Rstructuring of power system aims at involving the private power producers in the system to supply power. The restructured electric power industry is characterized by the competition in generation with guaranteed access to open transmission \[39,130\]. With the endeavor of achieving diversified customer choice of power suppliers and competitive electricity rates, vertically integrated utilities are broken down into generation, transmission and distribution entities. Transmission system, which acts as a common corridor between suppliers and customers, plays a significant role in the restructured market structure.

4.1 Total transfer capability

In restructured power market, power producers and customers will share the transmission network and try to maximize their benefits by procuring power

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from the cheapest available resources. This results in the violation of line flows, voltage and generation limits, affecting the system security and reliability to a greater extent. Hence there exists a technical challenge of finding the optimal balance between maximum power transfer capability and system stability margins. This is important as transfer capability values dominate critical decision making of many power system operations and planning. Hence, utilities need to accurately evaluate the total transfer capability (TTC) to ensure that system reliability is maintained. Total transfer capability is defined as the maximum power that can be transferred between different areas without violating system constraints. The value of TTC can be made more accurate by considering transmission reliability margin (TRM), which is the amount of transmission capability necessary to protect the transmission system against overloading.

A wide variety of mathematical methods and algorithms have been developed for calculating TTC. These methods can be divided into four types as follows: continuation power flow (CPF) method, repetitive power flow (RPF) method, linear available transfer capability (LATC) method and optimal power flow (OPF) based method.

The CPF method traces the power flow solution curve, starting at a base load, leading to the steady state voltage stability limit or the critical maximum loading point of power systems [41]. This method can overcome the singularity of the Jacobian matrix near the saddle node bifurcation point, or the critical point. However, more computational effort and convergence time are needed for this method.

The RPF method, based on a generalized search method, repeatedly solves conventional power flow equations, where the successive power flow solutions are obtained to establish the maximum transfer capability [131]. RPF uses a common loading factor to increase certain power for a cluster of generators
and loads. This leads to conservative TTC, since the optimal distribution of generation and load are ignored.

The LATC method is based on linear incremental power flow approximation, which calculates power transfer distribution factors (PTDF) to determine the transfer capabilities of power system \[45\]. This method is attractive since the factors are easy to calculate and can give rough figures of TTC quickly. However, this method is based on dc load flow, ignoring voltage and reactive power effects. This results in a stressed system with insufficient reactive power support and voltage control.

Yan Ou et al \[48\] have obtained TTC using transfer based security constrained optimal power flow method for IEEE 24 bus RTS system. Shaaban et al \[47\] calculated total transfer capability by considering the effect of reactive power using sequential quadratic programming. But this method is very sensitive to the initial starting point by which local optimum is detected.

To overcome the shortcomings of the above methods, many researchers have tried to calculate transfer capability by means of artificial intelligence techniques such as evolutionary programming (EP) \[67\], and hybrid continuous ant colony optimization \[132\]. Sensitivity based methods \[131,133,134\], and probabilistic methods \[62–64\] are also used to consider the impact of system uncertainties and evaluated transmission reliability margin.

In the present study, DE is used as an optimization tool to solve maximum power transfer optimal power flow problem in restructured power market. Contingencies in terms of single and multi line outages, generator outages and three phase faults are considered to evaluate TRM. While computing TTC between two areas, it is assumed that there is no change in load and generation of other connected areas since TTC value will be affected by such changes. The applicability of the method is investigated on IEEE 30 bus and Indian utility 62 bus systems with various cases of power transfers.
4.2 Problem formulation

In this section, estimation of total transfer capability is formulated as an optimal power flow problem. The objective is to maximize the power that can be transferred from a specific set of generators in a source area to loads in a sink area, subject to the constraints of load flow equations and system operation limits. The sum of real power loads in the sink area at the maximum power transaction is defined as the TTC value.

The objective function for the OPF-based TTC calculation is expressed mathematically as

\[
\text{Max } F = \sum_{i=1}^{ND_{SNK}} P_{Di}
\]

\[
P_{Gi} - P_{Di} - \sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) = 0
\]

\[
Q_{Gi} - Q_{Di} + \sum_{j=1}^{N} V_i V_j Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j) = 0
\]

\[
P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max} \quad i = 1, 2, \ldots, NG
\]

\[
Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \quad i = 1, 2, \ldots, NG
\]

\[
V_i^{\min} \leq V_i \leq V_i^{\max} \quad i = 1, 2, \ldots, N
\]

\[
|S_{Lij}| \leq S_{Lij}^{\max} \quad i, j = 1, 2, \ldots, NL
\]

where \( F \) is the total real power load of load buses in the sink area. \( P_{Gi} \) and \( Q_{Gi} \) are the real and reactive power generation at bus \( i \). \( P_{Di} \) and \( Q_{Di} \) are the real and reactive power load at bus \( i \). \( V_i \) and \( V_j \) are the voltage magnitudes at bus \( i \) and \( j \) respectively. \( Y_{ij} \) and \( \theta_{ij} \) are the magnitude and angle of the element \( i, j \) of bus admittance matrix. \( \delta_i \) and \( \delta_j \) are the voltage angles of bus \( i \) and \( j \). \( P_{Gi}^{\min} \) and \( P_{Gi}^{\max} \) are the lower and upper limits of real power generation at bus \( i \). \( Q_{Gi}^{\min} \) and \( Q_{Gi}^{\max} \) are the lower and upper limits of reactive power.
power generation at bus $i$, $V_{i}^{\text{min}}$ and $V_{i}^{\text{max}}$ are the lower & upper limits of voltage magnitude at bus $i$. $|S_{Lij}|$ is the apparent power flow and $S_{Lij}^{\text{max}}$ is the maximum MVA rating of the transmission line connecting buses $i$ and $j$. $N$ is the total number of buses. $NG$ is the total number of generators. $NL$ is the total number of branches and $ND_{SNK}$ is the total number of load buses in sink area.

4.3 Solution methodology

The TTC from the source area to the sink area is calculated using OPF based differential evolution method. From NERC’s definition $[39,130]$, TRM is the transfer capability that is reserved for any uncertainties that may occur in the near future. TRM can be calculated by deterministic and probabilistic methods $[39,48,130,133]$. In this work, TRM is included by introducing contingencies such as single & multi line outages, generator outages and a 3-Φ to ground fault. A base case ac power flow is established initially, in which the system load is supplied without violating the system constraints. Figures 4.1 and 4.2 show the base case power flows in the transmission lines of IEEE 30 & Indian utility 62 bus systems respectively. The base case is modified by varying the generation in the source area and the load in sink area simultaneously. This process continues until the contingency causes the violation of any one of the system limits such as thermal limit, voltage limit and stability limit. The minimum amount of power transfer among all the contingencies under any one of this violation, is taken as the TTC for the corresponding power transaction which is given by

$$TTC = \text{Min} \ (TTC_0, TTC_K) \quad (4.8)$$

where $TTC_0$ and $TTC_K$ are the maximum amount of power transfers without and with contingency $K$, respectively. The detailed algorithm of calculating
Chapter 4. Total transfer capability

Figure 4.1: Base case line flows – IEEE 30 bus system

Figure 4.2: Base case line flows – Indian utility 62 bus system
TTC using OPF based differential evolution method is given in the flow chart as shown in the figure 4.3. The adopted formulation for TTC calculation finds out the maximum additional allowable transactions without curtailing the existing ones.

![Flow chart for the evaluation of TTC](image)

Figure 4.3: Flow chart for the evaluation of TTC

4.4 Case study and results

The IEEE 30 bus (figure 4.4) and Indian utility 62 bus systems (figure 4.5) are used as the test systems to demonstrate the effectiveness of the proposed
method in determining the value of TTC. The IEEE 30 bus system is split into three areas with two generators in each area. Area 1 and Area 2 are interconnected by a tie line 4-12. The lines 10-17, 10-20 and 23-24 are the tie lines which connect areas 2 and 3. The base case real power loads in each area are 84.5, 56.2 and 48.5 MW respectively.

![Figure 4.4: One line diagram of IEEE 30 bus system with different areas](image)

An Indian utility 62 bus system has 19 generators, 89 numbers of transmission lines, 11 tap changing transformers with a power demand of 2909 MW. The system is divided into 3 areas with six generators in area 1 and area 3 respectively, whereas area 2 has seven generators. The base case real power loads of each area are 795, 1190 and 924 MW respectively. The simulation parameters for DE and PSO are given in Table 3.1.
4.4.1 Calculation of TTC without TRM

4.4.1.1 Transfer of power from area 2 to 1 – IEEE 30 bus system

In this case, the generating powers of area 2 and the real power load of area 1 are taken as the control variables and are varied randomly from their base values. The active loading vector of area 1 before and after this transaction is shown in the Table 4.1. It is found that the generation of area 2 reaches its maximum limit when the load of area 1 is 105.3972 MW which is the needed value of TTC. Figure 4.6 shows the convergence characteristics of TTC using
Table 4.1: Active loading of area 1

<table>
<thead>
<tr>
<th>Load bus numbers</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case load (MW)</td>
<td>21.7</td>
<td>2.4</td>
<td>7.6</td>
<td>22.8</td>
<td>30.0</td>
</tr>
<tr>
<td>Increased load using DE (MW)</td>
<td>33.0</td>
<td>2.9124</td>
<td>7.7439</td>
<td>30.0</td>
<td>31.7409</td>
</tr>
</tbody>
</table>

DE and PSO. It can be seen that DE gives more optimal values of TTC than PSO. The CPU time needed for DE and PSO are 31.6057 and 43.8154 seconds respectively for the above case.

![Figure 4.6](image)

Figure 4.6: Convergence characteristics for the transaction from area 2 to area 1 – IEEE 30 bus system

### 4.4.1.2 Transfer of power from area 2 to 3 – IEEE 30 bus system

In this case, the load of area 3 is varied randomly until any one of the system constraints is violated. Simultaneously, the generation of area 2 is also varied to meet the changing load in area 3. Using the proposed algorithm, the value of TTC is found to be 66.4664 MW. This value is taken when the generation of area 2 reaches its maximum limit. The active loading vector of area 3 before
and after transaction is shown in Figure 4.7. The CPU time required for DE and PSO are found to be 33.5843 and 44.5734 seconds respectively for this case. The TTC values obtained for both the cases of power transfer with their limiting conditions and other published results are given in Table 4.2. It is found that in both the cases of power transfer (2–1 and 2–3) TTC values given by DE are 6.4881% and 5.6548% greater than that obtained using PSO. This shows the robustness of DE over PSO. Such a better estimation of the TTC value helps the system operator to enhance the utilization of system capability for further operation and planning of the transmission network.

4.4.1.3 Transfer of power from area 1 to 2 – Indian utility 62 bus system

In this case, the load of area 1 is varied randomly until any one of the system constraints is violated. Simultaneously, the generation of area 2 is also varied to meet the changing load in area 1. Using the proposed algorithm, the value
Table 4.2: Comparison of results – IEEE 30 bus system

<table>
<thead>
<tr>
<th>Area</th>
<th>From</th>
<th>To</th>
<th>CPF</th>
<th>EP</th>
<th>PSO*</th>
<th>DE*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>88.50 (6-8)</td>
<td>98.77 (Generation of area 2)</td>
<td>98.9756 (6-8)</td>
<td>105.3972 (Generation of area 2)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3</td>
<td>51.50 (6-8)</td>
<td>62.65 (Generation of area 2)</td>
<td>62.9090 (6-8)</td>
<td>66.4664 (Generation of area 2)</td>
</tr>
</tbody>
</table>

*Results obtained in this study

of TTC is estimated to be 1608.7906 MW where the limiting condition is the violation of thermal limit in line 43. The variation of loads for this case is given in figure 4.8.
4.4.2 Calculation of TTC with TRM

4.4.2.1 Transfer of power from area 2 to 1 – IEEE 30 bus system

TTC including contingencies which involves single and multi line outages is carried out for this case. The tie line between area 2 and area 1(4–12), and transmission lines (5–7) & (14–15) of area 1 and area 2 respectively, are made out of service individually, and simultaneously. The outage of the line 5–7 is taken as the critical contingency which gives the least value of 99.9897 MW with the line 6–8 exceeding its maximum limits as shown in the figure 4.9. Apart from the line contingencies, a 3-Φ to ground fault is also introduced as an uncertainty in the transmission line connected between the buses 6 & 9. Due to this fault, the generator rotor angles swing rapidly and may result in
system instability. To ensure stability, this fault is subsequently cleared by isolating the faulty line from the system after 50ms. Rotor angle characteristics of each generator of the system are shown in the figure 4.10. It can be seen that rotor angles are within the safer limit (−45° to 45°) and hence the system security is ensured. The value of TTC obtained for the above case is found to be 97.8425MW.

4.4.2.2 Transfer of power from area 2 to 3 – IEEE 30 bus system

The tie lines between area 2 and area 3 (10-17, 10-20 and 23-24), are made out of service individually and multi line contingency is introduced by the outage of one of the tie line 10-17 and the line 14-15 of area 2 simultaneously. The TTC value obtained for each transfer case, and their respective limiting conditions are given in Table 4.3. The value of TTC obtained for the above

![Figure 4.10: Generator relative rotor angle curves – IEEE 30 bus system](image-url)
Table 4.3: TTC with TRM for area 2–3 — IEEE 30 bus system

<table>
<thead>
<tr>
<th>Cases</th>
<th>TTC (MW)</th>
<th>Limiting condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>66.4664</td>
<td>Generation of area 2</td>
</tr>
<tr>
<td>10-17</td>
<td>76.0019</td>
<td>6-8</td>
</tr>
<tr>
<td>10-20</td>
<td>60.7472</td>
<td>15-18</td>
</tr>
<tr>
<td>23-24</td>
<td>58.1763</td>
<td>21-22</td>
</tr>
<tr>
<td>10-17 and 14-15</td>
<td>66.7877</td>
<td>6-8</td>
</tr>
</tbody>
</table>

case is found to be 58.1763MW, after the outage of tie line (23-24). Figure 4.11 shows the convergence characteristics for the above case. Figure 4.12 shows the line flows in MVA for the transaction from area 2 to area 3 using DE algorithm. Lines 11(6-8), line 27(15-18) and line 32(21-22) are the violated lines as shown in the figure 4.12 corresponding to the respective contingencies. The variation of real power loads in the sink area (area 3) with respect to the base case values is shown in figure 4.13.

Figure 4.11: Convergence characteristics for various contingencies from area 2 to area 3 using DE – IEEE 30 bus system
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Figure 4.12: Line flows for the transaction from area 2 to area 3 using DE – IEEE 30 bus system

Figure 4.13: Variation of loads for the transaction from area 2 to area 3 using DE – IEEE 30 bus system
A 3-Φ to ground fault is introduced in the transmission line connected between buses 10 & 21. This is cleared after 50ms as before, and the system is found to be stable. The value of TTC for this case is found to be 56.3531MW.

### 4.4.2.3 Transfer of power from area 1 to 2 – Indian utility 62 bus system

In this case, contingencies such as single line, multi line and generator outages are included in the system. The tie lines between area 1 and area 2, and the largest generator among the two areas, are made out of service individually and multi line contingency is introduced by the outage of lines 49-50 and 58-60 of area 1 and 2 simultaneously. The TTC values obtained for each case are given in Table 4.4. The lowest among these values (1564.27MW), is obtained during the multi line contingency by limiting the line 43 connected between the buses 31 and 32. Figure 4.14 shows convergence characteristics for the above case. Lines 43(31-32), 78(55-58) and 58(39-42) are found to be the most violated lines during various contingencies as shown in the figure 4.15.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Normal</th>
<th>line 52-61</th>
<th>line 55-58</th>
<th>line 59-61</th>
<th>line 62-61</th>
<th>lines 49-50 &amp;58-60</th>
<th>largest generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTC</td>
<td>1608.79</td>
<td>1577.82</td>
<td>1604.47</td>
<td>1613.25</td>
<td>1580.80</td>
<td>1564.27</td>
<td>1605.81</td>
</tr>
</tbody>
</table>

### 4.5 Conclusions

This chapter presents a detailed formulation and implementation of the OPF based TTC calculation with transmission reliability margin using differential evolution algorithm. The algorithm is tested on the IEEE 30 bus and Indian
Figure 4.14: Convergence characteristics for various contingencies from area 1–2 using DE – Indian utility 62 bus system

Figure 4.15: Line flows (MVA) for area 1–2 using DE – Indian utility 62 bus system
utility 62 bus systems. Results show that the proposed method is very effective with good convergence characteristics compared to particle swarm optimization, in determining the TTC between the different areas subjected to the system operation limits. Also, the results obtained by DE are better than the previously reported methods like CPF \[47\] & EP \[67\] (Table 4.2) and the CPU time needed for convergence is less. The accuracy of TTC is improved by considering TRM in the calculation. Also it is concluded that the total transfer capability is less when TRM is considered.