A Novel Approach for Optimal Allocation of Series FACTS Device for Transmission Line Congestion Management

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Summary: In competitive environment of electricity market, management of congestion has become utmost important so that the benefits of competitive electricity market remains intact. In this paper, one such scheme has been proposed to manage congestion efficiently. This has been accomplished by implementing TCSC at its optimal location as well as at its optimal parameter setting. Line flow sensitivity factor has been proposed to find the optimal location of TCSC. The optimal parameter setting of TCSC is obtained using particle swarm optimization algorithm. The optimal location and parameter setting of TCSC thus obtained with proposed method are validated through implementation of TCSC based on its minimum installation cost. Two different penalty factors for violation of system constraints are introduced to manage the congestion efficiently. The proposed method is tested on IEEE 30-bus system and IEEE 118-bus system. A 33-bus Indian network has also been considered to analyze the effectiveness of the proposed methodology.

Keywords: Deregulation; congestion management; FACTS; TCSC; line flow sensitivity factor.

1 Introduction

Power system restructuring has transformed its monopolistic structure to three different entities which are independent of each other. These entities are generation companies (GENCOS), transmission companies (TRANSCO) and distribution companies (DISCO) [1]-[3]. This has led to paradigm shift in power sector and has introduced competition in electricity market. Although the competition in electricity market is limited to generation and distribution sides only, it has been proved fruitful to operate the transmission system by a single entity due to economy of scale and to keep the system secure and reliable. However due to introduction of competition in electricity market and with the increase in electricity demand globally, it enforces the transmission system operator to operate the system near its operating limit. This increases the prospect of system constraints violation and could hamper the transmission system security. The violation of system operating constraints causes the transmission line to become congested. Although the paradigm shift in electricity market, due to introduction of competition, promises greater benefits to all, the congestion of transmission network due to violation of its any operating constraint may wash away all the prospects of benefits of competitive electricity market. Therefore, management of congestion is not only important for secure operation of power system but is also vital in achieving the power system economy.

A number of literatures are available for different congestion management schemes developed to relieve the congestion efficiently [4]-[8]. This includes generation rescheduling [9]-[10], load curtailment [11], use of the FACTS devices [12], distributed generations [13] etc.

In new scenario of electricity market, wherein several bilateral and multilateral transactions co-exist, some of the lines may get overloaded due to flow of power above their thermal limit while other lines may be underutilized. It makes obligatory for the system operator to utilize the available transfer capability properly and judiciously. This task can be efficiently accomplished by installing FACTS devices which regulate the power flow by altering the transmission line parameters such as line reactance, voltage magnitude and voltage angle [14]. These devices can also be used for voltage stability improvement, transient stability improvement, sub-synchronous resonance mitigation etc. [15]. However, its power regulating feature as well as advantages over other congestion management methods has made it popular to utilize for managing congestion in deregulated environment of power system [16]-[19].

FACTS devices involve heavy installation cost, therefore its optimal location, size and setting plays a very vital role in maximizing the social welfare which deregulation promises to the society. Therefore this paper focusses on these aspects of implementation of FACTS devices to manage congestion. A number of works have been reported in literature on application of FACTS devices for congestion management [20]-[23].

A novel method to place a TCSC and SVC is proposed by authors in [24] for managing congestion in the system considering the static security margin improvement. A method to maximize the social welfare by optimal placement and size of TCSC for congestion management has been presented in [25]. The similar aspect of TCSC is considered by authors [26] to relieve congestion from the system. Authors have presented a method based on real power performance index and total system VAR power losses to optimally place the TCSC for congestion management. A comparison has been presented by authors to place the series FACTS device based on LMP difference across a line and total congestion rent [27]. The authors have proposed the use of FACTS devices along with demand response to relieve congestion from the transmission lines [28] while in [29] a curtailment strategy based on FACTS device has been proposed. In [30] and [31], line outage sensitivity factor is utilized to optimally place the series FACTS devices for congestion alleviation in deregulated environment. However, the authors in [32] have considered dc load flow in their problem.

It is evident from the literature survey that TCSC is one of the widely used FACTS devices around the world. Its simple construction and implementation as well as low cost compared to other FACTS devices make it preferable over others for congestion management [32]-[34]. Therefore in this paper also, TCSC is considered for the purpose of managing congestion. In this paper, line flow sensitivity factor based on real power flow is proposed to find the optimal location and setting of TCSC for congestion alleviation in deregulated electricity market. Line limit violation factor and voltage limit violation factors are introduced to penalize for congestion and hence the minimum generation cost as well as cost of installation of TCSC is found by optimally placing TCSC using line flow sensitivity factor.

2 Modelling and implementation of TCSC

All Power flow in a transmission network can be adjusted by varying the net series reactance. Application of series capacitor to increase transmission line capacity is a well-known method of series compensation which helps to reduce net series reactance thereby allowing flow of additional power through the lines. However, the conventional methods of series compensation use capacitors with mechanical switches such as circuit breakers over a limited range while compensation using thyristor controllers rapidly controls the line compensation over a continuous range with flexibility. Therefore TCSC is widely adopted to regulate the power flow in a line. This section deals with the modelling and implementation of TCSC.

Figure 1 shows a π-equivalent transmission line model connected between bus-i and bus-j.

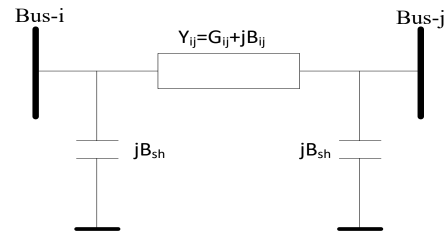

Fig. 1. Transmission line model

If $V_i\angle\delta_i$ and $V_j\angle\delta_j$ are the voltages at bus-i and bus-j respectively, the equations for active and reactive power flow from bus-i to bus-j can be given by equation (1) and (2) respectively.

$$P_{ij} = V_i^2 G_{ij} - V_i V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})] \tag{1}$$

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

where, $\delta_{ij} = \delta_i - \delta_j$. Similarly, the power flows from bus-j to bus-i are given by equations (3) and (4).

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

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

The application of TCSC in a transmission network can be visualized as a control reactance connected in series to the specific transmission line. Fig. 2 shows the transmission network model with a TCSC. During steady-state condition, a TCSC can be taken as a static capacitor/reactor with impedance $-jX_C$ [35].

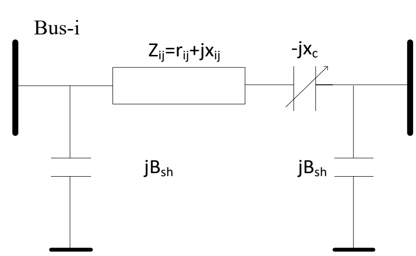

Fig. 2 Transmission line model with TCSC

With the implementation of TCSC, the power flow from bus-i to bus-j is modified as given in equation (5) and (6).

$$P'_{ij} = V_i^2 G'_{ij} - V_i V_j [G'_{ij} cos(\delta_{ij}) + B'_{ij} sin(\delta_{ij})] \quad (5)$$

$$Q'_{ij} = -V_i^2 (B'_{ij} + B'_{sh}) - V_i V_j [G'_{ij} sin(\delta_{ij}) + B'_{ij} cos(\delta_{ij})] \quad (6)$$

where,

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

and

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

Generally, a congestion management problem employs static model of FACTS device injecting power at sending and receiving end of line [36]. According to this model FACTS device can be represented as PQ element injecting definite amount of power to the specific node. *Fig.* 3 shows the power injection model of TCSC.

The real power injected at bus-i and bus-j due to implementing TCSC is given by equation (7) and (8).

$$P'_i = V_i^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} cos\delta_{ij} + \Delta B_{ij} sin\delta_{ij}] \quad (7)$$

$$P'_j = V_j^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} cos\delta_{ij} + \Delta B_{ij} sin\delta_{ij}] \quad (8)$$

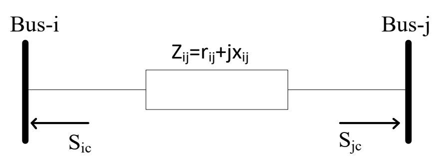

Fig. 3 Power injection model

Similarly the reactive power injected at bus-i and bus-j after implementing TCSC is given by equation (9) and equation (10).

$$Q'_i = -V_i^2 \Delta B_{ij} - V_i V_j [\Delta G_{ij} sin\delta_{ij} + \Delta B_{ij} cos\delta_{ij}] \quad (9)$$

$$Q'_j = -V_j^2 \Delta B_{ij} - V_i V_j [\Delta G_{ij} sin\delta_{ij} + \Delta B_{ij} cos\delta_{ij}] \quad (10)$$

where,

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

and

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

3 Problem formulation for congestion management using TCSC

The main objective of this work is to manage congestion by optimally placing TCSC in the power system network which is achieved by minimizing the cost of installation of FACTS device along with penalty for violation of line flow limits and bus voltage limits due to congestion as shown in equation (11).

$$Min\ [C_i(P_i) + C_{TCSC} + \lambda_1.VLV + \lambda_2.FLV] \tag{11}$$

where

$$C_{TCSC} = C_t \text{ x } S \text{ x } 1000 \quad (\$/hr) \tag{12}$$

$$C_t = 0.0015\, S^{\,2} + 0.713S + 153.75\ (\$/KVAR) \tag{13}$$

$$S = |Q_1 - Q_2| \tag{14}$$

where, C_t is the unit cost of TCSC

S is the operating range of TCSC in MVAR

Q1 and Q2 are the reactive power flow in the line before and after installation of TCSC

P_L^2 is the power flow in line k to which TCSC is connected

λ_1 and λ_2 are the penalty coefficients in the range of 10^5 to 10^8

VLV is the voltage violation factor

FLV is the line flow limit violation factor

The objective function comprises of two parts. The first part is the installation cost of TCSC whereas the second part is composed of penalty cost due to violation of bus voltage limit and the line flow limit which are given as:

$$\text{VLV} = \left(\frac{\text{V}_\text{b} - \text{V}_\text{ref}}{\text{V}_\text{ref}}\right)^2, \ \text{if } \text{V}_\text{b} < \text{V}_\text{ref}^\text{min} \text{ or } \text{V}_\text{b} > \text{V}_\text{ref}^\text{max} \tag{15}$$

$$= 0 \qquad \text{if } \text{V}_\text{ref}^\text{min} < \text{V}_\text{b} < \text{V}_\text{ref}^\text{max} \tag{16}$$

$$FLV = \left(\frac{P_{ij} - P_{ij}^{max}}{P_{ij}^{max}}\right)^2, \quad \text{if } P_{ij} > P_{ij}^{max} \tag{17}$$

$$= 0 \qquad \text{if } P_{ij} < P_{ij}^{max} \tag{18}$$

The reactance of TCSC is chosen such that $X_{ck}^{min} < X_{ck} < X_{ck}^{max}$. For static model of TCSC, the maximum compensation allowed is 70% of the reactance of line [27]. The voltages V_{ref}^{min} is taken as 0.94 pu while V_{ref}^{max} is taken as 1.06 pu.

4 Optimal placement of TCSC

TCSC involves a heavy investment for its installation. Therefore, its appropriate location and size play a very vital role in managing congestion efficiently. Otherwise, it would not be proved beneficial as compared to other methods of congestion management. Therefore, the size and location of TCSC must be chosen with utmost care [37].

In this paper, the TCSC is optimally placed in the system considering the line flow sensitivity factor which is defined as a change in real power flow in a transmission line connected between bus-i and bus-j due to change in control parameter of TCSC.

Since the real power flow of a transmission line changes with the change in its reactance, the real power flow in the network paths changes due to the change in series reactance of the line by placing TCSC. This change in real power flow is a function of control parameter (i.e. reactance setting) of TCSC. Thus change in real power flow of a line due to change in control parameter of TCSC gives an indication for optimal placement of TCSC in managing congestion.

Mathematically, the line flow sensitivity factor with respect to the parameters of TCSC placed at line-k can be defined as:

$$LSF_c^k = \left.\frac{\partial P_{LT}}{\partial X_{ck}}\right|_{X_{ck}=0} \tag{19}$$

where, P_{LT} is the real power flow in line connected between bus i and bus j

X_{ck} is the control parameter of TCSC

The lines with high negative values of line flow sensitivity factor are the potential locations for placing TCSC in the network in order to manage congestion efficiently. Equation (19) is calculated by differentiating the power flow in a line with respect to TCSC control parameters which is given as:

$$LSF_c^k = \left.\frac{\partial P_{LT}}{\partial X_{ck}}\right|_{X_{ck}=0} \tag{20}$$

$$= C_{ij}\left[-V_i^2 + V_j V \cos\delta_{ijj}\right] - D_{ij}\left[V_i V_j \sin\delta_{ij}\right] \tag{21}$$

where

$$C_{ij} = \left(\frac{-2r_{ij}x_{ij}}{\left(r_{ij}^2 + x_{ij}^2\right)^2}\right)$$

$$D_{ij} = \left(\frac{r_{ij}^2 - x_{ij}^2}{\left(r_{ij}^2 + x_{ij}^2\right)^2}\right)$$

Once the optical location of TCSC is found, its optimal setting for congestion alleviation is found using PSO algorithm described in [38].

5 Results and discussions

The FACTS device should be placed on the most sensitive line. With the sensitive factor computed for TCSC, the TCSC should be placed in a line having the most negative line flow sensitivity factor. The proposed method for congestion management using TCSC is implemented and tested with IEEE 30-bus and IEEE 118-bus systems in order to analyse its effectiveness and robustness. The proposed method has been also tested with 33-bus Indian network and the results thus obtained are compared with those presented in [39]. Optimizations are carried out with PSO [38] developed in MATLAB language. The values of various parameters taken for PSO are given in appendices.

5.1 IEEE 30-bus system

The data for IEEE 30-bus system has been taken from [40]. The load flow solution for IEEE 30 bus system is given in Table 5 which shows that that line-1 (connected between bus 1 and 2) is congested. The power flow through this line is 1.010 pu. The line flow sensitivity factor with respect to TCSC control parameter has been computed for the congested line and is shown in Table 1.

From Table 1, it is observed that line-2, line-3 and line-6 (connected between bus-1and bus-3, bus 2 and bus-4, bus-2 and bus-6 respectively) have high negative values of line flow sensitivity factor as compared to other lines which can also be inferred from Fig. 4. Therefore these lines have high priority for placement of TCSC in order to mitigate congestion. Line-2, having the highest negative value of sensitivity factor, is selected for placement of TCSC to manage congestion.

Table 1 Line flow sensitivity factor of IEEE 30-bus system for congested line-1

S. no.	Line no.	From bus	To bus	Sensitivity
1	2	1	3	-0.4239
2	3	2	4	-0.0481
3	6	2	6	-0.0386

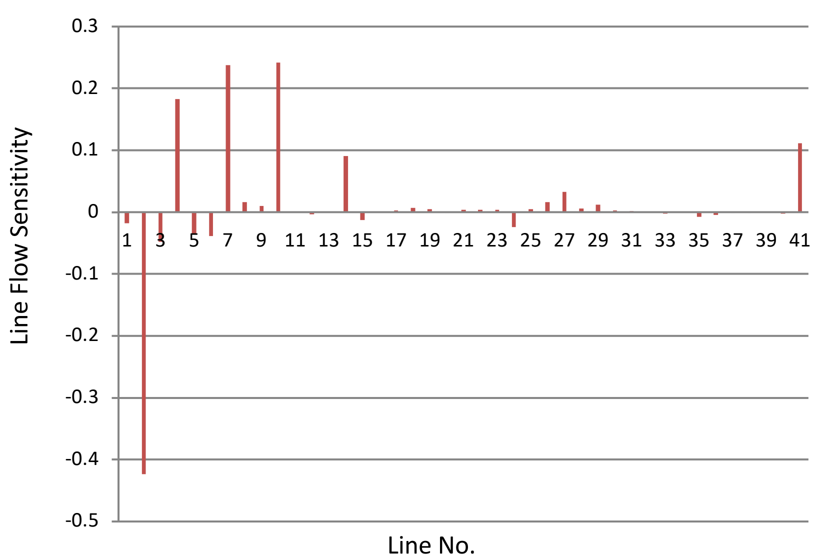

Fig. 4 Line Flow Sensitivity Factor for IEEE 30-bus system

Table 2 Power flow in congested line of IEEE 30-bus system for different locations of TCSC

Line no.	Power flow in p.u.			
	Without TCSC	Location of TCSC		
		Line-2	Line-3	Line-6
1	1.010	0.919	0.980	0.993

From the optimization algorithm, it has been found that for optimal setting of TCSC control parameter at 0.06278 pu, the congestion from the system is managed efficiently. For this setting of TCSC, the power flow in congested line is shown in Table 2 which reveals that the power flow in line-3 which was earlier congested is within its limit after placing TCSC in line-7. The performance of the proposed algorithm is also analyzed by placing TCSC to other potential locations i.e line-3 and line-6. It has been found that for control parameter setting of TCSC at 0.2866 pu and 0.0161pu respectively for these two locations of TCSC placement, the congestion is effectively alleviated from the system which can be observed from power flow results shown in Table 2. The percentage line loading for the considered potential locations of TCSC is illustrated in Fig. 5 which shows that placement of TCSC at these locations alleviates the system congestion.

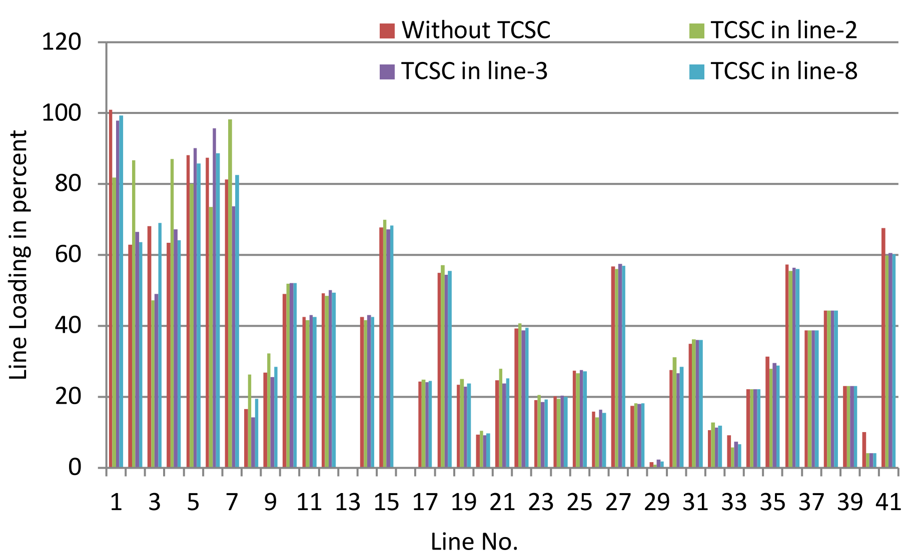

Fig. 5 Percentage line loading for IEEE 30-bus system

Although the placement of TCSC at all potential locations manages the congestion successfully, it is necessary to perform the cost-benefit analysis for FACTS device in order to analyse its cost effective location among various potential locations. Therefore, installation cost of TCSC and hence the system generation cost is calculated using equation (11).

Due to high cost involved with installation of FACTS devices, its investment cost should be analysed such that its placement gives the low installation cost. The installation cost of TCSC for different potential locations is calculated using equations 12-14 and is shown in Table 3 which reveals that placement of TCSC in line-2 is more economical as compared to other potential locations for TCSC placement. It can be also observed from Table 3 that placement of TCSC in line-3 gives minimum generation cost of the system as compared to other locations. Hence, the location found to place the TCSC with the proposed method gives minimum cost as well as system generation cost as compared to other locations.

The cost-benefit analysis for these potential locations of TCSC placement has been performed and the results are given in Table 6 from which it can be observed that placement of TCSC in line-2 gives its minimum installation cost as well as minimum generation cost of the system. Hence the proposed methodology gives optimal location for the placement of TCSC in order to manage congestion efficiently.

Table 3 Cost results for IEEE 30-bus system

Location of TCSC	Installation cost of TCSC ($/KVAR)	Total Generation Cost ($/hr)
Without TCSC	-	3336.7
Line-2	159.5	2469.1
Line-3	162.6	2496.7
Line-6	167.2	2542.9

5.2 33-bus Indian network

To analyse the effectiveness of the proposed methodology, a 33-bus Indian network [39] has been considered. A comparative study of the results obtained with the proposed methodology and those obtained with the methodology proposed in [39] has been done in order to analyse the performance.

The load flow solution for the considered system gives that line-18 (connected between bus-8 and bus-23 is congested. The power flow through the line is 1.036 pu. The line flow sensitivity factor thus evaluated for the congested system is shown in Table 4 from which it can be observed that line-2, line-14 and line-19 (connected between bus-1and bus-33, bus 12 and bus-31, bus-8 and bus-22 respectively) have high negative values of line flow sensitivity factor as compared to other lines. Therefore these lines have high priority for placement of TCSC in order to mitigate congestion and can also be observed from Fig. 6. Line-2, having the highest negative value of sensitivity factor, is selected for placement of TCSC to manage congestion.

Table 4 Line flow sensitivity factor of 33-bus Indian network for congested line-18

S. No.	Line No.	From Bus	To Bus	Sensitivity
1	2	1	33	-1.1442
2	14	12	31	-0.8713
3	19	8	22	-0.6855

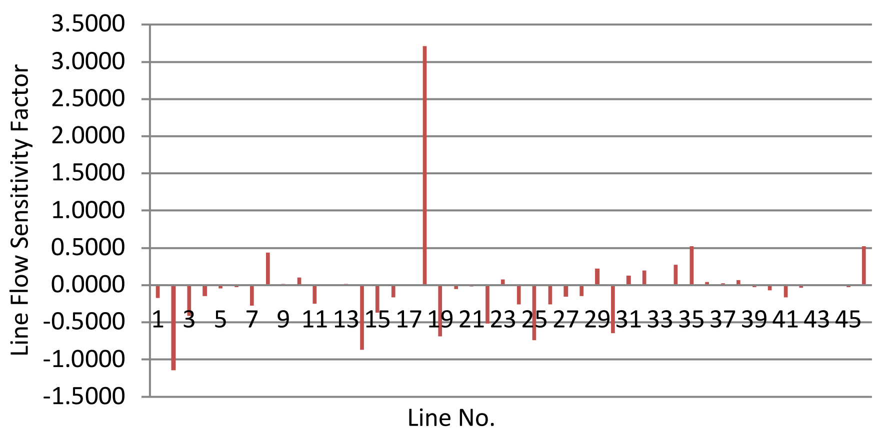

Fig. 6. Line Flow Sensitivity Factor for 33-bus Indian network

After placing TCSC in line-2, it has been found from optimization algorithm that for optimal setting of TCSC control parameter at 0.00419 pu, the congestion from the system is managed effectively. For this setting of TCSC, the power flow results are shown in Table 5 which illustrates that the power flow in line-18, which was earlier congested, is within its limit. The performance of the proposed algorithm is also analyzed by placing TCSC to other potential locations i.e. line-3 and line-6. It has been found that for control parameter setting of TCSC at 0.00250 pu and 0.00347 pu respectively for these two locations of TCSC placement, the congestion is effectively alleviated from the system which can also be observed from power flow results shown in Table 5. The percentage line loading for the considered potential locations of TCSC is illustrated in Fig. 7 which shows that placement of TCSC at these locations alleviates the system congestion.

The cost-benefit analysis for these potential locations of TCSC placement has been performed and the results are given in Table 6 from which it can be observed that placement of TCSC in line-2 gives its minimum installation cost as well as minimum generation cost of the system.

Table 5 Power flow in congested line of 33-bus Indian network for different locations of TCSC

Line No.	Power flow in p.u.			
	Without TCSC	Location of TCSC		
		Line-2	Line-14	Line-19
18	1.036	0.995	0.998	0.999

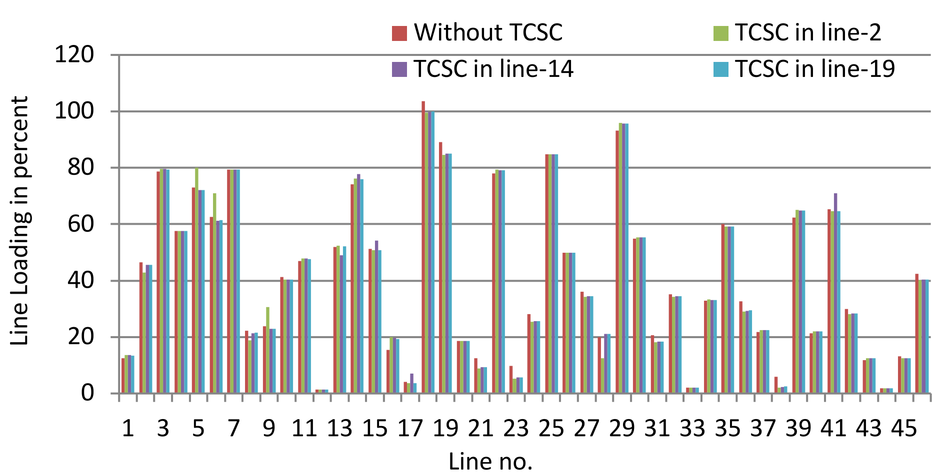

Fig. 7. Percentage line loading for 33-bus Indian network

Table 6 Cost results for 33-bus Indian network

Location of TCSC	Installation cost of TCSC ($/KVAR)	Total Generation Cost ($/hr)
Without TCSC	-	108062.4
Line-2	155.1	107731.2
Line-14	166.7	107753.1
Line-19	172.2	107731.3

To further analyse the performance of the proposed method, the results obtained are compared with those reported in [39]. The authors in [39] have adopted a sensitivity loss method in which the line having most positive loss sensitivity factor is selected to place TCSC for managing congestion.

However, the results show that placement of TCSC in line-44 having most positive loss sensitivity factor does not alleviate congestion from the system. Therefore, the authors have selected another bus and this process is repeated until the system is relieved from congestion. Finally, the congestion is alleviated by placing TCSC in line-38 which is ranked twelfth in location priority as shown in Table 7. Thus, the method consumes a lot of time in order to find the optimal location of TCSC. While in this paper, the optimal location is found within no time as the congestion is managed by placing the TCSC in line which is ranked first in location priority. The TCSC placement at other lower ranked locations found with the proposed method also manages congestion effectively as shown in Table 7. Also, the potential locations obtained with the proposed method are ranked very low in location priority in [39] as shown in Table 8. Besides this, the minimum installation cost of TCSC evaluated with the proposed method is 155.14 $/KVAR which is lower than that reported in [39] as shown in Table 9. Thus the proposed method gives more optimal location for TCSC as compared to the method reported in [39].

Table 7 Result comparison for 33-bus Indian network

TCSC Location Priority	Proposed Method		Method reported in [39]	
	TCSC Location	System Condition	TCSC Location	System Condition
1	Line-2	Not Congested	Line-44	Congested
2	Line-14	Not Congested	Line-12	Congested
3	Line-19	Not Congested	Line-46	Congested
4	-	-	Line-32	Congested
5	-	-	Line-21	Congested
6	-	-	Line-33	Congested
7	-	-	Line-16	Congested
8	-	-	Line-23	Congested
9	-	-	Line-20	Congested
10	-	-	Line-17	Congested
11	-	-	Line-18	Congested
12	-	-	Line-38	Not Congested

Table 8 Location priority ranking

TCSC location	Priority rank	
	Proposed method	Method reported in [39]
Line-2	1	39
Line-14	2	44
Line-19	3	21

Table 9 TCSC installation cost comparison

	Proposed method	Method reported in [39]
TCSC installation cost ($/KVAR)	155.14	241.74

5.3 IEEE 118-bus system

Further to analyse the effectiveness of the proposed methodology on a larger network, modified IEEE 118-bus system [40] is considered. The system is modified to have bus-1 as slack bus. A comparative study of the results obtained with the proposed methodology and those obtained with the methodology proposed in [39] is also carried out for the considered system in order to analyse the performance.

The load flow solution for the considered system gives that line-81 (connected between bus-49 and bus-66) is congested. The power flow through the line is 1.036 pu. The line flow sensitivity factor thus evaluated for the congested system is shown in Table 10 from which it can be observed that line-99, line-105 and line-106 (connected between bus-60 and bus-61, bus-63 and bus-64, bus-64 and bus-65 respectively) have high negative values of line flow sensitivity factor as compared to other lines. Therefore these lines have high priority for placement of TCSC in order to mitigate congestion and can also be observed from Fig. 8. Line-99, having the highest negative value of sensitivity factor, is selected for placement of TCSC to manage congestion.

After placing TCSC in line-99, it has been found from optimization algorithm that for optimal setting of TCSC control parameter at 0.2897 pu, the congestion from the system is managed effectively. For this setting of TCSC, the power flow results are shown in Table 11 which illustrates that the power flow in line-81, which was earlier congested, is within its limit.

Table 10 Line flow sensitivity factor of IEEE 118-bus system for congested line-81

S. no.	Line no.	From bus	To bus	Sensitivity
1	99	60	61	-4.4619
2	105	63	64	-2.7808
3	106	64	65	-2.6791

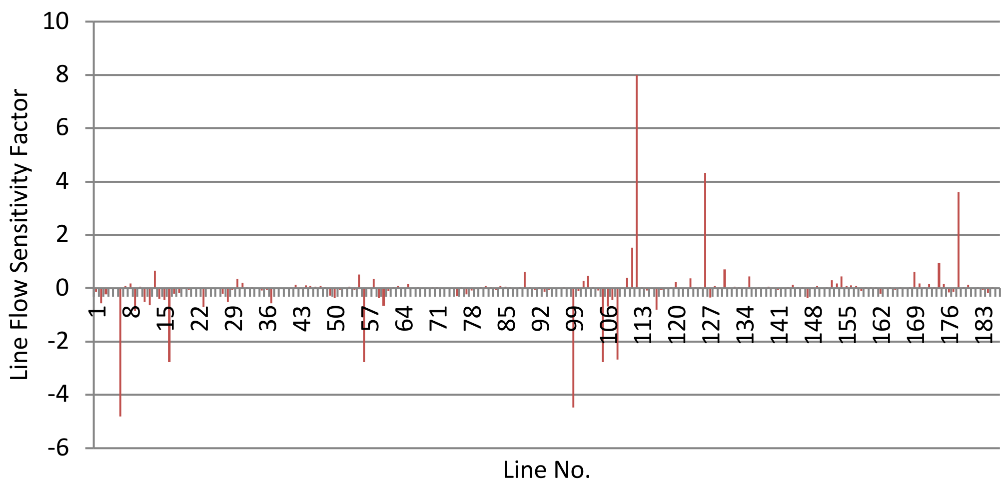

Fig. 8. Line Flow Sensitivity Factor for IEEE 118-bus system

The performance of the proposed algorithm is also analyzed by placing TCSC to other potential locations i.e. line-105 and line-106. It has been found that for control parameter setting of TCSC at 0.2973 pu and 0.3051 pu respectively for these two locations of TCSC placement, the congestion is effectively alleviated from the system which can also be observed from power flow results shown in Table 11. The percentage line loading for the considered potential locations of TCSC is illustrated in Fig. 9 which shows that placement of TCSC at these locations alleviates the system congestion.

Table 11 Power flow in congested line of IEEE 118-bus system for different locations of TCSC

Line no.	Power flow in p.u.			
	Without TCSC	Location of TCSC		
		Line-99	Line-105	Line-106
81	1.409	0.995	0.997	0.998

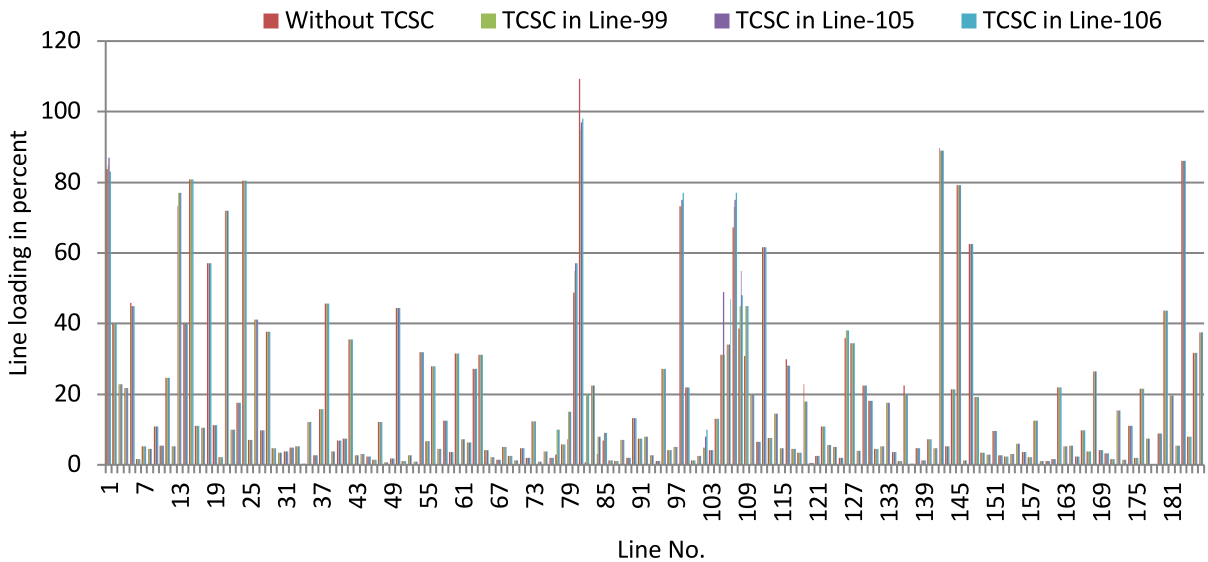

Fig. 9. Percentage line loading for IEEE 118-bus system

The cost-benefit analysis for these potential locations given in Table 12 from which it can be observed that placement of TCSC at the location found by the proposed method i.e. in line-99 gives its minimum installation cost as well as minimum generation cost of the system.

Table 12 Cost results for IEEE 118-bus system

Location of TCSC	Installation cost of TCSC ($/KVAR)	Total Generation Cost ($/hr)
Without TCSC	-	8453.7
Line-99	210.6	8371.1
Line-105	218.7	8391.6
Line-106	222.4	8398.3

To further analyse the performance of the proposed method, the results obtained are compared with those obtained with the method reported in [39]. With the loss sensitivity method reported in [39], the results show that placement of TCSC in line-14 having most positive loss sensitivity factor does not alleviate congestion from the system. Therefore, another bus is selected and this process is repeated until the system is relieved from congestion. Finally, the congestion is alleviated by placing TCSC in line-106 which is ranked thirty-third in location priority as shown in Table 13. While the highest priority ranked location of TCSC for management of congestion with the proposed method is ranked thirty-fifth according to the method in [39]. Thus, the loss sensitivity method consumes a lot of time in order to find the optimal location of TCSC. While in this paper, the optimal location is found within no time as the congestion is managed by placing the TCSC in line which is ranked first in location priority. The TCSC placement at other lower ranked locations found with the proposed method also manages congestion effectively as shown in Table 10. Also, the potential locations obtained with the proposed method are ranked very low in location priority in [39] as shown in Table 14. Besides this, the minimum installation cost of TCSC evaluated with the proposed method is 155.14 $/KVAR which is lower than that reported in [39] as shown in Table 15. Thus the proposed method gives more optimal location for TCSC as compared to the method reported in [39].

Table 13 Result comparison for IEEE 118-bus system

TCSC Location priority	Proposed method		Method reported in [39]	
	TCSC location	System condition	TCSC location	System condition
1	Line-99	Not Congested	Line-14	Congested
2	Line-105	Not Congested	Line-108	Congested
3	Line-106	Not Congested	Line-2	Congested
4	-	-	Line-15	Congested
5	-	-	Line-13	Congested
6	-	-	Line-50	Congested
7	-	-	Line-1	Congested
8	-	-	Line-3	Congested
9	-	-	Line-4	Congested
10	-	-	Line-38	Congested
11	-	-	Line-60	Congested
12	-	-	Line-112	Congested
13	-	-	Line-28	Congested
33	-	-	Line-106	Not Congested
35	-	-	Line-99	Not Congested

Table 14 Location priority ranking

TCSC location	Priority rank	
	Proposed method	Method reported in [39]
Line-99	1	35
Line-105	2	41
Line-106	3	33

Table 15 TCSC installation cost comparison

	Proposed Method	Method reported in [39]
TCSC Installation Cost ($/KVAR)	210.61	261.15

6 Conclusion

In this paper, impact of TCSC is analysed in managing congestion of transmission lines. A static model of TCSC is considered in problem formulation. Since FACTS devices involve a huge investment, therefor its optimal location plays an important role in order to achieve the market economics. A sensitivity based approach using power flow in lines with respect to TCSC control parameters is proposed to find the optimal location of TCSC. The line flow sensitivity factor is calculated for each line based on which the optimal location of TCSC has been determined. The effectiveness of the proposed method has also been analysed for minimizing the cost of TCSC installation as well as total generation cost. The proposed method has been tested on IEEE 30-bus system, IEEE 118-bus system and 33-bus Indian network. It has been observed from test results that the placement of TCSC in most sensitive line determined from sensitivity analysis gives minimum installation cost of TCSC as well as minimum generation cost as compared to other potential locations for TCSC placement. The proposed method is found to be effective for small as well as large power system network.

Appendix A

Table A1 PSO parameters values

PSO Parameters	Values
w_{min}	0.4
w_{max}	0.9
c_1	2
c_2	2
Maximum iterations	500
Particle size	70

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