Optimal Locating and Sizing of TCSC for Social Welfare Maximization in Deregulated Power Markets

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Introduction

The restructuring in electric power industries from the last two decades was introduced with privatization in their sectors to improve their efficiency. However, as the deregulation progresses among power utilities, the utility operators face new problems and challenges [1]. Moreover, the provision of bilateral transaction, that allows GENCO and DISCO pairs to negotiate power transactions, has lead to uncertainty in the amount and direction of power flows. Evidently, the overall consequence of this issue is the congestion in transmission network. The issue of transmission congestion is more pronounced in deregulated and competitive markets and it needs a special treatment [1]. In this environment, independent system operator (ISO) has to maximize social welfare and relieve the congestion, so that the system is maintained in secure state. To maximize social welfare and relieve the congestion ISO can use mainly two types of techniques, which are as follows [1–4]:

A. Cost free means:
   • Out-ageing of congested lines;
   • Operation of transformer taps/phase shifters;
   • Operation of FACTS devices particularly series devices.

B. Non-Cost free means:
   • Re-dispatching the generation amounts. By using this method, some generators back down while others increase their output. The effect of re-dispatching is that generators no longer operate at equal incremental costs;
   • Curtailment of loads and the exercise of load interruption options.

Among the above two main techniques cost free means do have advantages such as not touching economical matters, so GENCO and DISCO will not be involved.

This paper deals with the optimal locating and sizing of a TCSC, for social welfare maximization in competitive power markets. Up to now, different approaches have been proposed for optimal locating of FACTS devices in both vertically integrated and unbundled power systems [1–4]. Sensitivity-based congestion management with optimally placed FACTS controllers is presented in [1–4]. However, there are some disadvantages for this method such that it may not capture the non-linearity associated with the power system. Genetic algorithm as an evolutionary method can be applied as a good solution for optimization of OPF problem by incorporating FACTS devices and consequently considering the non-linearity of the system into account. However, various optimization techniques are available to OPF problem. Distributed generators locating for social welfare maximization is presented in [5]. Maximization social welfare is represented as marginal benefit versus demand function in [6]. [7] discovered a method for increasing social welfare under congestion probability in transmission network.

Mathematical model Of TCSC

In this paper, the Newton-Raphson (N-R) power flow formulation is used and TCSC is represented using the Power Injection Model (Fig. 1). The real and reactive power injections at buses i and j with a TCSC connected in line ij can be expressed as [7]:

\[
P_i^P = V_i^2 \Delta G_y - V_i V_j \Delta G_y \cos \delta_y + \Delta B_y \sin \delta_y,
\]

\[
P_j^P = V_j^2 \Delta G_y - V_i V_j \Delta G_y \cos \delta_y - \Delta B_y \sin \delta_y,
\]

\[
Q_i^Q = -V_i^2 \Delta B_y - V_i V_j \Delta B_y \sin \delta_y - \Delta G_y \cos \delta_y,
\]

\[
Q_j^Q = -V_j^2 \Delta B_y + V_i V_j \Delta B_y \sin \delta_y + \Delta G_y \cos \delta_y,
\]
where \( \Delta G_{ij} = x_c r_{ij} (x_c - 2x_{ij}) / (r_{ij}^2 + x_{ij}^2) \) and \( \Delta B_{ij} = -x_c (r_{ij}^2 + x_{ij}^2) / (r_{ij}^2 + x_{ij}^2) \).

(1)–(4) are added to Jacobin matrix in N-R load flow formulations.

Fig. 1. Power Injection Model of transmission line with a TCSC

**Problem formulation**

In the double-sided auction market model, both DisCos and GenCos participate in the market and offer their bid-quantity packages to the market operator. The objective of market operator is to maximize the social welfare, including load flow equality and operational inequality constraints [7]:

\[
\begin{align*}
\text{Max} & 
\left\{ \sum_{j=1}^{N_Q} (a_{dj} + b_{dj} P_{Dj} + c_{dj} f_{Dj}^2) - \right. \\
& \left. \sum_{i=1}^{N_G} (a_{gi} + b_{gi} P_{Gi} + c_{gi} P_{Gi}^2) + \right. \\
& \left. F(V, \delta, P, Q) \right\} \\
\text{subject to} & 
\begin{align*}
F_{\text{line flow \_Limit}} & 
\leq P_{\text{max \_g}}, \quad g = 1, \ldots, N_G, \\
F_{\text{bus voltage \_Limit}} & 
\leq P_{\text{max \_D}}, \quad D = 1, \ldots, N_D, \\
Q_{\text{min \_g}} & 
\leq Q_{\text{max \_g}}, \quad g = 1, \ldots, N_G, \\
Q_{\text{min \_D}} & 
\leq Q_{\text{max \_D}}, \quad D = 1, \ldots, N_D, \\
0.95 & \leq V_i \leq 1.05, \quad b_i = 1, \ldots, N_b, \\
\left| S_{ij} (\theta, V) \right| & \leq (S_{ij}^\text{max})^2, \quad l = 1, \ldots, N_L, \\
x_i^c & \leq x_i \leq x_i^\text{max},
\end{align*}
\]

(5)

**Proposed algorithm**

A detailed step by step procedure for the proposed GA based social welfare maximization by incorporating all the constraint in the objective function is expressed as follows:

**Step 1.** Prepare input power system parameters (e.g., system topology, line and load specifications, generation limits, line flow limits and cost coefficient parameters).

**Step 2.** Assume a suitably population size \( N_{ch} \) and maximum number of generations \( N_{gen\_max} \), crossover rate \( (Pc) \), and mutation rate \( (Pm) \). Set initial counters and parameter values (e.g., \( N_{ch} = N_{gen\_max} = 1 \)).

**Step 3.** Generate random chromosomes by real coding which include power generation schedule, Location and size of TCSC, as follow:

- The values of power generation corresponding to the \( i \)-th generator may be expressed

\[
P_{g_i} = \lambda \times P_{g_{max}}, \quad 0 \leq \lambda \leq 1.
\]

(7)

- The location and size of TCSC device is described by:

\[
\text{FACTS}_\text{location} = \text{INT}[\text{NL} \times \lambda] + 1, \quad 0 \leq \lambda \leq 1,
\]

(8)

\[
\text{TCSC}_\text{Size} = \lambda \times X_f 
\]

(9)

where \( \text{NL} \) is the number of transmission lines.

**Step 4.** Run power flow. Check the equality and non-equality constraints of the system as described before.

**Step 5.** If any of the constraints is violated compute proposed penalty functions (Fig. 2) using outputs of the applied power flow. Compute objective function for chromosome \( Nch \). Set \( Nch = Nch + 1 \).

**Step 6.** If \( Nch \leq N_{ch\_max} \) go to Step 4.

**Step 7.** Calculate the value of objective function corresponding to each set of a chromosome.

**Step 8.** Find and store maximum social welfare among all valid chromosomes and corresponding pattern.

**Step 9.** Set generation count \( gen\_count = 1 \).

**Step 10.** Select two chromosomes based on “tournament” mechanism. Set \( Nch = N_{ch} + 1 \). If \( Nch \leq N_{ch\_max} \) go to Step 10.

**Step 11.** Select a random number (RND1) for mating two parent chromosomes.

**Step 12.** If RND1 is less than the crossover rate \( (Pm) \) then combine the two parents, generate two offspring using Eq. 10 and go to Step 13. Else, transfer the chromosome with no crossover

\[
P_{new} = \beta (P_{max} - P_{da}) + P_{ma}.
\]

(10)

**Step 13.** Repeat steps 11 to 12 for all chromosomes.

**Step 14.** Select a random number (RND2) for mutation of one chromosome.

**Step 15.** If RND2 is less than the mutation rate then apply the mutation process using (7) and go to Step 16. Else, transfer the chromosome with no mutation

\[
x'_{i} = x_{i} \times \left\{1 + (-1)^t \left[1 - r^{(i-1)/p}ight] \right\},
\]

(11)
where \( r \) is a uniform random number on the interval \((0,1)\), \( t \) is the current generation number, \( T \) is the maximum number of generations and \( b \) (e.g., \( b=2 \) in this paper) is a parameter determining the impact of mutation on the new generations.

**Step 16.** Repeat Steps 14 to 15 for all chromosomes.

**Step 17.** Replace the old population with the improved population generated by Steps 3 to 16.

**Step 18.** Run power flow. Check the equality and non-equality constraints of the system as described before.

**Step 19.** If any of the constraints is violated compute proposed penalty functions (Fig. 2) using outputs of the applied power flow. Compute fitness functions (5) for chromosome \( N_{ch} \). Set \( N_{ch} = N_{ch} + 1 \).

**Step 20.** If \( N_{ch} \leq N_{ch,\text{max}} \) go to Step 18.

**Step 21.** Calculate and store the value of objective function.

**Step 22.** Find and store maximum social welfare among all valid chromosomes. Set \( N_p = N_p + 1 \).

**Step 23.** If the maximum number of iterations is achieved then print optimal generation and demand amount, optimal TCSC size and location and stop, else go to Step 9.

### Results and discussions

This section presents the basic operation of the IEEE 14-bus system \([4]\) and optimal locating and sizing of one TCSC unit with smooth/nonsmooth generators cost curves (5), without/with line flow constraints (6) to illustrate the ability of proposed method. Simulation results are analyzed as follows:

- Without line flow constraints by using smooth cost curve, lines 7–10, 12, 13, 15–17 are congested. The same lines (except for line 8) will be congested when nonsmooth cost curve are used (Table 1, columns 2 and 5).
- Transmission line limits (6) overcome the congestion problem; however, social benefit decreases from 1972.3$/h to 1490.8$/h and from 1956.6$/h to 1436.3$/h for smooth and nonsmooth cost curves, respectively.
- In addition, total generation and total load decreases from 381.9MW to 334.8MW/h and from 313.8MW to 261.1MW/h for smooth and nonsmooth cost curves, respectively.
- As expected, line flow constraints cause significant decrease in social welfare. Therefore, line flow constrains are the main causes of low social benefit and low loading levels. Therefore, it is necessary for ISO to encourage competition and reduce the waste. FACTS devices can be used to direct power through uncongested transmission line(s) and provide cheaper power to be transferred from generators to consumers.
- According to Table 2, optimal sizing and placement of one TCSC (Table 3) will increases the generation cost; however, it will also improve social benefit from 1490.8$/h to 1504.2$/h and from 1436.3$/h to 1511.7$/h for smooth and nonsmooth cost curves, respectively. The main reason is the increase in total load from 331.1MW to 334.8MW/h and from 313.8MW/h to 313.2MW/h for smooth and nonsmooth cost curves, respectively. Therefore, optimal placement/sizing of TCSC has proven to be beneficial for IEEE 14-bus system.

- According to Table 2, without any line flow constraints, there are very high load demands at nodes 11–14 (corresponding to lines 5–8) due to higher benefit coefficients. However, when the line flow constrains are considered, there is substantial reductions in load demands and social benefit at thrones nodes.

### Table 1. Line flows in MVA and congestion status. Bold letters show congested lines

<table>
<thead>
<tr>
<th>Line number</th>
<th>Smooth generation cost curve</th>
<th>Nonsmooth generation cost curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>With line flow constraints &amp; without TCSC</td>
<td>Without line flow constraints &amp; without TCSC</td>
<td>With line flow constraints &amp; without TCSC</td>
</tr>
<tr>
<td>1</td>
<td>31.6163328.1725730.932238</td>
<td>36.71299932.73982</td>
</tr>
<tr>
<td>2</td>
<td>71.0453869.8479461.2526676.3250297.0408969.043055</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>13.4516315.1287413.4668411.882713.2407613.677353</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7.3482259.117726.5216872.486172.3906772.09152</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>77.5627577.3366268.0818382.4547777.1855975.6515</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>89.8404668.1290789.9406259.3031389.5908688.732858</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>79.6630710.844711.546188.88900530.2306515.976311</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>31.7331720.3639319.3966882.5202919.87304423.869742</td>
<td></td>
</tr>
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<td>9</td>
<td>54.3740823.4807526.3163150.2499125.32272</td>
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</tr>
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<td>10</td>
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<td>11</td>
<td>11.367046.33172954.6352611.536646.3434446.946561</td>
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</tr>
<tr>
<td>12</td>
<td>11.9195528.3234916.5990316.309916.2169964.604331</td>
<td></td>
</tr>
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<td>13</td>
<td>23.9605984.413598.489999.251760914.038286.823108</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>27.8810523.517728.6159582.7530417.0304512.10772</td>
<td></td>
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<td>15</td>
<td>69.0441925.6086726.4886672.1320240.7408626.20642</td>
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<td>16</td>
<td>30.5676924.1858426.3696841.3508624.5176927.103051</td>
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<td>17</td>
<td>55.856069.87854510.4156949.4385427.9883396.067097</td>
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<td>18</td>
<td>9.11592712.4592211.0160670.026049.64694375.712248</td>
<td></td>
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<td>19</td>
<td>4.23732310.0942610.0269472.0435986.9634165.984619</td>
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<td>20</td>
<td>15.0911969.5658769.4442883.3458510.1882670.85112</td>
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</table>

### Table 2. The optimal generation and load levels in MW

<table>
<thead>
<tr>
<th>Generator or load</th>
<th>Smooth generation cost curve</th>
<th>Nonsmooth generation cost curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without line limits &amp; without TCSC</td>
<td>With line limits &amp; without TCSC</td>
<td>With line limits &amp; without TCSC</td>
</tr>
<tr>
<td>Without line limits &amp; with TCSC</td>
<td>With line limits &amp; with TCSC</td>
<td>With line limits &amp; with TCSC</td>
</tr>
<tr>
<td>G1</td>
<td>94.2208</td>
<td>89.8534</td>
</tr>
<tr>
<td>G2</td>
<td>100</td>
<td>100.530</td>
</tr>
<tr>
<td>G3</td>
<td>100</td>
<td>100.200</td>
</tr>
<tr>
<td>G4</td>
<td>92.8325</td>
<td>51.1333</td>
</tr>
<tr>
<td>L1</td>
<td>58.1066</td>
<td>108.712</td>
</tr>
<tr>
<td>L2</td>
<td>55.6320</td>
<td>135.506</td>
</tr>
<tr>
<td>L3</td>
<td>5.6311</td>
<td>6.6354</td>
</tr>
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<td>21.5454</td>
<td>33.1993</td>
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<td>L5</td>
<td>35.7925</td>
<td>25.67435</td>
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<tr>
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<td>51.8876</td>
<td>30.1815</td>
</tr>
<tr>
<td>L7</td>
<td>71.9098</td>
<td>5.31819</td>
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</table>
In this paper an algorithm for social welfare maximization with optimal locating (and sizing) of one TCSC unit and optimal rescheduling of generation and demand levels is proposed. Based on the simulation results for IEEE 14-bus system, the following conclusions are drawn:

- TCSC has the ability to redistribute power flow, influence loads and generations levels at different buses, and significantly increase the social benefit. Installation of TCSC offers benefit that far exceeds its cost for the system conditions studied.
- TCSC may have different impacts on the welfare of individual participants and may affect the pool price of each bus differently. Therefore, some participants may benefit more than others.
- The smoothness of the generator cost curves shows no significant impact on the line congestions; however, it will increase generation cost. This needs to be considered by ISO to get more accurate results and realistic cost analysis.

References


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This paper presents a genetic algorithm GA to perform congestion management and maximize social welfare by placement and sizing of one TCSC device. Conventional quadratic smooth and augmented quadratic nonsmooth generator cost curves and quadratic smooth consumer benefit functions are considered. By adding the valve point effect, the model presents nondifferentiable and nonconvex regions that challenge most gradient-based optimization algorithms. The aim of this paper is locating/sizing of TCSC and inclusion of customer benefit in the congestion management objective function, consideration of nonsmooth generator characteristics.

Table 3. Optimal location and size of one unit TCSC

<table>
<thead>
<tr>
<th>TCSC location</th>
<th>Smooth cost curve</th>
<th>Nonsmooth cost curve</th>
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<tbody>
<tr>
<td>Line 1</td>
<td>33.24946</td>
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</tr>
<tr>
<td>Line 14</td>
<td>15.57667</td>
<td>33.24946</td>
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Table 4. Cost coefficient parameters for the generators and loads

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>f</th>
<th>p^min</th>
<th>p^max</th>
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<tbody>
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<td>0</td>
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<tr>
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<td>0</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>L5</td>
<td>11</td>
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<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>L7</td>
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<td>L8</td>
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<td>12</td>
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</table>

Conclusions

In this paper an algorithm for social welfare maximization with optimal locating (and sizing) of one