A novel approach for optimal allocation of series FACTS device for transmission line congestion management

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Abstract
The reformed electricity market structure has forced the transmission network to operate near its operational limits. Due to competition in electricity market and with increasing demand, the probability of occurrence of congestion in transmission network has also increased. This resulted in insecure operation of power system and inefficient operation of the electricity market. The main aim of this article is to achieve efficient management of congestion in terms of minimum cost of electricity. This is accomplished by optimally allocating thyristor-controlled series capacitor (TCSC) in the system. Since flexible alternating current transmission system (FATCS) devices involve heavy installation cost, its proper allocation plays a vital role in achieving the electricity market economics. Therefore, in this article, a new sensitivity index called line flow sensitivity factor is proposed to find the optimal location of TCSC while its control parameter setting is optimally obtained with particle swarm optimization algorithm. The obtained results are validated through implementation of TCSC based on its minimum installation cost. Further, two different penalty factors for violation of system constraints are also introduced in the problem formulation to effectively consider the competitive nature of the electricity market. The proposed method is tested on IEEE 30-bus system, IEEE 118-bus system, and 33-bus Indian network and the results are found to be encouraging. The performance of the optimization algorithm on different systems is also analyzed in this article.

KEYWORDS
congestion management, deregulation, flexible alternating current transmission system devices, line flow sensitivity factor, thyristor-controlled series capacitor

1 INTRODUCTION
Restructuring has transformed the monopolistic structure of power system into three different independent entities which are generation companies (GENCOS), transmission companies (TRANSCOS), and distribution companies (DISCOS).\textsuperscript{1,2} This has led to paradigm shift in power sector which 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.\textsuperscript{3} But, due to introduction of competition in electricity market and increase in electricity demand globally, the transmission system operator is enforced to operate the system near its operating limits. It increases the prospect of system constraints violation which could hamper the transmission system security. The violation of any system operating constraint causes the transmission line to become congested. Although the competition in electricity market promises greater benefits to all the stakeholders, the congestion of transmission network may take away all its prospects of benefits. Hence, management of congestion is pivotal in achieving secure operation of power system as well as the power system economy.

A number of schemes are presented in literature to manage congestion efficiently such as load curtailment,\textsuperscript{4} generation re-dispatch,\textsuperscript{5} use of flexible alternating current transmission system (FACTS) devices,\textsuperscript{6} and distributed generations\textsuperscript{7}. Each of these schemes has their own pros and cons. Therefore, their application depends upon the requirement and topology of the network.\textsuperscript{8} The former two methods result in loss of revenue of the system as it makes the system to operate at sub-optimal point. The latter two methods provide a more robust, economic, and efficient operation of the system even though a huge capital cost is involved.

In new scenario of electricity market, wherein several bilateral and multilateral transactions co-exist,\textsuperscript{9} 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 accomplished with any of the schemes mentioned above. Although load curtailment and generation re-dispatch are being used since a long time, their use is very limited in the present scenario of competitive electricity market due to various reasons such as generator ramp time, market power, loss of prioritized or emergency load etc. Therefore, the use of FACTS devices comes into picture\textsuperscript{10} which provides a dynamic and fast control to enhance the available transfer capability of the transmission network. The installation of FACTS devices at an appropriate location in the transmission network and with its optimal setting is a key to achieve maximum benefit from it. The inherent property of the FACTS devices to regulate the power flow by altering the transmission line parameters such as line reactance, voltage magnitude, and voltage angle\textsuperscript{11} proved a boon for the system operator to operate the system securely, reliably and more efficiently. These devices can also be used for voltage stability improvement, transient stability improvement, sub-synchronous resonance mitigation, and so on.\textsuperscript{12} 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.\textsuperscript{13-16}

FACTS devices involve heavy installation cost which includes capital and operation cost, therefore its optimal location, size, and setting play a very significant role in maximizing the benefits of deregulation to the society. Since its inception, several authors proposed different methods to achieve these objectives. An optimal power flow (OPF) based method to allocate thyristor-controlled series capacitor (TCSC) for congestion management is presented in Reference 17. The location and size of the TCSC are obtained based on the evaluation of social welfare which is measured in terms of the unit cost of TCSC along with total generation cost. It is performed for each potential location of TCSC in the system. However, no attempt is made to minimize the search space for the location of TCSC. This issue is somehow addressed in References 18-20. The location and size of TCSC are obtained using VAR loss sensitivity factor and real power flow sensitivity factor in Reference 18 while line outage sensitivity factor is utilized in References 19 and 20 to find its optimal allocation. These methods make use of dc load flow which fails to capture the non-linearity associated with the power system. The methods presented in References 21-23 consider ac load flow sensitivity factors to account for power system non-linearity. TCSC is located in References 21 and 22 based on power flow analysis approach, while fast voltage sensitivity index is used by authors in Reference 23 to find the optimal location. These methods allocate TCSC based on the sensitivity factors which fail to capture the best possible locations of TCSC allocation. Besides sensitivity method, several authors have utilized different optimization techniques to solve for congestion management problem with the use of TCSC.\textsuperscript{24-28} Bender’s decomposition method is used by Ziaee and Choobineh\textsuperscript{24} to solve the non-linear problem of finding TCSC location and size. The authors in References 25 and 26 tried to solve the congestion management problem incorporating TCSC using moth swarm based optimization algorithm. In Reference 27, the authors have proposed a hybrid form of optimization method based on antlion, salp swarm, and mothflame to manage congestion using TCSC. The improvement in line congestion is measured by determining the locations and size of TCSC devices using multi-objective genetic algorithm in Reference 28. Similarly, the location and sizing of TCSC is determined using ageist spider monkey optimization algorithm and fuzzy based approach in Reference 29. The reported optimization algorithms solve the economic dispatch problem including the cost of TCSC to obtain the optimal location and size of TCSC with the assumption that initially all lines will have this device. This would be difficult in present scenario of competitive electricity market. Also,
the authors have only presented the convergence characteristic of the algorithm to show its robustness. The other performance parameters, such as success rate, number of fitness evaluations, and so on, are not explored to claim the robustness of the algorithm.

The above reported works reveals that the location and size of FACTS devices are important aspects. These are utilized to minimize the generation cost and active power loss along with their cost. However, the above methods fail to capture every potential location for the placement of FACTS devices. In this article, a new method to find the best location and optimal setting of series FACTS device based on line flow sensitivity factor (LSF) is proposed. Also, due to competitive nature of the electricity market, the methods must have provision to penalize for the occurrence of congestion. Line limit violation factor (FLV) and voltage limit violation factor (VLV) are introduced here to take care of this. The best location and size of the FACTS device are found with optimum system generation cost in case of congestion in the system.

Furthermore, it is evident from the literature survey that TCSC is one of the widely used FACTS devices around the world. Its simple construction, implementation, low cost as well as very effective power regulating capability compared to other FACTS devices make it preferable to use for congestion management. So, optimal location and size of TCSC is evaluated to manage congestion in this work. The problem is formulated as a non-linear problem incorporating system generation cost, TCSC installation cost and the penalty cost, the solution of which is obtained by particle swarm optimization algorithm (PSO). The robustness of the PSO is also analyzed in this work on the basis of different parameters such as success rate, number of fitness evaluations, mean time of execution, and so on.

The implementation of the proposed work is organized in the following sections as: modeling and implementation of TCSC in Section 2, problem formulation in Section 3, optimal placement of TCSC in Section 4, results and discussion in Section 5 followed with performance evaluation of PSO in Section 6. The conclusions and future scope of the proposed work is presented in Section 7.

2 | MODELING AND IMPLEMENTATION OF TCSC

The 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. With the introduction of thyristor controllers, the line compensation is rapidly achieved over a continuous range with more flexibility. Among these thyristor controllers, TCSC is one of the most widely adopted FACTS devices to regulate the power flow in a line. This section deals with the modeling and implementation of TCSC.

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

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 power flow (\( P_{ij} \)) and reactive power flow (\( Q_{ij} \)) from bus-i to bus-j can be given by Equation (1) and (2) respectively.

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

\[
Q_{ij} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j [G_{ij} \sin(\delta_{ij}) + B_{ij} \cos(\delta_{ij})]
\]
where $G_{ij}$ and $B_{ij}$ are the conductance and susceptance of transmission line connected between bus-i and bus-j, respectively and $B_{sh}$ is the susceptance between bus and ground. The bus angle between two buses connected through a line is given by $\delta_{ij} = \delta_i - \delta_j$. Similarly, the power flows from bus-j to bus-i are given by Equations (3) and (4).

$$P_{ji} = V_j^2 G_{ij} - V_i V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})]$$  \hspace{1cm} (3)$$

$$Q_{ji} = -V_j^2 (B_{ij} + B_{sh}) - V_i V_j [G_{ij} \sin(\delta_{ij}) + B_{ij} \cos(\delta_{ij})]$$  \hspace{1cm} (4)$$

where $P_{ji}$ and $Q_{ji}$ are active and reactive power flow from bus-j to bus-i respectively.

The application of TCSC in a transmission network can be visualized as a control reactance connected in series to the specific transmission line. The transmission network model with a TCSC connected between bus-i and bus-j is presented in Figure 2. During steady-state condition, a TCSC can be taken as a static capacitor/reactor with impedance $jX_c$.32

With the implementation of TCSC the line reactance changes, thereby changing the power flow between bus-i and bus-j given by Equations (5) and (6).

$$P'_{ij} = V_i^2 G'_{ij} - V_i V_j [G'_{ij} \cos(\delta_{ij}) + B'_{ij} \sin(\delta_{ij})]$$  \hspace{1cm} (5)$$

$$Q'_{ij} = -V_i^2 (B'_{ij} + B'_{sh}) - V_i V_j [G'_{ij} \sin(\delta_{ij}) + B'_{ij} \cos(\delta_{ij})]$$  \hspace{1cm} (6)$$

where $P'_{ij}$ and $Q'_{ij}$ are active and reactive power flow between bus-i and bus-j, respectively when TCSC is installed. Similarly, $G'_{ij}$ and $B'_{ij}$ are the conductance and susceptibility of transmission line connected between bus-i and bus-j with TCSC connected to the line respectively and is given as:

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

and

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

where $r_{ij}$ and $x_{ij}$ are resistance and reactance of the line connected between bus-i and bus-j respectively and $x_c$ is the reactance of the TCSC.

Generally, a congestion management problem employs static model of FACTS device injecting power at sending and receiving end of line.33 According to this model FACTS device can be represented as PQ element injecting definite amount of power to the specific node. Figure 3 shows the power injection model of TCSC.

The real power $P'_i$ and $P'_j$ injected at bus-i and bus-j, respectively, due to implementing TCSC is given by Equations (7) and (8).
Similarly the reactive power $Q'_i$ and $Q'_j$ injected at bus-i and bus-j, respectively, after implementing TCSC is given by Equations (9) and (10).

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

(9)

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

(10)

where

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

and

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

Thus any variations in the power flow through the lines due to the series PQ element can be represented as a line without series PQ element, with power injected at the receiving and sending ends of the line, as shown in Figure 3.

3 Problem Formulation for Congestion Management using TCSC

In pre-deregulated era, the power system is operated with economic dispatch as main objective. With the paradigm shift in electricity market post-deregulation, this objective is associated with others to achieve economy in the operating cost. In the previous work, attempts were made to combine the FACTS device cost with the generation cost. To exploit the present scenario of electricity market in order to achieve efficient and economic operation, the problem is formulated to include penalty factors in the proposed work. The main objective of this work is to manage congestion by optimally placing TCSC in the power system network. This is achieved by minimizing the generation cost and TCSC installation cost along with penalty cost for violation of line flow limits and bus voltage limits due to congestion. The objective function is given by Equation (11).

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

(11)

where

$$C_{TCSC} = C_t \times S \times 1000 \ \ ($/hr)$$

(12)

$$C_t = 0.0015 \ S^2 - 0.7135 \ S + 153.75 \ ($/kVar)$$

(13)

$$S = |Q_1 - Q_2|$$

(14)
where $C_i(P_i)$ is the cost of real power generation by the generators in ($$/hr$).

$C_{TCSC}$ is the installation cost of TCSC in $$/hr$.

$C_i$ is the cost of TCSC $$/kVar$.

$S$ is the operating range of TCSC in MVar.

$Q_1$ and $Q_2$ are the reactive power flow in the line before and after installation of TCSC.

$\lambda_1$ and $\lambda_2$ 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 congestion management problem given by Equation (11) is formulated as an OPF problem which is subjected to the constraints presented in Reference 34 such as power balance, power generation limit, bus voltage magnitude, and angle limit TCSC reactance limit and line limit. The proposed OPF problem is similar in formation to the conventional OPF problem but differs in some aspects presented in Table 1. The relation to find the cost of TCSC is presented by Equations (12) to (14). 34,36

The objective function comprises of two parts. The first part combines the generation cost and 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:

$$VLV = \left( \frac{V_b - V_{ref}}{V_{ref}} \right)^2, \quad \text{if } V_b < V_{ref}^{min} \text{ or } V_b > V_{ref}^{max}$$  \hspace{1cm} (15)

$$= 0 \quad \text{if } V_{ref}^{min} < V_b < V_{ref}^{max}$$  \hspace{1cm} (16)

$$FLV = \left( \frac{P_{ij} - P_{ij}^{max}}{P_{ij}^{max}} \right)^2, \quad \text{if } P_{ij} > P_{ij}^{max}$$  \hspace{1cm} (17)

$$= 0 \quad \text{if } P_{ij} < P_{ij}^{max}$$  \hspace{1cm} (18)

where $P_{ij}^{max}$ represents the power flow limit of line connected between bus-i and bus-j.

$V_b$ represents bus voltage obtained by power flow solution.

$V_{ref}$ represents bus reference voltage and $V_{ref}^{min}$ and $V_{ref}^{max}$ represent the min and maximum value of bus reference voltage, respectively.

The reactance $X_{ck}$ 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 line31. The voltage $V_{ref}^{min}$ is taken as 0.94 pu while $V_{ref}^{max}$ is taken as 1.06 pu.

### 4 | OPTIMAL PLACEMENT OF TCSC

FACTS devices involve a hefty investment for installation. Therefore, their appropriate location and size play a very vital role in managing congestion efficiently. Otherwise, it would not be beneficial in comparison to other congestion management techniques. Citing these facts, the size and location of FACTS devices are considered to be important aspects which play an important role in minimizing their investment cost. These parameters must be chosen very precisely.37
In this article, TCSC is optimally placed in the system based on LSF which is a measure of the sensitivity of the power flow over the lines. LSF 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, LSF with respect to the parameters of TCSC placed at line-k can be defined as:

\[
\text{LSF}_k^c = \left( \frac{\partial P_{LT}}{\partial X_{ck}} \right)_{X_{ck}=0}
\]  

(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 LSF 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:

\[
\text{LSF}_k^c = C_{ij} [-V_i^2 + V_i V_j \cos \delta_{ij}] - D_{ij}[V_i V_j \sin \delta_{ij}]
\]

(20)

where

\[
C_{ij} = \left( \frac{-2r_i x_{ij}}{r_i^2 + x_{ij}^2} \right)
\]

\[
D_{ij} = \left( \frac{r_i^2 - x_{ij}^2}{(r_i^2 + x_{ij}^2)^2} \right)
\]

Once the optimal location of TCSC is found, its optimal setting for congestion alleviation is found using PSO algorithm shown in Figure 4. PSO is chosen to solve the proposed problem due to its proven ability in solving similar type of power system problems.\(^3^7\)

The algorithm presented in Figure 4 is discussed in detail as below:

Step 1: Bus and line data of the system are given as input to obtain power flow solution.
Step 2: Power flow solution and the limit violation factors are obtained without using TCSC in the network.
Step 3: Location for placement of TCSC is determined using Equation (20).
Step 4: PSO parameters and convergence criterion for the algorithm are specified.
Step 5: Reactance setting of TCSC is selected as control variable and its boundary limits are specified.
Step 6: The population of the particles are randomly generated with initial position and velocity and the iteration count is set at 1.
Step 7: The fitness of the particles is evaluated using objective function given by Equation (11).
Step 8: The “personal best” (P\(_{\text{best}}\)) and “global best” (G\(_{\text{best}}\)) value of the particle is obtained.
Step 9: The position and velocity of the particles are updated using below equations\(^3^7\):

\[
V_{n+1}^t = w V_n^t + c_1 r_1 (P_{\text{best}}^t - X_n^t) + c_2 r_2 (G_{\text{best}}^t - X_n^t)
\]

(21)

\[
X_{n+1}^t = X_n^t + V_{n+1}^t
\]

(22)

where, \(w\) is a positive value called inertia weight and is given as

\[
w = (w_{\text{max}} - w_{\text{min}}) \left( \frac{t_{\text{max}} - t}{t_{\text{max}}} \right) + w_{\text{min}}
\]

The states of the particles are updated repeatedly according to the above equations until the convergence criterion is satisfied.
**FIGURE 4** Flowchart of PSO algorithm

\[ w_{\text{max}} \text{ and } w_{\text{min}} \] are maximum and minimum values of inertia weight.
\[ r_1 \text{ and } r_2 \] are random values between 0 and 1.
\[ c_1 \text{ and } c_2 \] are called acceleration coefficients.
\[ t \text{ and } t_{\text{max}} \] represent the iteration count and maximum number of iteration count.
\[ X_n \text{ and } V_n \] represent the position and velocity of \( n \)th particle.

Step 10 : If the maximum iteration count or specified convergence criterion is reached, the position of the global best particle obtained is the optimal solution. Otherwise increase the iteration count and go to step 7.

Step 11 : The obtained \( G_{\text{best}} \) value of the particle is the optimal reactance setting of TCSC and the corresponding value of the fitness function is the optimal value of generation cost of the system.

5 | RESULTS AND DISCUSSIONS

The measure of sensitivity of the power flow over line gives an indication of their loading. The FACTS devices are preferred to be placed on the most sensitive line. With the sensitivity factor computed for TCSC, the TCSC should be placed in a line having the most negative value of LSF. The effectiveness and robustness of the proposed method is tested on IEEE 30-bus, IEEE 118-bus systems, and 33-bus Indian network. The obtained results are compared with those presented by Khan and Siddiqui. The solution of the formulated problem is achieved using PSO developed in MATLAB language as illustrated earlier. The values of various parameters taken for PSO are given in Table 2.
**TABLE 2** PSO parameters values

| PSO Parameters | Values |
|----------------|--------|
| $w_{\text{min}}$ | 0.4    |
| $w_{\text{max}}$ | 0.9    |
| $c_1$ | 2      |
| $c_2$ | 2      |
| Maximum iterations | 500    |
| Particle size | 70     |

**FIGURE 5** LSF values for IEEE 30-bus system

**TABLE 3** LSF values of IEEE 30-bus system for congested line-1

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

**TABLE 4** Power flow in congested line of IEEE 30-bus system for different locations of TCSC

| Location of TCSC | Power flow in p.u. |
|------------------|--------------------|
| Line-2           | Line-3             | Line-6             |
| Without TCSC     | 1.010              | 0.919              | 0.980              | 0.993              |

**5.1 IEEE 30-bus system**

The data of IEEE 30-bus system is presented in Reference 39. The load flow solution performed on the test system gives that line-1 (connected between bus-1 and bus-2) is congested. The power flow through this line is 1.010 pu. The LSF values for different lines of the system with respect to TCSC control parameter are computed corresponding to the congested line and is plotted in Figure 5. The priority list of TCSC locations based on negative LSF values are observed that line-2, line-3, and line-6 have high negative values of LSF as compared to other lines and their values are presented in Table 3. Therefore, these lines are ranked at the top in the priority ranking to locate TCSC for congestion alleviation. Line-2 is ranked highest for its large negative value of sensitivity factor. Hence, it is selected for placement of TCSC to achieve the defined objective. For this particular location of TCSC, it is obtained that the congestion from the system is managed effectively with TCSC control parameter setting of 0.06278 pu as shown in Table 4. The power flow through the earlier congested line is well within its limit.

Moreover, the performance of the proposed algorithm in for capturing other potential locations of TCSC is also analyzed. Line-3 and line-6 being next to line-2 in the priority ranking are considered. The control parameter values for these two locations of TCSC are obtained as 0.2866 and 0.0161 pu, respectively. These locations and settings of TCSC control parameters bring back the line flow within its limit as shown in Table 4. Hence, the placement of TCSC with the proposed
method utilizes the available transfer capacity of the lines more appropriately. The load flow results of the system with TCSC in the captured potential locations gives that the congestion is effectively relieved from the system as illustrated in Figure 6.

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 due to high installation cost involved with it. In order to analyze its cost effective location among various potential locations, it should be allocated such that its minimum installation cost is achieved which would further minimize the system generation cost.

The installation cost of TCSC for different potential locations is calculated using Equations (12) to (14). The cost–benefit analysis results are presented in Table 5 which reveals that placement of TCSC in line-2 provides the lowest TCSC installation cost as well as system generation cost as compared to its other potential locations. For this particular location, a significant benefit of 3.2% and 8.5% in net saving of generation cost is achieved when compared to location of TCSC in line-3 and line-6 respectively. Hence, the proposed method captured the optimal location to allocate TCSC which gives minimum cost as well as system generation cost as compared to other locations.

### 5.2 33-bus Indian network

A 33-bus Indian network is considered to analyze the effectiveness of the proposed method for analysis on a practical network. The data for the system are taken from Reference 38. The congested line is identified through load flow solution. It is observed that line-18 (connected between bus-8 and bus-23) is congested as the power flow through it is 1.036 pu which is above its thermal limit. LSF values evaluated for different lines of the system corresponding to congested line-18 are plotted in Figure 7. It is found that line-2, line-14, and line-19 (connected between bus-1 and bus-33, bus 12 and bus-31, bus-8 and bus-22, respectively) have high negative values of LSF as compared to other lines, the values of which are listed in Table 6. Therefore, these lines are selected to have highest priority for the allocation of TCSC in order to mitigate congestion. Hence, line-2, having the highest negative value of sensitivity factor and at the top of the priority table, is selected for placement of TCSC to manage congestion.

After placing TCSC in line-2, it is found that the congestion is effectively alleviated from the system for its reactance setting of 0.00419 pu as shown in Figure 8. For this setting of TCSC, the power flow through initially congested line (line-18) is shown in Table 7. The performance of the proposed algorithm is also analyzed by placing TCSC at other potential locations i.e. in line-14 and line-19. It is observed that for reactance setting of TCSC in line-14 and line-19 at 0.00250 and 0.00347 pu, respectively, the congestion is effectively alleviated from the system. The percentage line loading
**Figure 7** LSF values for 33-bus Indian network

**Table 6** LSF values of 33-bus Indian network for congested line-18

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

**Figure 8** Percentage line loading for 33-bus Indian network

**Table 7** Power flow in congested line of 33-bus Indian network for different locations of TCSC

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

of the system for these two locations of TCSC is plotted in Figure 8. Nevertheless, these two locations of TCSC placement are also effective in managing the power flow through congested line as shown in Table 7.

Now the cost–benefit analysis for these potential locations of TCSC placement has been performed and the results are given in Table 8. It is observed that placement of TCSC in line-2 provides both minimum cost of generation as well as minimum cost of TCSC installation as compared to other potential locations. A significant benefit of 6.6% and 9.1% in net saving of generation cost is achieved when TCSC is placed in line-2 as compared to line-14 and line-19, respectively. Thus, the proposed method efficiently captures the optimal allocation of TCSC for managing congestion.

Furthermore, to analyze the performance and robustness of the proposed method, the results obtained are compared with those reported by Khan and Siddiqui. The authors have adopted a sensitivity loss method based on which the line having most positive loss sensitivity factor is selected to place TCSC for managing congestion. According to this method, line-44 is reported to have maximum positive value of loss sensitivity factor. Therefore, the authors have chosen to place
| Location of TCSC | Installation cost of TCSC ($/KVAR) | Total generation cost ($/hr) | Cost saving ($/hr) |
|-----------------|------------------------------------|-----------------------------|-------------------|
| Without TCSC    | —                                  | 108,062.4                   | —                 |
| Line-2          | 155.1                              | 107,731.2                   | 331.2             |
| Line-14         | 166.7                              | 107,753.1                   | 309.3             |
| Line-19         | 172.2                              | 107,761.3                   | 301.1             |

**TABLE 8**: Cost–benefit analysis results for 33-bus Indian network

**TABLE 9**: Result comparison for 33-bus Indian network

| TCSC location priority | Proposed method | System condition | Method reported in Reference 38 | 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 10**: Location priority ranking

| TCSC location | Priority rank | Proposed method | Method reported in Reference 38 |
|---------------|---------------|-----------------|---------------------------------|
| Line-2        | 1             | 39              |                                 |
| Line-14       | 2             | 44              |                                 |
| Line-19       | 3             | 21              |                                 |

TCSC in line-44 and tried to alleviate congestion. However, the reported results show that for this particular location of TCSC placement does not alleviate congestion from the system. Therefore, the authors have selected another location from the location priority table prepared based on positive value loss sensitivity factor. 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 9. Thus, the reported method is based on hit and trial which consumes a lot of time in order to find the optimal location of TCSC. While in this article, the optimal location for TCSC placement is captured more efficiently 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 9. Moreover, the potential locations obtained with the proposed method are ranked very low in location priority by the method reported by Khan and Siddiqui\(^3\) as shown in Table 10. Further, the installation cost of TCSC evaluated with the proposed method is $155.14$/KVAR which is significantly lower than that reported in Reference 38 as shown in Table 11. Hence, the proposed method captures more optimal location for allocation of TCSC as compared to the method reported in Reference 38.
TABLE 11  TCSC installation cost comparison

| Proposed method | Method reported in Reference 38 |
|-----------------|--------------------------------|
| TCSC installation cost ($/KVAR) | 155.14 | 241.74 |

FIGURE 9  LSF values for IEEE 118-bus system

TABLE 12  LSF values of IEEE 118-bus system for congested line-81

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

FIGURE 10  Percentage line loading for IEEE 118-bus system

5.3  IEEE 118-bus system

The proposed method proved to be effective in managing congestion for two smaller systems. To further show its effectiveness on a larger network, a modified IEEE 118-bus system is considered. The data of the system are taken from Reference 39. The system is modified to have bus-1 as slack bus. The load flow solution performed on the system gives that line-81 (connected between bus-49 and bus-66) is congested. The power flow through the line is found to be 0.409 pu above its thermal limit. LSF values corresponding to the congested line is evaluated and plotted in Figure 9. It is 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 LSF while other lines have low values. Therefore, these lines topped the priority ranking for the placement of TCSC and analyzed for their effectiveness in mitigating congestion from the system. The LSF values for these lines are listed in Table 12. Hence, line-99, having the highest negative value of sensitivity factor, is first selected to place TCSC for managing congestion. It is observed that for optimal reactance setting of TCSC at 0.2897 pu, the congestion from the system is managed effectively as shown in Figure 10. The power flow through the previously congested line is well within its thermal limit as shown in Table 13.
TABLE 13 Power flow in congested line of IEEE 118-bus system for different locations of TCSC

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

The other potential locations as given in Table 11 are also examined to show the robustness of the proposed method in capturing the potential locations for TCSC placement. It is obtained that by placing TCSC in line-105, the congestion is alleviated from the system at its reactance setting 0.2973 pu. Similarly, with TCSC in line-106, congestion is alleviated from the system at its reactance setting of 0.3051 pu as shown in Figure 10. The power flow through the previously congested line corresponding to these two locations of TCSC is well within its maximum limit as shown in Table 13. Hence, the proposed method effectively manages congestion from the system for the captured potential location of TCSC.

Moreover, the cost–benefit analysis for these potential locations is carried out to show the effectiveness of the proposed method on larger networks. The cost–benefit analysis results are shown in Table 14. TCSC installation cost and generation cost are found to be minimum when TCSC is placed in line-99. There is a considerable saving in the generation cost for this location as compared to other two locations in the priority table. Hence, the method is found to be efficient in capturing the TCSC location and managing congestion.

Furthermore, a comparative study of the results obtained with the proposed method and those obtained with the method reported in Reference 38 is carried out for the considered system. With the loss sensitivity method, line-14 is found to have the highest positive value of loss sensitivity factor and therefore topped the priority list of TCSC locations. However, the power flow results show that placement of TCSC in this particular line does not alleviate congestion from the system. Therefore, next line from location priority list prepared based on loss sensitivity factor is selected for TCSC and checked for its effectiveness in managing congestion. 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 33rd in location priority list as shown in Table 15. Also, the highest priority ranked location of TCSC for management of congestion with the proposed method is ranked 35th according to the method reported in Reference 38. Thus the proposed method captures the optimal location for TCSC placement more efficiently as compared to loss sensitivity method. Likewise, the TCSC placement at other lower ranked locations found with the proposed method also manages congestion effectively as discussed above. Moreover, the potential locations obtained with the proposed method are ranked very low in location priority list in Reference 38 as shown in Table 16. The installation cost of TCSC evaluated with the proposed method is 155.14 $/KVAR which is considerably lower than that obtained with method reported in Reference 38 and is shown in Table 17. Thus the proposed method provides more optimal allocation of TCSC as compared to the method reported in Reference 38.

6 PERFORMANCE EVALUATION OF PSO

The application of PSO in optimizing the congestion management problem is presented in Reference 40. In fact, OPF problem is one of the practical non-linear power system problems, the solution of which develops interests among a number of researchers. The researches try to be rational in their approaches to get the solution of this problem as their main objective irrespective of the execution time. They even do not analyze the performance of the solution algorithm...
### Table 15 Result comparison for IEEE 118-bus system

| TCSC Location priority | Proposed method | Method reported in Reference 38 |
|------------------------|-----------------|----------------------------------|
|                        | 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 16 Location priority ranking

| TCSC location | Priority rank |
|---------------|---------------|
|               | Proposed method | Method reported in Reference 38 |
| Line-99       | 1             | 35                             |
| Line-105      | 2             | 41                             |
| Line-106      | 3             | 33                             |

### Table 17 TCSC installation cost comparison

| TCSC Installation Cost ($/KVAR) | Proposed method | Method reported in Reference 38 |
|--------------------------------|-----------------|---------------------------------|
| 210.61                        |                 | 261.15                          |

Considering number of fitness evaluations that it would take to find an optimal solution. They are only interested in the mean best solution. In order to show the robustness of the particular algorithm, one must consider all these performance parameters along with mean best solution. Hence in this article, the performance of the PSO algorithm is analyzed in terms of mean best solution, success rate (SR), number of fitness evaluations (NFE), and mean execution time ($T_{mean}$).\(^{41}\)

Further, the algorithm is run for 50 trial simulations with swarm size and other PSO parameters mentioned in Table 2. The minimum, maximum, and mean value of fitness function, that is, total generation cost are noted and presented in Table 18. The number of successful runs is also recorded for these trial simulations. It is assumed here that the successful run is achieved when the algorithm converges to its minimum value less than or equal to the mean fitness value when the maximum number of iteration count is achieved. The SR and NFE are evaluated according to Equations (23) and (24), respectively\(^{42}\) and their values are presented in Table 19.

\[
SR = \frac{S_{times}}{TS_{runs}} \quad (23)
\]

\[
NFE = P_{size} \times \frac{t_{avg}}{SR} \quad (24)
\]
| Test systems                | Test systems | Performance parameters |
|-----------------------------|--------------|------------------------|
| Total generation cost ($/hr)| Maximum value| Minimum value | Mean value |
| IEEE 30-bus | 2953.9 | 2135.6 | 2469.1 |
| IEEE 118-bus | 8764.2 | 7857.5 | 8371.1 |
| 33-bus Indian network | 109, 835.1 | 105, 529.3 | 107, 731.2 |

**TABLE 18** Statistical results

| Test systems                | Performance parameters |
|-----------------------------|------------------------|
| Test systems | SR (%) | NFE | T<sub>mean</sub> (sec) |
| IEEE 30-bus | 88 | 24,357 | 89.53 |
| IEEE 118-bus | 74 | 12,997 | 117.42 |
| 33-bus Indian network | 84 | 18,800 | 96.39 |

**TABLE 19** Performance analysis of PSO for different systems

where \( S_{\text{times}} \) is the number of times the success criteria is achieved over total independent trial runs, \( TS_{\text{runs}} \) is the total number of independent trial runs, that is, 50, \( P_{\text{size}} \) is the population size, \( t_{\text{avg}} \) is the average number of iteration the success criteria is achieved over independent trial runs.

It is observed from Table 18 that IEEE 30-bus system has highest success rate followed by 33-bus Indian network and IEEE 118-bus system. Similarly, the algorithm gives the highest fitness evaluation for IEEE 30-bus system followed with 33-bus Indian network and IEEE 118-bus system. The algorithm is run on system having 2.00 GHz processor and 4 GB RAM. The mean time of execution of algorithm for different systems is also shown in Table 18. Hence, it can be concluded that the algorithm performs better for smaller test systems.

Further, the convergence characteristics are shown in Figure 11 for analyzing the effectiveness of the algorithm in obtaining solution of the proposed problem. The generation cost obtained for 33-bus Indian network is scaled down to draw the characteristic on same plot. The algorithm converges to optimum solution at 192, 270, and 352 iterations for IEEE 30-bus system, 33-bus Indian network, and IEEE 118-bus system, respectively. From here too, it is observed that the algorithm converges more rapidly for a smaller system.

7 | CONCLUSION

The main aim of the proposed work is to effectively alleviate congestion from transmission line while achieving electricity market economics. This is achieved through implementation of TCSC whose static model is considered in the problem formulation. Since FACTS devices involve a huge investment, its optimal location plays a significant role in reducing its cost and achieving the market economics. Therefore a new sensitivity index “LSF” is proposed to optimally locate TCSC.
in the transmission network. The calculation of LSF is based on the change in power flow through lines with respect to TCSC control parameters. It is evaluated for each line based on which the optimal location of TCSC is determined. The optimal reactance setting of TCSC is obtained using PSO. The effectiveness of the proposed method is measured in terms of the cost of TCSC installation as well as total generation cost. Three different test systems which are IEEE 30-bus system, IEEE 118-bus system, and 33-bus Indian network are considered for the implementation of the proposed work. It is observed from test results that LSF captures the potential locations for the allocation of TCSC more efficiently than the method reported in literature. The placement of TCSC in most sensitive line determined from LSF values gives minimum installation cost of TCSC as well as minimum generation cost when compared with other potential locations for TCSC placement. Hence, a significant saving in the TCSC installation cost and generation cost is achieved through the proposed method. Since PSO is a stochastic optimization algorithm, its performance is also analyzed based on different parameters such as mean fitness value, success rate, number of fitness evaluation, and mean execution time. The algorithm is found to be effective for both for small as well as large power system network. The proposed work can be extended to include power loss in future. Also, a comparison of different optimization algorithms to find optimal solution can be performed.

CONFLICT OF INTEREST
Authors have no conflict of interest relevant to this article.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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