This paper proposes two new methodologies for the placement of series FACTS devices in deregulated electricity market to reduce congestion. Similar to sensitivity factor based method, the proposed methods form a priority list that reduces the solution space. The proposed methodologies are based on the use of LMP differences and congestion rent, respectively. The methods are computationally efficient, since LMPs are the by-product of a security constrained OPF and congestion rent is a function of LMP difference and power flows. The proposed methodologies are tested and validated for locating TCSC in IEEE 14-, IEEE 30- and IEEE 57-bus test systems. Results obtained with the proposed methods are compared with that of the sensitivity method and with exhaustive OPF solutions. The overall objective of FACTS device placement can be either to minimize the total congestion rent or to maximize the social welfare. Results show that the proposed methods are capable of finding the best location for TCSC installation, that suite both objectives.

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Keywords: Congestion rent; LMP; OPF; TCSC

1. Introduction

Increasing attention has been given to application of FACTS devices in power systems in the recent past, as these devices are proven to be a promising solution for various power system problems. One pertinent issue related to FACTS application is the selection of appropriate location. Proper location is a key to maximize the benefits of the expensive FACTS devices.

Deregulation of electric utilities around the globe has changed the way the utilities have been operating their power system through years. Under the new framework, placement of new generating stations goes under the hand of private entities and is driven by the market forces and strict environmental constraints. It used to be determined based on integrated planning studies under the traditional “vertically integrated” utility structure. The competition in electricity trading has also lead to an increased volume of electricity trade. In some deregulated markets, the GENCO and DISCO pair can independently negotiate power transactions. This situation leads to an unexpected amount, direction and length of power flow through some transmission corridors. The present transmission networks, however, are not built to accommodate such trade. It is further endangered by the relative decline in transmission investment [1], problems in acquiring right of way for new transmission facilities and the concern towards environment. This may create congestion and violate system security. In deregulated markets, the economics of supply and demand governs the prices at each bus and with stiff constraints enforced in transmission line, effects are directly reflected in the prices (LMP) being high. The market participants can abuse the “market power” because of high price due to congestion and make more profit. It ultimately hinders the development of competitive electricity market and reduces the social welfare.

FACTS devices (especially series FACTS devices like TCSC) are considered one such technology that reduces the transmission congestion and allows better utilization of the existing grid infrastructure, along with many other benefits [2]. Various issues associated with the use of FACTS devices are proper location, appropriate size and setting, cost, modeling and controller interactions. This paper deals with the location aspect of the series FACTS devices, especially to manage congestion in the deregulated electricity markets.
The location of FACTS devices can be based on static or dynamic performances of the system. The sensitivity factor methods are generally used to find the best location to enhance the static performance of the system. In [3], an overload sensitivity factor (power flow index) is used for optimal location of series FACTS devices (i.e. TCSC and TCPAR) for static congestion management. A loss sensitivity factor method is used in [4] to determine the suitable location for FACTS devices. The disadvantage of these methods is that it may not capture the non-linearity associated with the system. The enumerative procedures combined with sensitivity analysis have been studied in [5], with the location decision made after evaluating all possibilities. For large systems, the enumerative approach is not practical given the large number of combinations that have to be examined. In [6] the Tabu search method and in [7] the Genetic algorithm is used to solve the combinatorial (i.e. to determine number and location) problem of FACTS device allocation. However, these methods are computationally demanding and less reliable.

This paper presents the new methodologies for proper location of series FACTS devices for congestion management in the deregulated electricity markets. These methods make use of economic signal given as LMP. The LMP based market is gaining popularity in recent years and is the preferred way of pricing energy and managing congestion in many deregulated electricity markets. The proposed methods are applicable to any type of series FACTS devices, however, in the paper they are used to locate TCSC. A pool type of market is considered in the paper, which is then modeled in OPF. The results are then compared with the established method based on sensitivity factor method [3].

The rest of the paper is organized as follows: Section 2 describes the importance of FACTS device location and sizing in the deregulated markets. Section 3 presents the formulation of OPF incorporating TCSC and the solution approach used to solve OPF. The proposed placement methodologies for series FACTS devices in deregulated market are described in Section 4. Numerical results along with some observations and discussions are presented in Section 5. Finally, the major contributions and conclusions of the paper are summarized in Section 6.

2. Location and sizing of FACTS devices

The best location, appropriate size and setting of FACTS devices are important in the deregulated electricity markets. On one hand, there is considerable risk in the investment of FACTS devices because of the high cost of FACTS devices [8] and the uncertain market transactions. There is a need to maximize the benefit from investment in FACTS devices. On the other hand, the location and setting of FACTS devices have direct and discriminatory impact on the market participants. Implementation of these devices can distort the prices at buses, directly affecting some generators and loads [9]. Therefore, the location and setting of FACTS devices require crucial consideration in the deregulated markets.

The location of FACTS devices can be based on static and/or dynamic performance of the system. The best placement of FACTS controllers to improve the dynamic performance requires the eigen value analysis and time domain simulation with proper dynamic modeling of FACTS controllers. For improving static performance, sensitivity factor method is generally used with the static modeling of FACTS devices. In static modeling, series FACTS device like TCSC is modeled simply as a series capacitor or reactor, which greatly simplifies the computation. This paper is concerned on the static aspect of the FACTS device location.

From static point of view, the placement of FACTS devices is to reduce the congestion and/or system losses. However, with congestion in the system, security and stability are issues that are more important than reducing losses. Congestion occurs because of the lines reaching the thermal limits and/or the voltage limits. When a system becomes congested, the effects are reflected in the prices and LMP increases. The difference in LMP across an interface gives a measure of degree of congestion across the link. Higher is the difference in LMP, the more the link is congested. Either the congested link or the neighborhood lines are the potential locations for installing series FACTS devices to reduce the level of congestion. This forms the basis of the proposed methods.

Sizing of FACTS devices is also important because cost of FACTS device is proportional to size. The sizing problem during the planning stage is to find the optimum size which gives the desired control objectives and at the same time with minimum investment. It is also necessary to assure the secure operation of the network for the likely transactions during the planning horizon and has the capacity to support the network during worst contingencies. In case of series FACTS devices like TCSC, once the location is optimized, some hint about the size can be obtained from the compensation level for that line. For static case, the maximum compensation allowed is generally limited to 70% of the reactance of the line [7,10]. However, the optimum result may be obtained at much less compensation level, which can be ascertained only from simulation of various scenarios. During the operational stage, the sizing problem is greatly simplified, as now the problem is to find the set point of the TCSC that meets the desired objective. The objective in the deregulated markets is to maximize the social welfare (or to minimize the total generation cost where there is no demand bidding). The set point for TCSC can be determined by incorporating TCSC in the OPF formulation.

3. Optimal power flow (OPF) with TCSC

3.1. Modeling of TCSC

For static applications, FACTS devices can be modeled by Power Injection Model (PIM) [11,12]. The injection model describes the FACTS as a device that injects a certain amount of active and reactive power to a node, so that the FACTS device is represented as PQ elements. The advantage of PIM is that it does not destroy the symmetrical characteristic of the admittance matrix and allows efficient and convenient integration of FACTS devices into existing power system analytical tools [11].
Fig. 1 shows a model of transmission line with TCSC connected between buses \(i\) and \(j\). The transmission line is represented by its lumped \(\pi\)-equivalent parameters connected between the two buses. During steady state, the TCSC can be considered as a static reactance \(-jx_c\). The controllable reactance \(x_c\) is directly used as the control variable in the power flow equations.

The corresponding power injection model of TCSC incorporated within the transmission line is shown in Fig. 2. The real and reactive power injections due to series capacitor (TCSC) at buses \(i\) and \(j\) are given by the following equations [3]:

\[
P_{ij}^F = V_i^2 \Delta G_{ij} - V_iV_j[\Delta G_{ij}\cos(\delta_i - \delta_j) + \Delta B_{ij}\sin(\delta_i - \delta_j)]
\]

(1)

\[
Q_{ij}^F = -V_i^2 \Delta B_{ij} - V_iV_j[\Delta G_{ij}\sin(\delta_i - \delta_j) - \Delta B_{ij}\cos(\delta_i - \delta_j)]
\]

(2)

\[
P_{ij}^F = V_j^2 \Delta G_{ij} - V_iV_j[\Delta G_{ij}\cos(\delta_i - \delta_j) - \Delta B_{ij}\sin(\delta_i - \delta_j)]
\]

(3)

\[
Q_{ij}^F = -V_j^2 \Delta B_{ij} + V_iV_j[\Delta G_{ij}\sin(\delta_i - \delta_j) + \Delta B_{ij}\cos(\delta_i - \delta_j)]
\]

(4)

where

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

(5)

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

(6)

In the present study, the above model is incorporated in the OPF. The maximum compensation by TCSC is limited to 70% of the reactance of the un-compensated line where TCSC is located [7,10].

### 3.2. OPF formulation

OPF tool has also been used in pool based deregulated electricity markets to calculate generation dispatch and load schedules, to price energy (nodal pricing or LMP) and to manage congestion in the systems. It is based on bids submitted by the generators and loads (if price elastic demand) and the network data. The generally accepted objective is to maximize the social welfare (or to minimize the generation cost if loads are inelastic).

In a centralized pool based market, the central dispatcher optimally dispatches the generators such that the total social welfare is maximized while satisfying the operational and security related constraints. The problem is stated mathematically as

\[
\min_{P_G} \sum_{i=1}^{N_G} C_G(P_G) - \sum_{i=1}^{N_D} B_D(P_D)
\]

Subject to:

Power balance equation

\[
P_i(\theta, V) - P_{G_i} + P_{D_i} = 0, \quad \text{for any node } i,
\]

\[
Q_i(\theta, V) - Q_{G_i} + Q_{D_i} = 0, \quad \text{for any node } i
\]

If TCSC is located in line between buses \(i\) and \(j\), the power balance equations in nodes \(i\) and \(j\) are given by

\[
P_i(\theta, V) - P_{G_i} + P_{D_i} + P_{ij}^F = 0, \quad \text{for node } i,
\]

\[
Q_i(\theta, V) - Q_{G_i} + Q_{D_i} + Q_{ij}^F = 0, \quad \text{for node } i
\]

Apparent line flow limit

\[
|S_{ij}(\theta, V)| \leq S_{ij}^{\max}
\]

Power generation limit

\[
P_{G_i}^{\min} \leq P_{G_i} \leq P_{G_i}^{\max}
\]

\[
Q_{G_i}^{\min} \leq Q_{G_i} \leq Q_{G_i}^{\max}
\]

Bus voltage limit

\[
V_i^{\min} \leq V_i \leq V_i^{\max}
\]

TCSC reactance limit

\[
x_c^{\min} \leq x_c \leq x_c^{\max}
\]

where \(N_G\) and \(N_D\) are the number of generators and loads respectively, \(C_G(P_G)\) is the bid curve of \(i\)th generator, \(B_D(P_D)\) is the benefit curve for the \(i\)th demand, \(P_{G_i}^{\min}\) and \(P_{G_i}^{\max}\) are minimum and maximum active power generation limits of generating unit at bus \(i\), \(Q_{G_i}^{\min}\) and \(Q_{G_i}^{\max}\) are minimum and maximum reactive
power generation limits of generating unit at bus \(i\), \(V_{i}^{\text{min}}\) and \(V_{i}^{\text{max}}\) are minimum and maximum voltage limits at bus \(i\), \(S_{ij}\) is the apparent power flow in transmission line connecting nodes \(i\) and \(j\), and \(S_{ij}^{\text{max}}\) is its maximum limit, \(P_{Gi}\) and \(Q_{Gi}\) are the active and reactive power generation at node \(i\), \(P_{Di}\) and \(Q_{Di}\) are the active and reactive power load at node \(i\), \(x_{c}^{\text{min}}\) and \(x_{c}^{\text{max}}\) are the minimum and maximum limits of TCSC reactance, and \(N\) is the number of nodes in the system.

In this work, it is assumed that the load is inelastic. This is actually the case with most of the deregulated electricity markets. Therefore, the social welfare function given by Eq. (7) becomes total cost of supplying electricity. However, the formulation can be easily extended to include demand bids to maximize the social welfare.

### 3.3. Solution technique

The Lagrange function of the optimization problem incorporating all the constraints in the objective function is formed as

\[
L = \sum_{i=1}^{N_{G}} C_{Gi}(P_{Gi}) + \sum_{i=1}^{N} \lambda_{P}(P_{i} - P_{Gi} + P_{Di} + P_{i}^{F}) + \sum_{i=1}^{N} \lambda_{Q}(Q_{i} - Q_{Gi} + Q_{Di} + Q_{i}^{F}) + \sum_{i=1}^{N_{L}} \mu_{Lij}(S_{ij} - S_{ij}^{\text{max}}) + \sum_{i=1}^{N_{G}} \mu_{P}^{\text{min}}(P_{Gi} - P_{i}^{\text{min}}) + \sum_{i=1}^{N_{G}} \mu_{P}^{\text{max}}(P_{i} - P_{Gi}^{\text{max}}) + \sum_{i=1}^{N_{G}} \mu_{Q}^{\text{min}}(Q_{Gi} - Q_{i}^{\text{min}}) + \sum_{i=1}^{N_{G}} \mu_{Q}^{\text{max}}(Q_{i} - Q_{Gi}^{\text{max}}) + \sum_{i=1}^{N} \mu_{x_{c}}^{\text{min}}(V_{i} - V_{Gi}) + \sum_{i=1}^{N} \mu_{x_{c}}^{\text{max}}(V_{Gi} - V_{i}^{\text{max}}) + \mu_{x_{c}}^{\text{min}}(\lambda_{P}^{\text{min}} - \lambda_{P}) + \mu_{x_{c}}^{\text{max}}(\lambda_{P} - \lambda_{P}^{\text{max}}) + \mu_{x_{c}}^{\text{min}}(\lambda_{Q}^{\text{min}} - \lambda_{Q}) + \mu_{x_{c}}^{\text{max}}(\lambda_{Q} - \lambda_{Q}^{\text{max}})
\]

where \(\lambda_{P}\) and \(\lambda_{Q}\) are the Lagrange multipliers associated with the equality constraints (power balance equations) and \(\mu_{L}, \mu_{P}^{\text{min}}, \mu_{P}^{\text{max}}, \mu_{Q}^{\text{min}}, \mu_{Q}^{\text{max}}, \mu_{x_{c}}^{\text{min}}, \mu_{x_{c}}^{\text{max}}\) are the Lagrange multipliers associated with the inequality constraints (line flow limit, generator real and reactive power limits, bus voltage limits and TCSC reactance limits, respectively). The solution of OPF gives the values of these multipliers along with the dispatch result.

Sequential Quadratic Programming (SQP) method is used for the solution of the OPF problem incorporating TCSC in the MATLAB environment.

### 3.4. Locational marginal price and congestion rent

Each Lagrange multiplier has economic significance. The important one is the Lagrange multiplier \(\lambda_{P}\) associated with the real power balance equations. It is actually the spot price or nodal price or LMP and form of pricing energy in OPF based deregulated market [13]. LMP is generally composed of three components, a marginal energy component (same for all buses), a marginal loss component and a congestion component. The decomposition of nodal spot price obtained from OPF into three components is described in [14]. The derivation of nodal spot prices applying the first order optimality condition to Lagrange function (8) is derived in [15]. For a case of real power spot price at bus \(i\), it is given by

\[
\rho_{i} = \lambda_{i} + \lambda_{P} \frac{\partial P_{ij}}{\partial P_{i}} + \lambda_{L} \frac{\partial L_{ij}}{\partial P_{i}} + \lambda_{C} \frac{\partial C_{ij}}{\partial P_{i}}
\]

where \(\lambda_{i}\) is the marginal energy component at the reference bus (same for all buses), \(\lambda_{L,ij} = \lambda_{P} \frac{\partial L_{ij}}{\partial P_{i}}\) is the marginal loss component and \(\lambda_{C,ij} = \lambda_{C} \frac{\partial C_{ij}}{\partial P_{i}}\) is the congestion component.

Therefore, the spot price at each bus is location specific and differs by the loss component and the congestion component. If the injection (or extraction) of power at a particular bus increases the total system losses, then the price of power at that location increases. Similarly, if any transmission line limit is binding, then corresponding \(\mu_{L}^{ij}\) will be non-zero and will have effect on prices at all the buses. If the injection (or extraction) at a particular bus increases the flows across the congested interface, the spot price at that bus increases.

Similarly, for bus \(j\), the spot price (LMP) can be written similar to (10):

\[
\rho_{j} = \lambda_{j} + \lambda_{L,j} + \lambda_{C,j}
\]

Taking the spot price difference between two buses \(i\) and \(j\), we get:

\[
\Delta \rho_{ij} = (\lambda_{L,i} - \lambda_{L,j}) + (\lambda_{C,i} - \lambda_{C,j})
\]

Eq. (12) shows that the nodal price difference between any two buses depend on the marginal losses and the congestion throughout the network. The price differential, by definition gives the congestion rent (i.e. merchandise surplus). The surplus arises because generators are compensated by LMP at the respective generator buses (which are generally low) and loads are charged by LMP at the respective load buses (which are generally high).

The total congestion rent is calculated as

\[
TCC = \sum_{ij=1}^{N_{L}} \Delta \rho_{ij} P_{ij}
\]

### 4. Proposed methods

#### 4.1. LMP difference method

The main concept behind the LMP difference method is to make use of the economic signal given as LMP to select the best location for TCSC to manage congestion. It is motivated
from the fact that LMP contains significant information regarding level of congestion in the system (9). LMP is composed of three components, an energy component, a loss component and a congestion component. For a meshed system, loss component is generally small. Hence, the difference in LMP between two buses gives direct hint regarding the level of congestion in that line (12). Since, LMP difference is highest for the congested/overloaded lines (i.e. line operating at limit) and overloaded lines are not always the best locations for placement of series FACTS devices [16], a neighborhood search method is required which will be taken care by formation of priority list. Hence, in this method, a priority list is formed based on the magnitude of the difference in LMPs. Priority list will essentially capture the congested lines as well as the neighborhood lines that are linked to the congested lines through which the power can be diverted when FACTS is placed. The number of lines to be considered for priority list depends on the size of the system, and there is no hard and fast rule. However, it should be at least greater than the number of congested lines in the system.

The advantage of the proposed method is that it helps to form the priority list for series FACTS device location directly from the OPF results and avoid excessive computation. Only few lines in the priority list need to be examined in detail to assess the best location. Since, these methods make use of economic signal given as LMP, it is easily applicable in the deregulate electricity markets. The LMP values are usually posted in the OASIS (open access same time information system) or ISO web page and are the by-product of the security constrained OPF. Therefore, this method presents additional advantage, where historical LMP values can be used to analyze the best location and avoid risk associated with the improper allocation.

4.2 Congestion rent contribution method

The LMP difference method is simple and easy to implement. However, there can be a situation, where a line of low rating is congested, that might lead to a large difference in LMP across that line. However, the effect in terms of congestion rent to the market participant due to such congested line may not be significant. The priority list formed by LMP difference alone may not capture the best possible location in such cases. So, to make the method more reliable, the proposed method is modified, but with only minor computation. In the modified method, the LMP difference is multiplied by the power flow through the line, which is nothing but the congestion rent in the line in base case (14). It is then divided by the total congestion rent to form an index (15). This index gives the contribution of individual line in total congestion rent. Therefore, if the LMP difference is high but power flow is small, this line is not represented in the priority list and makes the analysis more accurate. The ranking is now truly based on the congestion rent contribution of individual lines in the base case. If historical LMP values are used to find the best location for TCSC placement, then additional calculation needed for this refined method is just the load flow calculation to determine the power flow through each line section. It can be performed relatively quickly.

The congestion rent of individual line section is calculated as

\[ CC_{ij} = \Delta \rho_{ij} P_{ij} \]  

(14)

The congestion rent contribution of individual line is

\[ CCC_{ij} = \frac{CC_{ij}}{TCC} \]  

(15)

4.3. Procedure

Calculation procedure of the proposed methods is summarized in the following five steps:

- Step 1: Run the base case OPF to calculate the LMP at all buses and the power flow across all line sections.
- Step 2: Calculate the absolute value of the LMP difference and arrange in descending order of magnitude to form priority table (for LMP difference method).
- Step 3: Calculate congestion rent contribution of individual lines (using Eqs. (12)–(14)) using LMP values and power flows calculated in Step 1 and arrange in descending order of magnitude to form priority table (for congestion rent contribution method).
- Step 4: For each line in the priority list, run OPF with TCSC in that line and calculate the total congestion rent and the value of the objective function (i.e. total generation cost or the total social welfare).
- Step 5: The best location of TCSC is the one where by placing TCSC gives the minimum congestion cost or minimum value of the objective function (i.e. minimum generation cost or maximum social welfare). If the best location is between two generator buses, then the next best location is selected.

5. Results and discussions

5.1. Test systems

The proposed methodologies are tested on three different test systems with different sizes and complexities. A modified IEEE 14 bus, IEEE 30-bus and IEEE 57-bus test systems are used to show the robustness of the proposed methodologies. The network and load data for these systems are taken from [17]. Line limits for IEEE 14- and IEEE 30-bus system is taken from Refs. [18,19], respectively. For IEEE 57-bus system, a limit of 50 MVA is applied for line no. 1, 2, 15, 16 and 18, a 170 MVA limit for line no. 8, a 40 MVA limit for line no. 17 and a 70 MVA limit for line no. 22. The generator limits and cost coefficients

<table>
<thead>
<tr>
<th>Gen no.</th>
<th>Bus no.</th>
<th>a ($/MW2h)</th>
<th>b ($/MWh)</th>
<th>c ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.0252</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0.1400</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>0.5000</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>0.0667</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>0.2000</td>
<td>24</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 2
Look up table based on OPF with TCSC for IEEE 14-bus system

<table>
<thead>
<tr>
<th>Priority no.</th>
<th>Congestion rent with TCSC</th>
<th>TCSC location</th>
<th>Generation cost with TCSC</th>
<th>TCSC location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total congestion rent ($/h)</td>
<td></td>
<td>Total generation cost ($/h)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1600</td>
<td>Line 6: 3–4</td>
<td>6010</td>
<td>Line 2: 1–5</td>
</tr>
<tr>
<td>2</td>
<td>1906</td>
<td>Line 3: 2–3</td>
<td>6224</td>
<td>Line 6: 3–4</td>
</tr>
<tr>
<td>3</td>
<td>1982</td>
<td>Line 4: 2–4</td>
<td>6270</td>
<td>Line 3: 2–3</td>
</tr>
<tr>
<td>4</td>
<td>2036</td>
<td>Line 2: 1–5</td>
<td>6297</td>
<td>Line 7: 4–5</td>
</tr>
<tr>
<td>5</td>
<td>2065</td>
<td>Line 7: 4–5</td>
<td>6324</td>
<td>Line 1: 1–2</td>
</tr>
<tr>
<td>6</td>
<td>2134</td>
<td>Line 14: 7–8</td>
<td>6336</td>
<td>Line 10: 5–6</td>
</tr>
<tr>
<td>7</td>
<td>2144</td>
<td>Line 17: 9–14</td>
<td>6343</td>
<td>Line 4: 2–4</td>
</tr>
<tr>
<td>8</td>
<td>2160</td>
<td>Line 10: 5–6</td>
<td>6347</td>
<td>Line 14: 7–8</td>
</tr>
<tr>
<td>9</td>
<td>2164</td>
<td>Line 8: 4–7</td>
<td>6353</td>
<td>Line 8: 4–7</td>
</tr>
<tr>
<td>10</td>
<td>2169</td>
<td>Line 11: 6–11</td>
<td>6354</td>
<td>Line 11: 6–11</td>
</tr>
</tbody>
</table>

Table 3
Priority table based on LMP difference for IEEE 14-bus system

<table>
<thead>
<tr>
<th>Priority no.</th>
<th>LMP difference ($/MWh)</th>
<th>Priority location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.82</td>
<td>Line 3: 2–3</td>
</tr>
<tr>
<td>2</td>
<td>13.20</td>
<td>Line 6: 3–4</td>
</tr>
<tr>
<td>3</td>
<td>13.19</td>
<td>Line 2: 1–5</td>
</tr>
<tr>
<td>4</td>
<td>12.21</td>
<td>Line 1: 1–2</td>
</tr>
<tr>
<td>5</td>
<td>3.62</td>
<td>Line 4: 2–4</td>
</tr>
</tbody>
</table>

Table 4
Priority table based on congestion rent contribution for IEEE 14-bus system

<table>
<thead>
<tr>
<th>Priority no.</th>
<th>Congestion rent contribution (%)</th>
<th>Priority location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30.6</td>
<td>Line 3: 2–3</td>
</tr>
<tr>
<td>2</td>
<td>28.0</td>
<td>Line 1: 1–2</td>
</tr>
<tr>
<td>3</td>
<td>19.3</td>
<td>Line 2: 1–5</td>
</tr>
<tr>
<td>4</td>
<td>8.4</td>
<td>Line 6: 3–4</td>
</tr>
<tr>
<td>5</td>
<td>5.1</td>
<td>Line 4: 2–4</td>
</tr>
</tbody>
</table>

Table 5
Priority table based on sensitivity factor for IEEE 14-bus system

<table>
<thead>
<tr>
<th>Priority no.</th>
<th>Sensitivity factor</th>
<th>Priority location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.74</td>
<td>Line 2: 1–5</td>
</tr>
<tr>
<td>2</td>
<td>-0.97</td>
<td>Line 6: 3–4</td>
</tr>
<tr>
<td>3</td>
<td>-0.43</td>
<td>Line 15: 7–9</td>
</tr>
<tr>
<td>4</td>
<td>-0.38</td>
<td>Line 5: 2–5</td>
</tr>
<tr>
<td>5</td>
<td>-0.10</td>
<td>Line 18: 10–11</td>
</tr>
</tbody>
</table>

for IEEE 30- and 57-bus systems are taken from Ref. [16]. For IEEE 14-bus system, the cost coefficients are given in Table 1. There are 20 line sections in IEEE 14-bus system, 41 line sections in IEEE 30-bus system and 80 line sections in IEEE 57-bus system. For IEEE 14- and IEEE 30-bus system, the priority list is formed with five candidate lines, while for IEEE 57-bus system the priority list is formed consisting of 10 candidate locations.

5.2. Results for IEEE 14-bus test system

Tables 2–5 presents the result for IEEE 14-bus test system. In Table 2, the result of OPF when TCSC is placed on each line one at a time is shown. The 10 best locations are depicted in the table. It shows the location for TCSC to obtain the minimum total congestion rent and minimum total generation cost. The first best location to minimize total congestion rent is line 6, with congestion rent of 1600 US$/h. To achieve minimum total generation cost the first best location is line 2, with total generation cost of 6010. This table is constructed for verification purpose using exhaustive search. The priority list formed from proposed methods must capture these best locations.

Table 3 shows the priority location for the placement of TCSC based on the magnitude of LMP differences. Lines 6 and 2, which are the first best locations for the placement of TCSC to minimize total congestion rent and minimize total generation cost, respectively, are both captured in this priority list. This proves the effectiveness of the LMP difference method. So, the first best location in terms of minimum total congestion rent is line 6 (line 3–4), which has second priority in LMP difference method.

While, the first best location in terms of minimum total generation cost is line 2 (line 1–5), which has the third priority in LMP difference method. Whether, the criteria for selection are to minimize the total congestion rent or minimize the total generation cost, the priority list is able to capture the best locations for TCSC in both cases.

Table 4 shows the result of congestion rent contribution method, where priority list is formed according to the contribution of each line to total congestion rent. Line 3 (line 2–3) is the first priority that contributes 30.6% of the total congestion rent. Observation of Tables 2 and 4 shows that this method also captures the best location for the placement of TCSC. Line 6 (line 3–4) is the best location to minimize the total congestion rent and it has the fourth priority in Table 4, while line 2 (line 1–5) is the best location to minimize the total generation cost and it has the third priority in Table 4.

Table 5 shows the result of the sensitivity factor method. The sensitivity factor is calculated based on procedure described in [3]. It also shows that lines 6 and 2, are also captured in the priority list formed based on sensitivity factor. However, comparison of Tables 2–5 shows that, sensitivity factor method cannot capture other best locations. Sometimes, it may not be possible to install FACTS device at the first best location and we have to search for alternative locations. In such cases, the proposed two methods give results that are more promising. Tables 3 and 4 show that if the objective is to minimize the total
congestion rent, then the priority table based on LMP spread method and congestion rent contribution method can capture the first four best locations out of five candidate locations in Table 2. However, the sensitivity factor method can capture only the first and the fourth best locations.

5.3. Results for IEEE 30-bus test system

Tables 6–9 shows the result for IEEE 30-bus test system. Table 6 is constructed for verification purpose, by placing TCSC on each line one at a time and running OPF. As shown in Table 6, line 36 is the best location for TCSC installation that satisfies both criteria.

Comparison of Tables 6 and 7 shows that the priority table based on LMP difference method captures the best possible location (line 36) for TCSC installation to minimize either the congestion rent or the total generation cost. Table 8 shows that the priority table based on congestion rent contribution is also able to capture the best possible location for TCSC installation (line 36) to minimize either the congestion rent or the total generation cost.

However, sensitivity factor method as shown in Table 9 is not able to capture this best location for TCSC installation. The most impressive location capture by Table 9 is line 41. This location is the fifth best if a criterion for selection is minimum...
total congestion rent and fourth best if a criteria for selection is minimum total generation cost. This also depicts the advantage of proposed method and limitation of sensitivity factor method. Further, analysis of Tables 6–9 shows that the proposed methods capture other best locations like lines 40 and 10, as well.

### 5.4. Results for IEEE 57-bus test system

To show the reliability of the proposed method, the simulation is carried out on IEEE 57-bus test system as well. The results are shown in Tables 10–13. Again, Table 10 shows the actual priority based on minimum congestion rent and minimum generation cost. Line 12 is the first best location if criteria for selection is minimum total congestion rent and line 7 is the first best location if criteria for selection is minimum total generation cost.

### 5.5. Summary and recommendations

Based on the observed result for the three test systems it can be concluded that congestion rent contribution method gives more promising result than LMP difference method. Therefore, the congestion rent contribution method is recommended to be used to the extent possible. Further, the results also show that sensitivity factor method often fails to give the best location and should not be used.

### 6. Conclusions

LMP difference and congestion rent contribution methodologies are proposed for locating series FACTS devices to manage congestion in deregulated electricity markets. The proposed methodologies are based on LMPs that are by-products of OPF problem formulation. The proposed methods are tested on three test systems with different sizes and complexities, namely IEEE 14, IEEE 30 and IEEE 57, and validated through look-up tables formed by exhaustive search for each test case.

Result shows that proposed methods, unlike sensitivity methods where non-linearity in not captured, correctly capture the best locations for series FACTS devices for congestion management in deregulated electricity market.

### References


