CHAPTER 5

CHAPTER 5: AVAILABLE TRANSFER CAPABILITY COST ALLOCATION IN ELECTRICITY MARKET

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5.1 INTRODUCTION

In previous chapter, the analysis on reactive power and its cost allocation is presented. For that, different reactive power allocation including its cost allocation methods have been presented and analyzed.

In this chapter, the analysis of ATC using reactive power flows is discussed [24]. The power transaction based cost allocation of ATC is also presented.

ATC has an important role in the network to know the available capacity of the system. It serves the network in the case of contingency, system planning and future expansion. The estimation of ATC should be quick and accurate in the electricity market. The ATC is the measure of system transfer capability for further marketing activities over and above previously committed agreements.

Some possible errors are initiated by the linear methods while finding the ATC. These errors are:

i) Ignoring the nonlinear character of active power flows

ii) Neglecting reactive power flows

iii) Neglecting voltage limits

In this chapter, a novel method is proposed to overcome the above errors. By using this method, the ATC can be enhanced by considering reactive power flows. Further, it appears that no attempt has been made with respect to ATC cost analysis. Hence, in this chapter, ATC and its cost allocation based on power transactions are considered and an algorithm is developed.
In Section 5.2, the computation procedure of Linear ATC is presented. In Section 5.3, the computation procedure of Enhanced Linear ATC is presented. In Section 5.4, the power transaction based ATC and its cost allocation is presented. In Section 5.5, the case study I, sample 5 bus system including theoretical calculation and its results is presented. In Section 5.6, the results and analysis of IEEE 14 bus system are presented. In Section 5.7, the conclusions of the chapter are presented.

5.2 Linear ATC (LATC)

In this method [14], the DC power flow solution is used as a base case solution. The linear method of ATC considers the system as lossless system. In the lossless system, the variations in the branch active power flows are linearly interrelated with variations in the net active power insertions. For analysis, an end to end transfer from slack bus ‘s’ to any other bus ‘i’ is to be considered and this transfer should be maximized without crossing the line limits. In this section, an attempt has been made to calculate linear ATC by neglecting the reactive power flows in the system.

5.2.1 Power Shift Distribution Factor (PSDF)

In the procedure of calculating ATC, the MW power flows must be distributed to each branch in fraction to the power flow in MW is transmitting by each transaction. This can be done by using PSDF [44].

The PSDF is a coefficient of linear connection among the transaction and flow in a branch. The PSDF is the part of the quantity
of transaction from one bus to other over a transmission line. For illustration, it can be defined as the large variation sensitivities and are used to forecast the power flow variation in the line (j-k) due to the transfer (s to i). The PSDF can be formulated as:

\[ \rho_{j,k} = \frac{\partial P_{j}}{\partial P_{s}} = -\frac{\partial P_{j}}{\partial P_{i}} \]  

...(5.1)

where, \( \rho_{j,k} = \) PSDF

\( \partial P_{j} = \) Power flow variation in line j-k

\( \partial P_{s} = \) Power injected from bus 's'

\( \partial P_{i} = \) Power injected to bus 'i'

### 5.2.2 Computation of LATC

As the system considered in this procedure is a lossless system, the power injected from bus 's' is equal to the power received by the bus 'i'. For a specified positive line maximum power flow \( (P_{j,k}^{\text{max}}) \) and an initial positive line power flow \( (P_{j,k}^{0}) \), the size of the transfer that takes the line to its maximum value is equal to:

\[
\Delta P_{s}^{j,k} = \begin{cases} 
\frac{P_{j,k}^{\text{max}} - P_{j,k}^{0}}{\rho_{j,k,i}} & \rho_{j,k,i} > 0 \\
\frac{P_{j,k}^{\text{max}} - P_{j,k}^{0}}{-\rho_{j,k,i}} & \rho_{j,k,i} < 0 
\end{cases} 
\]  

...(5.2)

The linear ATC (LATC) can be calculated by taking the minimum value of \( \Delta P_{s}^{j,k} \) as:

\[ LATC_{s\rightarrow i} = \min \{ \Delta P_{s}^{j,k} : \text{all lines } jk \} \]  

...(5.3)
5.3 ENHANCED LINEAR ATC (ELATC)

To analyze the effect of ignoring the reactive power flows, an enhanced linear method of ATC [24] is discussed in this chapter. For that, a discussion on complex power flows is presented in this section.

5.3.1 Branch Complex Power Flows

From the \( \pi \) model of the transmission line shown in the Fig. 5.1, the complex power flow from bus 'j' to bus 'k' is formulated as [24]:

\[
S_{jk} = P_{jk} + jQ_{jk} \\
= V_j^2 G_{jk} - V_j V_k Y_{jk} \cos(\theta_j - \theta_k + \alpha_{jk}) + j[-V_j^2 B_{jj} - V_j^2 B_{jk} - V_j V_k Y_{jk} \sin(\theta_j - \theta_k + \alpha_{jk})]
\] ...(5.4)

The real and reactive terms in the Eqn. (6.4) can be separated as:

\[
P_{jk} - V_j^2 G_{jk} = -V_j V_k Y_{jk} \cos(\theta_j - \theta_k + \alpha_{jk})
\]
\[
Q_{jk} + V_j^2 B_{jj} + V_j^2 B_{jk} = -V_j V_k Y_{jk} \sin(\theta_j - \theta_k + \alpha_{jk})
\] ...(5.5)

By applying the square on both sides and adding to the Eqn. (5.5) becomes:

\[
(P_{jk} - V_j^2 G_{jk})^2 + (Q_{jk} + V_j^2 B_{jj} + V_j^2 B_{jk})^2 = (V_j V_k Y_{jk})^2
\] ...(5.6)

With the basic assumption of the linear ATC, the Eqn. (5.6) characterize a circle on the \( P_{jk} - Q_{jk} \) plane having a center and radius as:

\[
(P_{jk} \theta \cdot Q_{jk} \theta) = (V_j^2 G_{jk} ; -V_j^2 B_{jj} - V_j^2 B_{jk})
\] ...(5.7)
\[ S_{j\theta} = V_j V_k Y_{j\theta} \]  

...(5.8)

where, \( \Theta \) represents the constant circle component.

By substituting Eqns. (5.7) and (5.8) in Eqn. (5.6) it is obtained as:

\[ (P_j - P_{j\theta})^2 + (Q_j - Q_{j\theta})^2 = S_{j\Theta}^2 \]  

...(5.9)

But, the flow of complex power at the sending end is different from receiving end. The above equation represents the complex flow at bus ‘j’ and the complex flow at bus ‘k’ is formulated as:

\[ (P_{kj} - P_{kj\theta})^2 + (Q_{kj} - Q_{kj\theta})^2 = S_{kj\theta}^2 \]  

...(5.10)

The power flow in the line changes as the power transfer increases. But, all operating points of the \( P_j - Q_j \) plane are lying in the operating circle as shown in the Fig. 5.2.

**Fig. 5.2 Representation of Different Circles**

In this plane, the MVA rating of the branch is characterized as a circle having the center at origin and the thermal limit \( S_{j\theta}^{\text{max}} \) will be the radius and this circle is represented as limiting circle shown in Fig. 5.2.
The ELATC computation requires the finding of maximum $\Delta P_i$ for the transfer ‘s’ to ‘i’ by maintaining the flow within the limiting circle i.e., $|S_{ik}| \leq S_{ik}^{max}$ for all lines.

### 5.3.2 Inclusion of Reactive Power Flows

The maximum complex power flow for the branch $j-k$ is related to the point $(P^*_j, Q^*_j)$ as the complex power flow is controlled by operating and limiting circles. Based on the sign of PSDF, $P^*_j$ has two types of solutions.

The procedure for finding $P^*_j$ and $Q^*_j$ is as:

$$P^2_j + Q^2_j = (S_{j,k}^{max})^2 \quad \text{...(5.11)}$$

By expanding the Eqn. (6.9) and subtracting Eqn. (6.11) from that, it is obtained as:

$$Q_j = \frac{1}{2Q_{j,k}^{\theta}} \left( -2P_{j,k}^{\theta} + \left(S_{j,k}^{max} \right)^2 - M^2 \right) \quad \text{...(5.12)}$$

where, $M^2 = S_{j,k}^{2\theta} - P_{j,k}^{2\theta} - Q_{j,k}^{2\theta}$

By substituting Eqn. (6.12) in Eqn. (6.11), the quadratic equation in terms of $P^*_j$ is obtained as:

$$\left(P_{j,k}^{2\theta} + Q_{j,k}^{2\theta}\right)P^2_j - P_{j,k}^{2\theta} \left(S_{j,k}^{max} \right)^2 - M^2 \right)P^*_j + \frac{1}{4} \left(S_{j,k}^{max} \right)^2 - M^2 \right) = 0 \quad \text{...(5.13)}$$

Now, the maximum complex power flow solution is attained as:

$$P^*_j = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad \text{...(5.14)}$$

$$Q^*_j = \sqrt{(S_{j,k}^{max})^2 - P^*_j^2} \quad \text{...(5.15)}$$

where,
\[
\begin{align*}
    a &= \left( P_{jk}^2 + Q_{jk}^2 \right) \\
    b &= -P_{jk} \left( S_{jk}^\text{max}^2 - M^2 \right) \\
    c &= \frac{1}{4} \left( S_{jk}^\text{max}^2 - M^2 \right)^{\frac{3}{2}} - Q_{jk}^2 \left( S_{jk}^\text{max}^2 \right)^2
\end{align*}
\]

For a specified positive line maximum power flow \( P_{jk}^* \) and an initial positive line power flow \( P_{jk}^0 \), the size of the transfer that takes the line to its maximum value is equal to:

\[
\Delta P_{jk}^* = \begin{cases} 
    \frac{P_{jk}^* - P_{jk}^0}{\rho_{jk,i}} & \rho_{jk,i} > 0 \\
    \frac{-P_{jk}^* - P_{jk}^0}{\rho_{jk,i}} & \rho_{jk,i} < 0 
\end{cases} \quad \ldots(5.16)
\]

The Enhanced linear ATC (ELATC) can be calculated by taking the minimum value of \( \Delta P_{jk}^* \) as:

\[
\text{ELATC}_{i \rightarrow j} = \min \{ \Delta P_{jk}^*: \text{all lines } jk \} \quad \ldots(5.17)
\]

### 5.3.3 Algorithm for Computing ELATC

The steps in the algorithm for calculation of ELATC are arranged as:

i) Read input data, \( V_j, V_k, Y_{jk}, B_{jj}, G_{jk}, \text{ and } B_{jk} \)

ii) Compute PSDF \( (\rho_{jk,i}) \) using Eqn. (5.1)

iii) Compute \( P_{jk}^* \) using Eqn. (5.14)

iv) Calculate \( \Delta P_{jk}^* \) using Eqn. (5.16)

v) Calculate ELATC using Eqn. (5.17)

vi) Stop.
Flow Chart:

Start

Read input data and run the power flow

Compute PSDF using Eqn. (5.1)

Compute $P_{jk}^*$ using Eqn. (5.14)

Calculate $\Delta P_{jk}^{*s}$ using Eqn. (5.16)

Calculate ELATC using Eqn. (5.17)

Compute power transactions using Eqn. (5.18)

Allocate ATC & its cost to transactions using Eqns. (5.19) & (5.20)

Stop

Fig. 5.3 Flow Chart for ELATC and its Cost Allocation

The flow chart which describes the procedure of ELATC and its cost allocation is presented in the Fig. 5.3.
5.4 POWER TRANSACTION BASED ATC AND ITS COST ANALYSIS
In this chapter, an attempt has been made i.e., the cost analysis of ATC based on power transactions.

5.4.1 Creation of Power Transactions
As an initial step, the power transactions based on ATCs of branches have been created for each and every line in the given system. The creation of power transaction can be formulated as:

\[ PT_{jk} = \frac{\Delta P_{jk}^{+}}{\sum_{i} \Delta P_{i}^{+}} \times 100 \]  \hspace{1cm} \ldots(5.18)

5.4.2 ATC and its Cost Allocation
After the creation of power transactions, the ATC allocation for each transaction can be computed as:

\[ ATC_i = PT_{jk} \times \min(\Delta P_{i}^{+}) \]  \hspace{1cm} \ldots(5.19)

Now, the cost allocation of ATC for each transaction can be calculated as:

\[ ATC_{iC} = ATC_i \times C_{jk} \]  \hspace{1cm} \ldots(5.20)

where,  \[ C_{jk} = \text{Line Cost in Rs./MW}. \]

5.5 CASE STUDY – I: SAMPLE 5 BUS SYSTEM
In this chapter, the sample 5 bus system shown in Fig. A1 [24] is used as one of the case studies for illustration of different methods to calculate LATC and ELATC. The input data for this system is given in Appendix-A (Tables A1 and A2).

The theoretical calculations for the computation of LATC and ELATC are presented in this section.
5.5.1 Theoretical Calculations for PSDF

Using Eqn. (5.1), the values for PSDF for each line are obtained as follows from the load flow analysis when the bus 1 in the above 5 bus system is considered as seller bus and bus 3 is considered as buyer bus:

\[
PSDF = \begin{bmatrix}
0.5707 \\
1.4375 \\
0.7601 \\
-0.3303 \\
-0.1459 \\
0.2616 \\
\end{bmatrix}
\]

5.5.2 Theoretical Calculations for LATC

Using Eqn. (5.2), the LTAC for each line can be calculated as:

The calculation of \( P_{jk}^{\text{max}} \) for line 1 is as:

\[
P_{1}^{\text{max}} = \text{Sign}(PSDF) \times \text{Line Rate} = 1 \times 100 = 100 \text{ MW}
\]

where, line rate is taken from load flow analysis.

Similarly, the \( P_{jk}^{\text{max}} \) values obtained for line 2, 3, 4, 5 and 6 are 130MW, 140MW, -130MW, -130MW and 130MW.

Now, \( P_{jk}^{\text{max \ vector}} = \begin{bmatrix}
100 \\
130 \\
140 \\
-130 \\
-130 \\
130 \\
\end{bmatrix} \)
Now, the initial line flow vector for all lines, \( P_{jk}^0 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \)

Now, LATC for line 1 using Eqn. (5.2) can be calculated as:

\[
LATC_1 = \frac{100 - 0}{0.5707} = 175.22 \text{MW}
\]

Similarly, for lines 2, 3, 4, 5 and 6 the LATCs are 90.43MW, 184.19MW, 393.52MW, 890.80MW and 496.88MW.

Now, the LATC vector is, \( LATC = \begin{bmatrix} 175.22 \\ 90.43 \\ 184.19 \\ 393.52 \\ 890.80 \\ 496.88 \end{bmatrix} \)

Now, using Eqn. (5.3), the final linear ATC (LATC) is the minimum value of the LATC vector i.e., 90.43MW and this is the values of LATC without reactive power flows in the system.

**5.5.3 Theoretical Calculations for ELATC**

Using Eqn. (5.4), the values of \( V_j, V_k, Y_{jk}, B_j, G_{jk} \) and \( B_{jk} \) are calculated for complex power flows as:

From load flow analysis, the value of \( V_1 = 1.04 \) and the value of \( V_3 = 1 \).

\[
Y_{13} = \frac{1}{R + jX} = 0 - j12.5 \text{ and } Y_{13} = \text{abs}(Y_{13}) = 12.5
\]

\[
B_{11} = \frac{B_{jk}}{2} = 0
\]

\[
G_{13} = \Re(Y_{13}) = 0 \text{ and } B_{13} = \Im(Y_{13}) = -12.5
\]
Now, using Eqn. (5.7), the values of $P_{jk\theta}$ and $Q_{jk\theta}$ are calculated as:

$$P_{13\theta} = (1.04)^2 \times 0 = 0$$
$$Q_{13\theta} = -(1.04)^2 \times 0 - (1.04)^2 \times (-12.5) = 13.5$$

Now, using Eqn. (5.8), the value of $S_{jk\theta}$ is calculated as:

$$S_{13\theta} = (1.04) \times (1) \times 12.5 = 13$$
$$S_{13}^{\text{max}} = 1.3$$

Now, using Eqn. (5.12), the value of $M^2$ is calculated as:

$$M^2 = S_{13\theta}^2 - P_{13\theta}^2 - Q_{13\theta}^2 = 13^2 - 0 - 13.5^2 = -13.25$$

Now, using Eqns. (5.14) and (5.15) the values of $P^*_jk$ and $Q^*_jk$ are calculated as:

$$a = (P_{13\theta}^2 + Q_{13\theta}^2) = 182.25$$
$$b = -P_{13\theta} \left( S_{13}^{\text{max}} \right)^2 - M^2 \right) = 0$$
$$c = \frac{1}{4} \left( S_{13}^{\text{max}} \right)^2 - M^2 \right) - Q_{13\theta}^2 \left( S_{13}^{\text{max}} \right)^2 = -304.2$$

Now, $P^*_{13} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = 1.29$
$$Q^*_{13} = \sqrt{\left( S_{jk}^{\text{max}} \right)^2 - P^*_{jk}^2} = 0.16$$

The calculation of ELATC from the algorithm steps is as:

Now, replacement of $P_{jk}^{\text{max}}$ by $P^*_jk$ for line 2 is as:

$$P^*_{13} = 1 \times 129 = 129 \text{ MW}$$

Similarly, the $P^*_jk$ values attained for line 2, 3, 4, 5 and 6 are 100 MW, 140 MW, -130MW, -130MW and 130MW.
Now, the initial line flow vector for all lines, $P^0_{jk} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$

Now, ELATC for line 2 using Eqn. (5.16) is calculated as:

$$ELATC_2 = \frac{129 - 0}{1.4375} = 89.74 \text{ MW}$$

Similarly, for line 1, 3, 4, 5 and 6 the ELATC values attained are 175.22 MW, 184.19 MW, 393.52 MW, 890.80 MW and 496.88 MW.

Now, the ELATC vector is, $ELATC = \begin{bmatrix} 175.22 \\ 89.74 \\ 184.19 \\ 393.52 \\ 890.80 \\ 496.88 \end{bmatrix}$

Now, using Eqn. (5.17), the final ELATC is the minimum value of the ELATC vector i.e., 89.74 MW and this is the value of ELATC with reactive power flows in the system.

From the values of LATC and ELATC, it is observed that the values of line 2 (90.43 MW and 89.74 MW) are less when compared to other lines. So, the line 2 is the limiting line among all three lines.
But, the actual ATC value for line 2 is 89.00MW and is taken directly from the AC power flow. Now, the error in the ATC value from actual ATC and other two linear ATC values can be calculated.

The error between the actual ATC and LATC

$$\frac{|90.43 - 89|}{89} \times 100 = 1.6\%$$

The error between the actual ATC and ELATC

$$\frac{|89.74 - 89|}{89} \times 100 = 0.83\%$$

From the above error values it is observed that, the value of ELATC is very near to the value of actual ATC and the error (0.83%) is also less when compared LATC i.e., 1.6%.

5.5.4 Theoretical Calculations for ELATC and its Cost Allocation

Using Eqn. (5.18), the transactions for each line are calculated as:

Calculation of transaction 1:

$$PT_1 = \left[ \frac{175.22}{175.22 + 89.74 + 184.19 + 393.52 + 890.80 + 496.88} \right] \times 100 = 7.85\%$$

Similarly, for transactions 2, 3, 4, 5 and 6 are 4.02%, 8.25%, 17.65%, 39.93% and 22.28%

Using Eqn. (5.19), the allocation of ELATC is computed as:

Allocation of ELATC for transaction 1:

$$ELATC_1 = 0.0785 \times 89.74 = 7.04MW$$

Similarly, ELATC allocation for transaction 2, 3, 4, 5 and 6 are 3.6MW, 7.4MW, 15.83MW, 35.83MW and 19.99MW.

Using Eqn. (5.20), the cost allocation of ELATC is calculated as:
For cost allocation of ELATC, the transaction cost is considered as 150 Rs./MWh.

ELATC cost allocation to transaction 1:

\[ ELATC_{\text{Cost-1}} = 7.04 \times 150 = \text{Rs.} 1056/h \]

Similarly, the cost allocation for transaction 2, 3, 4, 5 and 6 are Rs. 540/h, Rs. 1110/h, Rs. 2374.5/h, Rs. 5374.5/h and Rs. 2998.5/h.

**5.5.5 Simulation Results for 5 Bus System**

The simulation results obtained for sample 5 bus system from MATLAB program are presented in this section. The analysis of the results is also discussed in this section.

The values of line limit, PSDF and LATC without reactive power when bus 1 is used as seller bus and bus 3 is used as buyer bus are presented in the Table 5.1.

**Table 5.1 Values of Linear ATC**

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Line Limit (MW)</th>
<th>PSDF</th>
<th>LATC (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100.00</td>
<td>0.5707</td>
<td>175.22</td>
</tr>
<tr>
<td>2</td>
<td>130.00</td>
<td>1.4375</td>
<td><strong>90.43</strong></td>
</tr>
<tr>
<td>3</td>
<td>140.00</td>
<td>0.7601</td>
<td>184.19</td>
</tr>
<tr>
<td>4</td>
<td>-130.00</td>
<td>-0.3303</td>
<td>393.52</td>
</tr>
<tr>
<td>5</td>
<td>-130.00</td>
<td>-0.1459</td>
<td>890.80</td>
</tr>
<tr>
<td>6</td>
<td>130.00</td>
<td>0.2616</td>
<td>496.88</td>
</tr>
</tbody>
</table>

In this, line 2 is the limiting line and the LATC is 90.43 MW.
The values of line limit, PSDF and ELATC with reactive power when bus 1 is used as seller bus and bus 3 is used as buyer bus are presented in the Table 5.2.

### Table 5.2 Values of Enhanced Linear ATC

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Line Limit (MW)</th>
<th>PSDF</th>
<th>ELATC (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100.00</td>
<td>0.5707</td>
<td>175.22</td>
</tr>
<tr>
<td>2</td>
<td>129.00</td>
<td>1.4375</td>
<td><strong>89.74</strong></td>
</tr>
<tr>
<td>3</td>
<td>140.00</td>
<td>0.7601</td>
<td>184.19</td>
</tr>
<tr>
<td>4</td>
<td>-130.00</td>
<td>-0.3303</td>
<td>393.52</td>
</tr>
<tr>
<td>5</td>
<td>-130.00</td>
<td>-0.1459</td>
<td>890.80</td>
</tr>
<tr>
<td>6</td>
<td>130.00</td>
<td>0.2616</td>
<td>496.88</td>
</tr>
</tbody>
</table>

In this also, line 2 is the limiting line and the ELATC value is 89.74MW.

The actual value of the ATC from AC power flow is 89MW. From the above results it is observed that the ELATC value i.e. 89.74MW is very near to the actual ATC value. The error between the actual ATC and the LATC is 1.6% and the error between actual ATC and ELATC is 0.83%.

Hence, it is concluded that, the ATC value with reactive power flows is very near to the actual ATC with less error. This reduction in error represents the benefit from ELATC. When considering bus 1 as seller bus and bus 3 as buyer bus, the line 2 will be the limiting bus.
i.e., the line between bus 1 and 3 and at this the system operator can get the ATC.

The values ELATC allocation and its cost allocation to each transaction when bus 1 is used as seller bus and bus 3 is used as buyer bus are presented in the Table 5.3.

**Table 5.3 ELATC and its Cost Allocation**

<table>
<thead>
<tr>
<th>Transaction No.</th>
<th>ELATC Allocation (MW)</th>
<th>ELATC Cost (in Rs./h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.04</td>
<td>1056.00</td>
</tr>
<tr>
<td>2</td>
<td>3.6</td>
<td>540.00</td>
</tr>
<tr>
<td>3</td>
<td>7.4</td>
<td>1110.00</td>
</tr>
<tr>
<td>4</td>
<td>15.83</td>
<td>2374.50</td>
</tr>
<tr>
<td>5</td>
<td>35.83</td>
<td>5374.50</td>
</tr>
<tr>
<td>6</td>
<td>19.99</td>
<td>2998.50</td>
</tr>
</tbody>
</table>

From the above results, the transaction 2 is allocated by less ELATC and its cost when compared to other transactions because this transaction is the limiting transaction. The system operator always allocates the less cost for the limiting transactions as their thermal limit is less compared to others.

**5.6 CASE STUDY – II: IEEE 14 BUS SYSTEM**

In this chapter, the IEEE 14 bus system is used as one of the case studies for illustrating the performance of different methods
calculating linear ATC. The input data for IEEE 14 bus system is presented in appendix-B (Tables B1 to B5) [23].

5.6.1 Simulation Results and Analysis of LATC and ELATC

In this section, the results obtained for LATC and ELATC from MATLAB programming using IEEE 14 bus system are presented.

The values of line limit, PSDF and LATC without reactive power when bus 1 is used as seller bus and bus 8 is used as buyer bus are presented in the Table 5.4.

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Line Limit (MW)</th>
<th>PSDF</th>
<th>LATC (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200.00</td>
<td>0.7475</td>
<td>56.53</td>
</tr>
<tr>
<td>2</td>
<td>100.00</td>
<td>0.3681</td>
<td>67.90</td>
</tr>
<tr>
<td>3</td>
<td>100.00</td>
<td>0.1584</td>
<td>166.61</td>
</tr>
<tr>
<td>4</td>
<td>100.00</td>
<td>0.3182</td>
<td>137.45</td>
</tr>
<tr>
<td>5</td>
<td>100.00</td>
<td>0.2290</td>
<td>254.04</td>
</tr>
<tr>
<td>6</td>
<td>100.00</td>
<td>0.1476</td>
<td>833.11</td>
</tr>
<tr>
<td>7</td>
<td>-100.00</td>
<td>-0.3526</td>
<td>113.15</td>
</tr>
<tr>
<td>8</td>
<td>100.00</td>
<td>0.6369</td>
<td>113.62</td>
</tr>
<tr>
<td>9</td>
<td>100.00</td>
<td>0.1649</td>
<td>510.54</td>
</tr>
<tr>
<td>10</td>
<td>100.00</td>
<td>0.2010</td>
<td>273.26</td>
</tr>
<tr>
<td>11</td>
<td>100.00</td>
<td>0.1224</td>
<td>753.25</td>
</tr>
<tr>
<td>12</td>
<td>100.00</td>
<td>0.0156</td>
<td>5920.50</td>
</tr>
<tr>
<td>13</td>
<td>100.00</td>
<td>0.0631</td>
<td>1296.48</td>
</tr>
<tr>
<td>14</td>
<td>100.00</td>
<td>0.9992</td>
<td>99.98</td>
</tr>
<tr>
<td>15</td>
<td>-100.00</td>
<td>-0.3623</td>
<td>352.04</td>
</tr>
<tr>
<td>16</td>
<td>-100.00</td>
<td>-0.1204</td>
<td>870.46</td>
</tr>
<tr>
<td>17</td>
<td>-100.00</td>
<td>-0.0769</td>
<td>1417.15</td>
</tr>
<tr>
<td>18</td>
<td>-100.00</td>
<td>-0.1201</td>
<td>797.86</td>
</tr>
<tr>
<td>19</td>
<td>100.00</td>
<td>0.0153</td>
<td>6439.21</td>
</tr>
<tr>
<td>20</td>
<td>100.00</td>
<td>0.0768</td>
<td>1223.02</td>
</tr>
</tbody>
</table>
In this, line 1 is the limiting line and the LATC is 56.53MW.

The values of line limit, PSDF and ELATC with reactive power when bus 1 is used as seller bus and bus 8 is used as buyer bus are presented in the Table 5.5.

**Table 5.5 Values of Enhanced Linear ATC**

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Line Limit (MW)</th>
<th>PSDF</th>
<th>ELATC (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>197.82</td>
<td>0.7475</td>
<td>53.61</td>
</tr>
<tr>
<td>2</td>
<td>100.00</td>
<td>0.3681</td>
<td>67.90</td>
</tr>
<tr>
<td>3</td>
<td>100.00</td>
<td>0.1584</td>
<td>166.61</td>
</tr>
<tr>
<td>4</td>
<td>100.00</td>
<td>0.3182</td>
<td>137.45</td>
</tr>
<tr>
<td>5</td>
<td>100.00</td>
<td>0.2290</td>
<td>254.04</td>
</tr>
<tr>
<td>6</td>
<td>100.00</td>
<td>0.1476</td>
<td>833.11</td>
</tr>
<tr>
<td>7</td>
<td>-100.00</td>
<td>-0.3526</td>
<td>113.15</td>
</tr>
<tr>
<td>8</td>
<td>100.00</td>
<td>0.6369</td>
<td>113.62</td>
</tr>
<tr>
<td>9</td>
<td>100.00</td>
<td>0.1649</td>
<td>510.54</td>
</tr>
<tr>
<td>10</td>
<td>100.00</td>
<td>0.2010</td>
<td>273.26</td>
</tr>
<tr>
<td>11</td>
<td>100.00</td>
<td>0.1224</td>
<td>753.25</td>
</tr>
<tr>
<td>12</td>
<td>100.00</td>
<td>0.0156</td>
<td>5920.50</td>
</tr>
<tr>
<td>13</td>
<td>100.00</td>
<td>0.0631</td>
<td>1296.48</td>
</tr>
<tr>
<td>14</td>
<td>100.00</td>
<td>0.9992</td>
<td>99.98</td>
</tr>
<tr>
<td>15</td>
<td>-100.00</td>
<td>-0.3623</td>
<td>352.04</td>
</tr>
<tr>
<td>16</td>
<td>-100.00</td>
<td>-0.1204</td>
<td>870.46</td>
</tr>
<tr>
<td>17</td>
<td>-100.00</td>
<td>-0.0769</td>
<td>1417.15</td>
</tr>
<tr>
<td>18</td>
<td>-100.00</td>
<td>-0.1201</td>
<td>797.86</td>
</tr>
<tr>
<td>19</td>
<td>100.00</td>
<td>0.0153</td>
<td>6439.21</td>
</tr>
<tr>
<td>20</td>
<td>100.00</td>
<td>0.0768</td>
<td>1223.02</td>
</tr>
</tbody>
</table>
In this also, line 1 is the limiting line and the ELATC value is 53.61MW.

The actual value of the ATC from AC power flow is 54.00MW. From the above results it is observed that the ELATC value i.e 53.61MW is very near to the actual ATC value. The error between the actual ATC and the LATC is 4.68% and the error between actual ATC and ELATC is -0.72%.

Hence, it is concluded that, the ATC value with reactive power flows is very near to the actual ATC with less error. This reduction in error represents the benefit from ELATC. When considering bus 1 as seller bus and bus 8 as buyer bus, the line 1 will be the limiting bus i.e., the line between bus 1 and 8 and at this the system operator can get the ATC.

The values ELATC allocation and its cost allocation to each transaction when bus 1 is used as seller bus and bus 8 is used as buyer bus are presented in the Table 5.6.
From the above results, the transaction 1 is allocated less ELATC and its cost when compared to other transactions because this transaction is the limiting transaction. The system operator always allocates the less cost for the limiting transactions as their thermal limit is less compared to others.
5.7 CONCLUSIONS

In this chapter, the calculation of linear ATC without and with reactive power flows is carried out. The transaction based allocation of ELATC and its cost is also carried out. The value of ELATC is very near to the actual ATC with less error compared to LATC. The reduction in error with ELATC indicates the benefit of ELATC to the system operator.