Optimal Placement of TCSC Based on A Sensitivity Approach for Congestion Management

Srinivas Rao Pudi, S.C. Srivastava, Senior Member, IEEE

Abstract—One of the major operating challenges in the electricity markets is to manage transmission system congestion to ensure its secure operation. This paper has mainly addressed the issue of congestion management utilizing Thyristor Controlled Series Compensator (TCSC). Proper location of a FACTS controller is key to maximize its benefits. This paper presents a sensitivity factor based approach for the optimal placement of the TCSC to minimize the congestion cost. The sensitivity of the congested line flow with respect to flow in other lines has been used for the placement of the TCSC. The effectiveness of the proposed method has been demonstrated on IEEE 30-bus system and a 75-bus Indian system.

I. INTRODUCTION

In a competitive electricity market, congestion occurs when the transmission network is unable to accommodate all the desired transactions due to violation of system operating limits. The open power market utilizes the transmission system intensively, which in turn leads to frequent congestion. The economic theory suggests that the most logical way to charge for electricity usage is through Locational Marginal Price (LMP)/spot price. When congestion begins to take place under heavy demand, price volatility and market imbalances may occur and the consumers, in such regions, have to bear the price spike. In such a case, the customers suffer and the very purpose of the restructuring and introducing competition is defeated. Hence, congestion management is an important issue to be addressed in the restructured market. This is generally handled by the system operator (SO), who is neither buyer nor seller of the electrical energy.

The restructured electricity markets, worldwide, have popularly used the Poolco model [2]. The Poolco model, in general, utilizes spot pricing of electricity [1] and an associated bid based dispatch to match generators supply with customers demand. Under the spot pricing scheme, the tariffs charged by GENCOs and paid by the customers are the nodal prices or the bus incremental prices. These are the by-product of security constrained optimal power flow. By using OPF, with stiff constraints enforced on transmission line one can ensure secure transfer of power to the customers without any curtailments. The impact of forcing line flow to remain within its limiting value, under congestion by the OPF, is reflected in the prices and the Locational Marginal Price (LMP) increases. The difference in the LMP across an interface gives a measure of degree of congestion across the link. Higher is the difference in the LMP, the more the link is congested. To reduce this difference in the LMP, leading to reduction in the congestion, Flexible AC Transmission Systems (FACTS) controllers can be used. However, due to their high cost, the optimal location, appropriate size and setting of the FACTS controllers is important. Implementation of these devices can change the prices at certain buses, directly affecting some generators and loads [10].

There are several methods for finding the optimal locations of the FACTS controllers in vertically integrated systems as well as unbundled power systems [4–8]. In [4], a loss sensitivity approach has been proposed for placement of series capacitors, phase shifters and static VAR compensators. Other works have incorporated FACTS controllers in optimal power flow formulation [6, 7] with different objective functions. Rajaraman et al. [5] have used continuation power flow method for obtaining the size and locations of series compensators to increase the loadability limit of the system. After placement of the series compensation in each line, the loadability with a uniform loading factor at each bus is computed with the help of the continuation power flow technique. In large power systems, where load change is not uniform, it is difficult to decide the optimal location of series compensation. In [8, 9], the optimal locations of FACTS devices are obtained by solving the economic dispatch problem including the cost of these devices making the assumption that all lines, initially, have these devices. In the presence of bilateral/multilateral contracts, it is difficult to use this method.

In ref. [12], optimal placement of TCSC for reducing congestion cost, has been presented by using a performance index, which incorporates two factors. One is the sensitivity matrix of the TCSC with respect to the congested line and the other is the shadow price corresponding to the congested line. In ref. [15], authors proposed LMP difference and congestion rent contribution methods for optimal location of TCSC to reduce the congestion cost. The proposed methodologies are based on LMPs that are by-products of OPF formulation. But, this method selects the line which is more congested as the best location of TCSC, causing it to operate in inductive mode and involves time intensive procedure.

This paper presents a new method for optimal location of series FACTS Controllers for congestion management in the...
deregulated electricity markets. The proposed method is a modification of the congestion rent contribution method [15], which makes use of economic signal given by the LMP for deciding congestion in a line. Thyristor Controlled Series Compensator (TCSC), a series FACTS controller, has been considered in this work for congestion management. A sensitivity based method has been suggested for optimal location of the TCSC. An OPF formulation has been used for deciding its optimal setting and studying its impact on the congestion cost. A pool type of market is considered in this paper. The rest of the paper is organized as follows. Section II presents the formulation of the OPF incorporating TCSC and the solution approach. The proposed placement methodology for TCSC in deregulated market is described in Section III. Numerical results along with some observations and discussions are presented in Section IV. The major contributions and conclusions of the paper are summarized in Section V. Finally, appendix for congestion rent contribution method [15] has been given in section VI.

II. MODELING AND OPTIMAL PLACEMENT OF TCSC

Although FACTS controllers are utilized in the system to perform their primary task of stability control, they also improve the steady state performance of the system. The present work has only considered their impact on the congestion management, formulated as a steady state problem.

A static Power Injection Model (PIM) [11, 13] of the TCSC has been used. The injection model represents the TCSC as a device that injects certain amount of active and reactive power in a node.

\[ P_i^F = V_i^2 \Delta G_{ij} - V_i V_j \left[ \Delta G_{ij} \cos(\delta_i - \delta_j) + \Delta B_{ij} \sin(\delta_i - \delta_j) \right] \]  
\[ Q_i^F = -V_i^2 \Delta B_{ij} - V_i V_j \left[ \Delta G_{ij} \sin(\delta_i - \delta_j) - \Delta B_{ij} \cos(\delta_i - \delta_j) \right] \]  
\[ P_j^F = V_j^2 \Delta G_{ij} - V_i V_j \left[ \Delta G_{ij} \cos(\delta_i - \delta_j) - \Delta B_{ij} \sin(\delta_i - \delta_j) \right] \]  
\[ Q_j^F = -V_j^2 \Delta B_{ij} + V_i V_j \left[ \Delta G_{ij} \sin(\delta_i - \delta_j) + \Delta B_{ij} \cos(\delta_i - \delta_j) \right] \]

where,

\[ \Delta G_{ij} = \frac{x_i r_j (x_i - x_j)}{(r_i^2 + x_i^2) (r_j^2 + (x_j - x_i)^2)} \]  
\[ \Delta B_{ij} = \frac{x_c (r_j^2 - x_j^2 + x_c x_j)}{(r_j^2 + x_j^2) (r_i^2 + (x_i - x_c)^2)} \]

Fig. 1: Static model of line with TCSC

\[ V_i \quad S_i \quad Z_{ij} = r_{ij} + jx_{ij} \quad S_i \quad V_j \]

\[ jB_{sh} \quad jB_{sh} \]

Fig. 2: Static power injection model of TCSC

where, \( V_i, V_j \) and \( \delta_i, \delta_j \) are voltage and angle at buses \( i \) and \( j \), respectively. \( G_{ij} \) and \( B_{ij} \) are the conductance and susceptance of the line-ij. In the present study, the above model is incorporated in the OPF. The maximum compensation by TCSC is assumed to be limited to 60% of the reactance of the un-compensated line, in which the TCSC is placed.

A. OPF Formulation:

Optimal Power Flow (OPF) has been used in this work under pool based electricity markets to calculate generation dispatch and load schedules, to obtain nodal prices or LMPs and to manage congestion in the systems. It is based on the bids submitted by the generators and loads (if the demand has price elasticity) 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 this work, it is assumed that the loads are inelastic to the price variations. Therefore, the social welfare function becomes the total cost of supplying electricity. However, the formulation can be easily extended to include demand bids to maximize the social welfare.

The problem is stated mathematically as

\[ \text{Min} \left\{ \sum_{i=1}^{N_G} C_i (P_{G_i}) \right\} \]  
subject to

Power balance equation:

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

If TCSC is located in line between buses \( i \) and \( j \), the power...
balance equations at nodes \( i \) and \( j \) are given by
\[
P_i(\theta, V) - P_{Gi} + P_{Di} + P_i^f = 0, \text{ for node } i
\]
\[
Q_i(\theta, V) - Q_{Gi} + Q_{Di} + Q_i^f = 0, \text{ for node } i
\]
\[
P_j(\theta, V) - P_{Gj} + P_{Dj} + P_j^f = 0, \text{ for node } j
\]
\[
Q_j(\theta, V) - Q_{Gj} + Q_{Dj} + Q_j^f = 0, \text{ for node } j
\]
Apparent line flow limit:
\[
S_{ij}(\theta, V) \leq S_{ij}^{\text{max}}
\]
Power generation limit:
\[
P_{Gi}^{\text{min}} \leq P_{Gi} \leq P_{Gi}^{\text{max}},
\]
\[
Q_{Gi}^{\text{min}} \leq Q_{Gi} \leq Q_{Gi}^{\text{max}}
\]
Bus voltage and angle limits:
\[
V_i^{\text{min}} \leq V_i \leq V_i^{\text{max}},
\]
\[
\theta_i^{\text{min}} \leq \theta_i \leq \theta_i^{\text{max}}
\]
TCSC reactance limit:
\[
x_c^{\text{min}} \leq x_c \leq x_c^{\text{max}}
\]

Where, \( N_G \) is the number of generators, \( C_i(P_{Gi}) \) is the bid curve of \( i \)th generator, \( P_{Gi}^{\text{min}} \) and \( P_{Gi}^{\text{max}} \) are the minimum and the maximum active power generation limits of a generator at bus \( i \), \( Q_{Gi}^{\text{min}} \) and \( Q_{Gi}^{\text{max}} \) are the minimum and the maximum reactive power generation limits of generating unit at bus \( i \), \( V_i^{\text{min}} \) and \( V_i^{\text{max}} \) are the minimum and maximum voltage limits at bus \( i \), \( S_{ij} \) is the apparent power flow in transmission line connected between buses \( i \) and \( j \), and \( S_{ij}^{\text{max}} \) is its maximum limit. \( P_{Gi} \) and \( Q_{Gi} \) are the active and reactive power generations at node \( i \), \( P_{Di} \) and \( Q_{Di} \) are the active and reactive power loads at node \( i \), \( P_i \) and \( Q_i \) are the net active and reactive power injections at node \( i \), \( x_c^{\text{min}} \) and \( x_c^{\text{max}} \) are the minimum and maximum limits of the TCSC reactance and \( N \) is the number of nodes in the system.

### B. Solution Technique

The augmented objective function of the above OPF problem augmenting all the constraints is expressed as
\[
L = \left[ \sum_{i=1}^{N_G} C_i(P_{Gi}) \right] + \sum_{i=1}^{N} \lambda_P \left( P_i - P_{Gi} + P_{Di} + P_i^f \right) + \sum_{i=1}^{N} \lambda_Q \left( Q_i - Q_{Gi} + Q_{Di} + Q_i^f \right) + \sum_{i=1}^{N} \lambda_V \left( V_i - V_i^{\text{max}} \right) + \sum_{i=1}^{N} \lambda_{\theta} \left( \theta_i - \theta_i^{\text{max}} \right)
\]
\[
+ \left( \sum_{i=1}^{N_G} \mu_{P_{Gi}} (P_{Gi}^{\text{min}} - P_{Gi}^{\text{max}}) \right) + \left( \sum_{i=1}^{N_G} \mu_{Q_{Gi}} (Q_{Gi}^{\text{min}} - Q_{Gi}^{\text{max}}) \right) + \left( \sum_{i=1}^{N_G} \mu_{V_i} (V_i^{\text{min}} - V_i^{\text{max}}) \right) + \left( \sum_{i=1}^{N_G} \mu_{\theta_i} (\theta_i^{\text{min}} - \theta_i^{\text{max}}) \right)
\]
\[
+ \mu_{x_c}^{\text{min}} (x_c^{\text{min}} - x_c) + \mu_{x_c}^{\text{max}} (x_c - x_c^{\text{max}})
\]

where, \( \lambda_P \) and \( \lambda_Q \) are the Lagrange multipliers associated with the equality constraints (power balance equations) and \( \mu_P, \mu_Q, \mu_V, \mu_{\theta} \) 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 the OPF gives the values of these multipliers along with the dispatch result. Optimal toolbox of the MATLAB has been used for the solution of the OPF problem incorporating the TCSC in the MATLAB environment.

Each multiplier in (8) has economic significance. The important one is the Lagrange multiplier \( \lambda_e \) associated with the real power balance equations. It is the real power spot price or nodal price or LMP and can be used for pricing energy in electricity markets [14]. LMP is generally composed of three components, a marginal energy component (same for all buses), a marginal loss component and a congestion component. In this, the congestion component arises because of line flow constraints and the voltage constraints. When these are inactive, LMP consists of marginal energy component and the marginal loss component only. Thus, one can get congestion component from the LMP by running the OPF, with and without congestion constraints, and take the difference of the LMP in both the cases.

The derivation of the nodal spot prices, applying the first order optimality condition to the augmented function shown in (8), is derived in [3]. For a case of real power spot price at bus \( i \), considering all constraints in the OPF, the decomposition of the nodal spot price into three components is as follows.

\[
\rho_i = \lambda_e + \delta \rho_{P_{Gi}} \frac{\delta P_i}{\delta P_{Gi}} + \sum_{j=1}^{N} \mu_{S_{ij}} \frac{\delta P_{ij}}{\delta P_i}
\]

\[
\rho_i = \lambda_e + \lambda_{L,i} + \lambda_{C,i}
\]

The decomposition of nodal spot price obtained from OPF without congestion constraints into two components is as follows.

\[
\rho_{i,\text{wo}} = \lambda_e + \lambda_{L,i}
\]

where, \( \lambda_e \) is the marginal energy component at the reference bus (same for all buses), \( \lambda_{L,i} \) is the marginal loss component and \( \lambda_{C,i} \) is the congestion component. The difference of the above two equations will give the congestion component of the LMP at bus \( i \).

\[
\lambda_i = \rho_i - \rho_{i,\text{wo}} = \lambda_{C,i}
\]

If the injection (or extraction) at a particular bus increases the flows across the congested interface, the spot price at that bus increases.

After finding congestion component of LMP using the above method, there may be small loss component that will exist since power flows will change with and without congestion constraints. This impact has been neglected in this work. Similarly, for bus \( j \), the spot price (LMP) can be written similar to the equations (10), (11) and (12), as

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

\[
\rho_{j,\text{wo}} = \lambda_e + \lambda_{L,j}
\]

\[
\lambda_j = \rho_j - \rho_{j,\text{wo}} = \lambda_{C,j}
\]

Taking the difference of the spot price between two buses \( i \) and \( j \), one gets
\[ \Delta \lambda_{ij} = (\lambda_i - \lambda_j) \]  
(16)

Equation (16) shows that the nodal price difference between any two buses depend on 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 congestion rent of individual line section and the total congestion cost are calculated as given in appendix in section VI.

III. SENSITIVITY FACTOR BASED METHOD

The proposed method finds out the sensitivity of flow in the most congested line with respect to flow in the other lines and places the TCSC in a line, which causes maximum reduction in the power flow of the most congested line. The most congested line has highest congestion rent. The proposed sensitivity factor method is explained below.

Consider that the most congested line is between buses \( i \) and \( j \). Let \( P_{ij} \) be the base case real power flow through that line. Consider another line between buses \( m \) and \( n \), having real power flow \( P_{mn} \) and \( P_{nm} \) from bus \( m \) to bus \( n \) and bus \( n \) to bus \( m \), respectively.

Let \( P_{ij\text{new}} \) be the new line flow between buses \( i \) and \( j \). If the flow in line-\( mn \), i.e. \( P_{mn} \) is changed by a small amount, the changes in the line flows can be written as,

\[ \Delta P_{ij} = P_{ij\text{new}} - P_{ij}. \]

The proposed sensitivity index is defined as the ratio of \( \Delta P_{ij} \) to the base case real power flow transmitted in the most congested line i.e. \( P_{ij} \) for a small change in flow in line-\( mn \).

\[ \text{sens}_{ij, mn} = \frac{\text{change in congested line flow}}{\text{original flow in congested line}} = \frac{\Delta P_{ij}}{P_{ij}} \]  
(17)

The sensitivity factor can be found by utilizing the sensitivity properties of Jacobian matrix obtained from Newton-Raphson load flow at a base case operating point. The changes in \( P_{mn} \) have been simulated by considering two fictitious generators at end buses of the line, having outputs \( \Delta P_{mn} \) and \( \Delta P_{nm} \). For the sensitivity analysis, the value of \( \Delta P_{mn} \) is taken as 5% of the actual flow of the line considered. Once voltage and angle mismatch vectors are calculated for all the buses, it is trivial to obtain line flows.

After getting the new power flows, the difference in power flows in the congested line i.e. \( \Delta P_{ij} \) and hence, the sensitivity factor can be computed. The lines, which have the most negative sensitivity factor value, can be selected for the optimal placement of the TCSC. Calculation procedure of the proposed method is summarized in the following steps:

Step 1: Run the base case OPF to calculate the LMP at all the buses and the power flow across all the line sections.

Step 2: Calculate congestion rent of individual lines using LMP values and power flows calculated in step 1. Select the most congested line, which has highest value of the congestion rent given by eq. (21).

Step 3: Find the sensitivity factors for the most congested line with respect to all other lines using eq. (17). Select a line-\( mn \), which has maximum negative value of the sensitivity factor for the TCSC placement.

Step 4: Run the OPF, with TCSC in the line-\( mn \) and calculate the congestion rent of the most congested line and the total congestion cost. If the optimal location is between two generator buses the next best location will be selected.

Step 5: Sometimes placement of FACTS causes congestion in some other lines. In such cases, go to the next line in descending order of the sensitivity value.

This method considers the TCSC operation in capacitive as well as inductive mode and separation of congestion component of LMPs. It directly identifies the line, where TCSC has to be optimally placed unlike priority list in the congestion rent contribution method [15].

IV. CASE STUDY

The proposed methodology for the optimal placement of the TCSC for congestion management has been implemented on IEEE 30-bus test system and 75-bus Indian system.

A. IEEE 30 bus system:

IEEE 30-bus system has 41 line sections. In Table 1, the result of OPF i.e. LMP values, with and without congestion constraints, are shown. Congestion component of LMP are also shown in Table 1. From the base case OPF, without any congestion constraints, power flow through line 11 is 137.73 MVA, which is above its maximum rating (137 MVA). These are also reflected in the LMP difference and congestion cost of that line. The congestion cost is 32.9459 $/hr, which is very high as compared to other lines. Congestion cost of each line in the system is shown in Table 3, with and without TCSC.

<table>
<thead>
<tr>
<th>Bus No</th>
<th>LMP with out constraints (( \mu_i )) (cents/MWh)</th>
<th>LMP with constraints (( \mu_i )) (cents/MWh)</th>
<th>Congestion component of LMP (cents/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without TCSC</td>
<td>with TCSC</td>
<td>Without TCSC</td>
</tr>
<tr>
<td>1</td>
<td>439.05</td>
<td>439.15</td>
<td>439.14</td>
</tr>
<tr>
<td>2</td>
<td>460.49</td>
<td>484.71</td>
<td>460.72</td>
</tr>
<tr>
<td>3</td>
<td>480.23</td>
<td>500.59</td>
<td>480.70</td>
</tr>
<tr>
<td>4</td>
<td>485.56</td>
<td>505.89</td>
<td>485.90</td>
</tr>
<tr>
<td>5</td>
<td>497.62</td>
<td>521.30</td>
<td>498.21</td>
</tr>
<tr>
<td>6</td>
<td>477.25</td>
<td>496.61</td>
<td>477.78</td>
</tr>
<tr>
<td>7</td>
<td>485.13</td>
<td>505.43</td>
<td>485.48</td>
</tr>
<tr>
<td>8</td>
<td>486.06</td>
<td>506.26</td>
<td>486.37</td>
</tr>
<tr>
<td>9</td>
<td>477.25</td>
<td>496.60</td>
<td>477.78</td>
</tr>
<tr>
<td>10</td>
<td>481.35</td>
<td>501.55</td>
<td>481.95</td>
</tr>
<tr>
<td>11</td>
<td>477.69</td>
<td>496.33</td>
<td>478.09</td>
</tr>
<tr>
<td>12</td>
<td>492.04</td>
<td>513.94</td>
<td>492.52</td>
</tr>
<tr>
<td>13</td>
<td>483.23</td>
<td>503.70</td>
<td>483.67</td>
</tr>
<tr>
<td>14</td>
<td>485.24</td>
<td>504.99</td>
<td>485.79</td>
</tr>
<tr>
<td>15</td>
<td>487.94</td>
<td>507.85</td>
<td>488.55</td>
</tr>
</tbody>
</table>
Utilizing the proposed sensitivity based method, the sensitivity of this line with respect to all other lines are obtained. Some of the lines with most negative sensitive values, in descending order of their magnitude are given in Table 2. From this table, it is observed that the line 12 has the maximum negative sensitive value. Hence, the line 12 is the best location for a TCSC placement. When TCSC is placed in the line 12, congestion cost of the line 11 gets reduced to 41.740.03 0.0145 0.0101 0.0043

### Table 2: Sensitivity of line-11 power flow with respect to other lines

<table>
<thead>
<tr>
<th>Line No</th>
<th>From bus</th>
<th>To bus</th>
<th>敏感值 normalized to line 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>1</td>
<td>27</td>
<td>-1.0</td>
</tr>
<tr>
<td>7</td>
<td>11</td>
<td>13</td>
<td>-0.3219</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>5</td>
<td>-0.2298</td>
</tr>
<tr>
<td>36</td>
<td>29</td>
<td>30</td>
<td>-0.2091</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>9</td>
<td>-0.1795</td>
</tr>
</tbody>
</table>

B. 75 bus Indian system:

Indian 75-bus system has 98 line sections. In Table 4, the result of OPF i.e. LMP values, with and without congestion constraints, are shown. Congestion component of LMP are also shown in Table 4. From the base case OPF, without any congestion constraints, power flow through line 91 is 323.41 MVA, which is above its maximum rating (300 MVA). These are also reflected in the LMP difference and congestion cost of that line. The congestion cost is 354250 INR/hr, which is very high as compared to other lines. Congestion cost of each line in the system is shown in Table 6 with and without TCSC.

### Table 3: LMP difference and congestion rent of each line with TCSC in line-12 and without any TCSC

<table>
<thead>
<tr>
<th>Line No</th>
<th>From bus</th>
<th>To bus</th>
<th>ΔLMP (cents/MWh)</th>
<th>Congestion rent (INR/hr)</th>
<th>Without TCSC</th>
<th>With TCSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2</td>
<td>13</td>
<td>0.2103</td>
<td>2.0443</td>
<td>0.1144</td>
<td>0.1001</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>2</td>
<td>0.1323</td>
<td>32.9459</td>
<td>0.1501</td>
<td>0.1018</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>27</td>
<td>0.2548</td>
<td>8.772</td>
<td>0.2043</td>
<td>0.1376</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>11</td>
<td>0.1835</td>
<td>2.4944</td>
<td>0.0822</td>
<td>0.0616</td>
</tr>
<tr>
<td>16</td>
<td>9</td>
<td>15</td>
<td>0.0885</td>
<td>0.1018</td>
<td>0.0161</td>
<td>0.0121</td>
</tr>
<tr>
<td>23</td>
<td>8</td>
<td>20</td>
<td>0.0794</td>
<td>0.0153</td>
<td>0.0063</td>
<td>0.0042</td>
</tr>
<tr>
<td>33</td>
<td>27</td>
<td>11</td>
<td>0.061</td>
<td>1.7852</td>
<td>0.0328</td>
<td>0.0254</td>
</tr>
<tr>
<td>35</td>
<td>10</td>
<td>30</td>
<td>0.0758</td>
<td>0.0501</td>
<td>0.0054</td>
<td>0.0040</td>
</tr>
<tr>
<td>37</td>
<td>3</td>
<td>28</td>
<td>0.0003</td>
<td>0.0146</td>
<td>0.0043</td>
<td>0.0035</td>
</tr>
<tr>
<td>41</td>
<td>7</td>
<td>4</td>
<td>0.0145</td>
<td>0.0101</td>
<td>0.0043</td>
<td>0.0035</td>
</tr>
</tbody>
</table>

### Table 4: LMP values and congestion component of LMP with TCSC in line-92 and without any TCSC

<table>
<thead>
<tr>
<th>Bus No</th>
<th>LMP with out constraints (INR/MWh)</th>
<th>LMP with constraints (p(i)</th>
<th>Congestion component of LMP (INR/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1650</td>
<td>1881.6</td>
<td>231.5</td>
</tr>
<tr>
<td>8</td>
<td>1845.5</td>
<td>1830.2</td>
<td>187.9</td>
</tr>
<tr>
<td>14</td>
<td>1664.8</td>
<td>1830.2</td>
<td>187.9</td>
</tr>
</tbody>
</table>

Some of the lines with most negative sensitive values, in descending order of their magnitude are given in Table 5. From this table, it is observed that the line 92 has the maximum negative sensitive value. Hence, the line 92 is the best location for a TCSC placement. When TCSC is placed in the line 92, congestion cost of the line 91 gets reduced to 267990 INR/hr and the congestion cost of the total system also reduces from 754040 INR/hr to 621770 INR/hr.

### Table 5: Sensitivity of line-91 power flow with respect to other lines

<table>
<thead>
<tr>
<th>Line No</th>
<th>From bus</th>
<th>To bus</th>
<th>敏感值 normalized to line 92</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>73</td>
<td>45</td>
<td>-1.0</td>
</tr>
<tr>
<td>68</td>
<td>73</td>
<td>45</td>
<td>-0.2734</td>
</tr>
<tr>
<td>55</td>
<td>54</td>
<td>63</td>
<td>-0.1763</td>
</tr>
<tr>
<td>87</td>
<td>25</td>
<td>72</td>
<td>-0.1557</td>
</tr>
<tr>
<td>42</td>
<td>54</td>
<td>28</td>
<td>-0.1547</td>
</tr>
</tbody>
</table>

### Table 6: LMP difference and congestion rent of each line with TCSC in line-92 and without any TCSC

<table>
<thead>
<tr>
<th>Line No</th>
<th>From bus</th>
<th>To bus</th>
<th>ΔLMP (INR/MWh)</th>
<th>**Congestion rent = (ΔLMP ij *Pij) (INR/hr)</th>
<th>Without TCSC</th>
<th>With TCSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>23</td>
<td>24</td>
<td>82.3</td>
<td>0.1513</td>
<td>0.1316</td>
<td>0.1316</td>
</tr>
<tr>
<td>10</td>
<td>90</td>
<td>37</td>
<td>38.9</td>
<td>0.1898</td>
<td>0.1566</td>
<td>0.1566</td>
</tr>
<tr>
<td>19</td>
<td>40</td>
<td>11</td>
<td>17.7</td>
<td>0.0383</td>
<td>0.0247</td>
<td>0.0247</td>
</tr>
<tr>
<td>23</td>
<td>44</td>
<td>15</td>
<td>47.1</td>
<td>0.2798</td>
<td>0.1741</td>
<td>0.1741</td>
</tr>
<tr>
<td>24</td>
<td>45</td>
<td>44</td>
<td>121.8</td>
<td>0.3589</td>
<td>0.298</td>
<td>0.298</td>
</tr>
<tr>
<td>36</td>
<td>24</td>
<td>54</td>
<td>216.9</td>
<td>0.2705</td>
<td>0.2521</td>
<td>0.2521</td>
</tr>
<tr>
<td>45</td>
<td>56</td>
<td>30</td>
<td>41.2</td>
<td>0.0166</td>
<td>0.0065</td>
<td>0.0065</td>
</tr>
<tr>
<td>67</td>
<td>74</td>
<td>31</td>
<td>36.4</td>
<td>0.0744</td>
<td>0.0463</td>
<td>0.0463</td>
</tr>
<tr>
<td>68</td>
<td>74</td>
<td>33</td>
<td>389.4</td>
<td>0.7211</td>
<td>0.5768</td>
<td>0.5768</td>
</tr>
<tr>
<td>91</td>
<td>55</td>
<td>44</td>
<td>1220.8</td>
<td>3.5425</td>
<td>2.6999</td>
<td>2.6999</td>
</tr>
</tbody>
</table>

** all values are multiple of 10^5

V. CONCLUSIONS

In this paper, a sensitivity factor based method has been proposed for optimal location of TCSC to manage congestion in the electricity markets. From the results obtained on the IEEE 30 bus and 75 bus Indian systems, the following main conclusions can be drawn:

- Optimal placement of TCSC causes reduction in the congestion cost of the most congested line and reduces the LMP values.
The proposed method of sensitivity based optimal placement of TCSC performs better than the congestion rent based method [15]. The congestion rent based method involves additional simulation to check the impact of placement of TCSC in each of the lines, in the priority table, on the congestion cost. Invariably it selects the most congested line itself for the TCSC placement, which will operate in inductive compensation mode. On the other hand the proposed method directly identifies a line, having highest impact on the flow in congested line, for the TCSC placement.

VI. APPENDIX

A. Congestion rent contribution method [15]:

According to this method, the decomposition of the nodal spot price at bus i into three components is as follows.

\[ \rho_i = \lambda_i + \lambda_{L_i} + \lambda_{C_i} \]  

(18)

Similarly, for bus j, the spot price can be written as

\[ \rho_j = \lambda_j + \lambda_{L_j} + \lambda_{C_j} \]  

(19)

Taking the spot price difference between two buses i and j, one gets

\[ \Delta \rho_{ij} = (\lambda_{L_{ij}} - \lambda_{L_{ij}}) + (\lambda_{C_{ij}} - \lambda_{C_{ij}}) \]  

(20)

The congestion rent of the individual line is calculated as

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

(21)

The total congestion cost is calculated as

\[ TCC = \sum_{i=1}^{N} \Delta \rho_i P_i \]  

(22)

The congestion rent contribution of the individual line is defined as

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

(23)

Finally, in this method a priority list is formed with high priority lines having larger magnitude of the CCC_{ij}. The number of lines to be considered for priority list depends on the size of the system. For each line in the priority list, OPF can be run with TCSC placed in that line and the total congestion rent can be computed. The best location of the TCSC is the one where by placing TCSC, minimum congestion cost is achieved.

VII. REFERENCES


 VIII. BIOGRAPHIES

Srinivasa Rao Pudi received his B.E. degree from SRKR Engineering College Bhimavaram, India, and M.Tech degree from Indian Institute of Technology Kanpur, India, both in Electrical Engineering, in 2006 and 2008, respectively. His research interests include FACTS controllers and power system restructuring.

S. C. Srivastava received his PhD in Electrical Engineering from Indian Institute of Technology Delhi, India. He is presently working as Professor in the Department of Electrical Engineering at the Indian Institute of Technology Kanpur, India. His research interests include energy management system, power system optimization, security analysis, voltage stability and power system restructuring. He is a fellow of the Indian National Academy of Engineering (INAE), Institution of Engineers (India) & IETE (India) and senior member of the IEEE.