method			Results reported in [11]		
	MSL (%)	*N*	IC ($\times 10^6$ US$)	MSL (%)	*N*	IC ($\times 10^6$ US$)
TCSC	132	31	14.7	135	32	15.1

IEEE 118-bus test system

As per the procedure mentioned in the previous sections, the results obtained in IEEE 118 bus system are compared with the results reported in [11] and it is given in Table 9. From the table it can be seen that the MSL and the minimum number of TCSC devices obtained in proposed method are nearly equal to the results in [11].

Overall results show that the proposed method is capable of finding the best location for TCSC installation. Placing TCSC in the bottleneck location in the minimum cut reduces search space and gives better results in terms of MSL solution and optimal installation cost of TCSC devices, therefore enhancing the power system performance.

Conclusion

Maximum system loadability and optimal installation cost of TCSC devices is one of the most important issues in the electricity market operation. The proper location and optimal setting of TCSC is a key for solving this problem. Searching space will be very large if there is not an effective method. This paper has applied the minimum cut methodology on the power system to reduce search space as well as using Kirchhoff's law of current to establish clearly formulation for determining the best possible setting of TCSC devices.

The study results on IEEE6- and IEEE 30- and IEEE 118-bus system have proved the effectiveness of the method. The proposed method is capable of finding the location, quantity and size of TCSC in such effective way for enhancing system loadability and minimum installation cost of TCSC devices. 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.

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