CHAPTER 4

FORMULATION OF MARKET AND ECONOMIC PARTICIPATION FACTORS UNDER DIFFERENT MODELS

4.1 INTRODUCTION

The operation of power system under deregulated environment differs with market models. Each market model adopts its unique procedure to clear the auction mechanism. The procedure adopted to determine the in-merit GENCOs and DISCOs with their allocated power is discussed in chapter 3. The participation factors are calculated by the end of auction procedure. Once, determined these values are send forthwith to the GENCOs. The scheduling of GENCOs to meet the contracted demand and rescheduling of generation of willing GENCOs with un-allotted power during violation is done with the aid of LFC.

Efficient and effective performance of LFC is guaranteed by proper formulation of market and violation participation factors. This chapter gives a detailed description of formulation of these factors for single buyer, bilateral and poolco market model. These factors are determined either trailing the auction procedure or through contract made between GENCO and DISCO. This chapter explains in detail the chronicle of auction based market procedures for different market conditions. A generalised formulation is then developed to calculate the percentage participation of each in-merit GENCO during contract period. Formula to compute epf of GENCOs are also developed based on offer price of GENCOs willing to contribute for violated demand. Later the calculated participation factors are incorporated in the complete mathematical model of two area power system operating under respective market model and simulated in MATLAB/Simulink. The performance of LFC under different market models is finally validated by comparing GENCOs and TRANSCO responses with the tabulated values.

4.2 FORMULATION OF MARKET PARTICIPATION FACTORS

Under contracted condition, LFC’s main objective is to meet scheduled demand in an area or DISCO, by driving GENCOs to generate power based on market participation factors. Hence, proper calculation of participation factors is important for an effective operation of LFC. The representation market participation factor of each GENCO under different market
models is different and can be constituted in a matrix. For each GENCO, market participation factor is calculated based on the allotted power of respective GENCO and total allotted power of all GENCOs or on the contract made between the GENCO and DISCO. This section gives a vast narration on the formulation of participation factors when the system operates under single buyer model, bilateral model and poolco model.

4.2.1 Formulation of GENCO participation factors under single buyer model

The auction mechanism in single buyer model is done under the supervision of pool operator. For a time period, the operator accepts offers from all GENCOs in the pool, plots the supply curve and finds the intersection point between the supply curve and vertical line that corresponds to the predicted demand for a time slot. The point of intersection is then extrapolated to y-axis to find the MCP. The trading is done by the in-merit GENCOs lying to the left of intersection point along the supply curve. The auction mechanism under single buyer market model is shown in Figure 4.1.

![Figure 4.1: Market clearing under single buyer model](image)

From Figure 4.1, it is clear that the market is cleared at the point ‘a’ where generation equals demand. Each in-merit GENCO ‘k’ with allotted power represented as $P_{Gk}$ participate in meeting its own demand. The percentage contribution of each GENCO given by $gpf$, as explained in section 3.4.1.1, is based on its allotted power and the total allotted power of all GENCOs meeting that demand. The percentage contribution of $k^{th}$ GENCO in an area to meet its own demand, is represented as $gpf_k$, and is given as per equation (4.1).

$$gpf_k = \frac{P_{Gk}}{\sum_{k=1}^{n} P_{Gk}} \tag{4.1}$$

Since, the total demand in an area is met by all GENCOs, the sum of participation factors of all GENCOs in the pool is unity and is as given in equation (4.2).
\[ \sum_{k=1}^{n^G} gpf_k = 1 \]  

\textbf{4.2.2 Formulation of contract participation factors under bilateral model}

In bilateral model, as explained in section 3.4.1.2, GENCOs and DISCOs enter into negotiations independently and finally agree for a contracted power at settled price. It is at this settled price, the power trading is done among these GENCOs and DISCOs. Bilateral contract is made between any GENCOs and DISCOs for any amount of power and duration. Under bilateral market model, a GENCO can sign up contract with more than one DISCO. Thus, each generating unit produces part of its output power to meet demand of many DISCO. This means that each GENCO participate in meeting the demand of many DISCO. This participation, represented in percentage, is denoted as \( cpf \). The \( cpf \) value for each GENCO to meet a demand of a DISCO is obtained from the contracted power between the GENCO and DISCO and the total power generated by the respective GENCO. If, the power generated by GENCO ‘\( k \)’ to meet demand of DISCO ‘\( i \)’ is represented as \( P_{Gki} \), then the \( cpf \) of GENCO ‘\( k \)’ to meet demand in \( i^{th} \) DISCO is given as per equation (4.3).

\[ cpf_{ki} = \frac{P_{Gki}}{\sum_{k=1}^{n^G} P_{Gki}} \]

The demand in DISCO ‘\( i \)’ is met by many GENCOs and hence, the sum of participation factors of these GENCOs that satisfy demand of a DISCO ‘\( i \)’ is unity and is as given in equation (4.4).

\[ \sum_{k=1}^{n^G} cpf_{ki} = 1 \]

Where,

\( cpf_{ki} \) is the contract participation factor of \( k^{th} \) GENCO that meets demand in \( i^{th} \) DISCO

\textbf{4.2.3 Formulation of area participation factors under poolco model}

As described in section 3.4.1.3, the double sided auction mechanism in poolco model is done under the supervision of ISO. For a prescribed time window, ISO accepts offers and bids from the GENCOs and DISCOs in all the pools. The offers and bids include the amount of power the player is willing to sell or buy and the corresponding price. Once the offers and bids are received, the ISO plots supply and demand curves of all pools together to find the MCP. The MCP is then extrapolated to meet the supply and demand curves of individual pools to determine the in-merit GENCOs, in-merit DISCOs and their allotted power. When the intersection point (MCP) is extrapolated to individual pools, the total in-merit GENCO
power in an area may be greater or lesser than total in-merit DISCO power. If the total allotted power in an area is greater than the total allotted demand, then the area is called as surplus area. While, the area with total allotted supply power is less than the total allotted demand becomes deficit area. The demand in surplus area is met by same area GENCos and the extra power of these surplus area GENCos is wheeled through TRANSCO to the other interconnected deficit area. This power meets a part of the demand in the interconnected area, while its own GENCos meet the remaining part of demand. This instance creates power flow through TRANSCO.

Also, there can be occasion of market condition with no intersection between the supply and demand curves in both areas. In such case, market is cleared on the supply demand curve, where the total offered power equals total bid power. The GENCos in each area meets its own demand and there remains no extra power with any GENCos to meet the other area demand. Hence, the TRANSCO power in such situation is zero.

Irrespective of the market conditions, it is clear that each GENCo meets sits own demand and / or demand of neighbour area. The participation of each GENCO expressed in percentage in poolco market model is represented as \( apf \). \( apf_{ij} \) represents the percentage participation of \( i^{th} \) GENCO to meet demand in \( j^{th} \) area. The following sub-sections explains in detail the formulation of \( apf \) of each GENCO for the explained market conditions under poolco model.

4.2.3.1 When both areas have equilibrium point

The market condition with equilibrium point in both areas under poolco model is shown in Figure 4.2. As explained in chapter 3, the SO finds the MCP and MP from the intersection of combined supply and demand curves.

![Figure 4.2: Market clearing under poolco model with equilibrium point in both areas](image-url)
From Figure 4.2, it is clear that the combined supply and demand curves intersect at point ‘a’. The total offered power (G) is equal to the total bid power (D), at this point. Extrapolation of this point along y axis gives the MCP – the price at which power trading is done in both the areas. The MCP is extrapolated further towards the supply and demand curves of area ‘i’ and area ‘j’ to meet at Gi, Dj and Gj, Di respectively. Gi, Gj, Di and Dj gives the allotted power of GENCOs and DISCOs in respective areas. The allotted power of kth GENCO in ith area and lth GENCO in jth area is represented as P_Gki and P_Glj respectively. From Figure 4.2, the generation in ith area (Gi) is greater than its allotted demand (Di). Therefore ith area is surplus in generation. Similarly, allotted demand (Dj) in jth area is greater than its allotted generation (Gj) and thus jth area is deficient in generation. However, the sum of allotted GENCO power of both areas is equal to the sum of allotted DISCO powers. The combined generation (G) equals combined demand (D). This is given in equation (4.5) – (4.6).

\[ G_i + G_j = D_i + D_j \]  
\[ G_i - D_j = D_j - G_i \]  

The players to the left of Gi and Di are selected as in-merit GENCOs and DISCOs of ith area respectively. Similarly, players to the left of Gj and Dj are selected as in-merit GENCOs and DISCOs in jth area respectively.

The GENCO ‘k’ in surplus area ‘i’ (P_Gki) meets its own demand (Di). The remaining power (P_T), given as per equation (4.7) flows through TRANSCO to meet part of the demand in jth area.

\[ P_T = G_i - D_i = P_{Gki} = P_{Gk}^* - P_{Gki} \]  
Where,

\[ P_{Gk}^* \] is the allotted power of kth GENCO in area ‘i’

\[ P_{Gki} \] is the kth GENCO power that meets demand in area ‘i’

\[ P_{Gkj} \] is the power of kth GENCO that meets demand of in area ‘j’

Thus demand (Dj) of deficient area, is met by power ‘P_T’ from ith area and along with the GENCO power (Gj) in jth area. Thus,

\[ P_T + G_j = D_j \]
The percentage contribution of each GENCO, given by \( \text{apf} \) in section 3.4.1.3, to meet demand in an area, is based on its allotted power and the total allotted power of all GENCOs meeting that demand. The percentage contribution of \( k^{th} \) GENCO of \( i^{th} \) area to meet its own demand, is represented as \( \text{apf}_{ki} \), is given as per equation (4.9).

\[
\text{apf}_{ki} = \frac{P_{Gki}}{\sum_{k=1}^{n_{Gi}} P_{Gki}} \tag{4.9}
\]

The demand in deficient area (area ‘j’) is met by same area GENCOs (\( P_{Glj} \)) and GENCOs in surplus area (area ‘i’) (\( P_{Gkj} \)). The percentage contribution of each GENCO in area ‘i’ and area ‘j’, to meet \( j^{th} \) area demand is given by \( \text{apf}_{kj} \) and \( \text{apf}_{lj} \) respectively and is as per equation (4.10) and (4.11).

\[
\text{apf}_{kj} = \frac{P_{Gkj}}{\sum_{k=1}^{n_{Gi}} P_{Gkj} + \sum_{l=1}^{n_{Gj}} P_{Glj}} \tag{4.10}
\]
\[
\text{apf}_{lj} = \frac{P_{Glj}}{\sum_{k=1}^{n_{Gi}} P_{Gkj} + \sum_{l=1}^{n_{Gj}} P_{Glj}} \tag{4.11}
\]

The GENCOs in \( j^{th} \) area (deficient area) do not contribute to any demand in \( i^{th} \) area (surplus area). Thus, the corresponding participation factor, \( \text{apf}_{lj} \) is zero.

\[
\text{apf}_{lj} = 0 \tag{4.12}
\]

The sum of participation factors of all surplus area GENCOs contributing to its own demand is unity and is as given in equation (4.13).

\[
\sum_{k=1}^{n_{Gi}} \text{apf}_{ki} = 1 \tag{4.13}
\]

Similarly, the sum of participation factors all deficient area GENCOs to meet the demand in surplus area is zero.

\[
\text{apf}_{li} = 0 \tag{4.14}
\]

The sum of participation of GENCOs in surplus and deficient area to meet the demand in deficient area is unity.

\[
\sum_{k=1}^{n_{Gi}} \text{apf}_{kj} + \sum_{l=1}^{n_{Gj}} \text{apf}_{lj} = 1 \tag{4.15}
\]

There can be occasions when the total offered power can be less than total bid power. In such situation, the total allotted power of in-merit GENCOs is less than the total allotted power of in-merit DISCOs. Thus this area is called deficit area. The deficit power is met by the other area GENCOs. This means that the supplying area GENCOs must have in-merit power to meet its own in-merit power demand and demand of deficit area.
4.2.3.2 When both areas have no equilibrium point

The state with both the areas with total offered power less than total bid power is shown in Figure 4.3.

The market is cleared at the point where total offered power is equal to the total bid power.

Figure 4.3: Individual supply demand curve under poolco model with no equilibrium point in both areas

In Figure 4.3, the market is cleared at point where $G_i = D_i$ in $i^{th}$ area and at $G_j = D_j$ in $j^{th}$ area. Power trading is initiated between the players to the left of $G_i$ and $D_i$ in $i^{th}$ area and between the players to the left of $G_j$ and $D_j$ in $j^{th}$ area. Each GENCO in an area meets the demand in its own area, and hence, there is no scheduled power flow through the TRANSCO.

The participation of each GENCO in an area to meet its own area demand, expressed in percentage, is represented as $apf$. The $apf$ of a GENCO is obtained from its allotted power and the total offered power in that area. $apf$ of $k^{th}$ GENCOs in $i^{th}$ area, $apf_{ki}$ is as given in equation (4.16).

$$apf_{ki} = \frac{P_{Gki}}{\sum_{k=1}^{n} P_{Gki}}$$ (4.16)

Where,

$P_{Gki}$ represents the allotted power of GENCO ‘k’ in area ‘i’

The demand of $j^{th}$ area is met by the same area GENCOs. Thus, the participation factor of $l^{th}$ GENCOs in $j^{th}$ area, $apf_{lj}$ is as given in equation (4.17).

$$apf_{lj} = \frac{P_{Glj}}{\sum_{l=1}^{n} P_{Glj}}$$ (4.17)
Where, 

\( P_{Gi} \) represents the allotted power of GENCO ‘1’ in area ‘j’

The \( i^{th} \) area GENCOs do not contribute to the demand in \( j^{th} \) area and vice versa. Thus,

\[ apf_{ki} = 0 \]  \hspace{1cm} (4.18)

\[ apf_{ii} = 0 \]  \hspace{1cm} (4.19)

The sum of participation factors of GENCOs in area ‘i’ and area ‘j’, to meet the demand in same area is unity. Thus,

\[ \sum_{k=1}^{nGi} apf_{ki} = 1 \]  \hspace{1cm} (4.20)

\[ \sum_{i=1}^{nGi} apf_{ij} = 1 \]  \hspace{1cm} (4.21)

Thus, it is seen that the auction mechanism is performed in such a way that the market is cleared separately for the two areas. In other words, the SO assesses each area as a separate pool. Hence, under such circumstances, it is economical to adopt the single buyer or bilateral trading.

4.3 FORMULATION OF VIOLATION PARTICIPATION FACTOR

One of the main challenges in the operation of LFC is varying demand. There can be situations where an area or a DISCO demands extra power. During this scenario, a control strategy must be used that allows some of the GENCOs to meet the violated power, thereby meeting the other objective of LFC. Commonly used control strategy known as tie line bias control strategy allows GENCOs in same area to meet the un-contracted power so that TRANSCO power is kept at scheduled. This brings system frequency to nominal value. This is possible only if the deviation in TRANSCO power and deviation in system frequency is used as \( ACE \). Thus, under tie line bias control strategy, change in system frequency and TRANSCO power error are given as \( ACE \) for all willing GENCOs. The willing GENCOs are called for submitting a second set of offer.

The contribution of each GENCO willing to participate in LFC during violation under single buyer or poolco model, represented by \( epf \), is formulated based on the offer price submitted during the second phase auction to clear for unscheduled power. The participation factor of \( k^{th} \) willing GENCO participating to meet contract violation in area ‘i’ is given as in equation (4.22).
\[ ep_{f_k} = \frac{(1/\text{Price}_{\text{off-un k}})}{\sum_{j=1}^{\text{nwGi}} (1/\text{Price}_{\text{off-un j}})} \quad \text{for } k = 1 \text{ to } \text{nwGi} \]  

(4.22)

Where,

\text{Price}_{\text{off-un k}} \text{ represents the offer price of } k^{th} \text{ GENCO in } i^{th} \text{ area to meet its unscheduled power}

\text{nwGi} \text{ represents number of GENCOs in area ‘i’ participating in second round auction}

Throughout this chapter, the two area LFC system is incorporated with tie line bias control strategy that makes same area GENCOs to reschedule its generation, thereby maintaining TRANSCO power at scheduled value.

### 4.4 ANALYSIS OF LFC UNDER SINGLE BUYER MODEL INCORPORATING gpf AND epf

The formulation of market and violation participation factors under different market models are explained in section 4.2 and section 4.3. The effectiveness of these formulation methods can be verified by conducting suitable analysis. This section illustrates calculation of GENCO (gpf) and violation (epf) participation factor for different market conditions. The considered two area deregulated system is analysed with the calculated values of these factors to verify the operation of LFC based on gpf and epf.

#### 4.4.1 Simulation for calculation of gpf and epf

This section formulates market (gpf) and violation (epf) participation factors of GENCOs of two area power system shown in Figure 3.6, operating under single buyer model. To determine gpf and epf of GENCOs, it is required to plot the supply demand curve for a time slot. A MATLAB code is developed that accepts the offers from individual GENCOs, plots the supply and demand curves and then finds MCP. Using the data given in Appendix I, supply demand curves are plotted using the developed code and is shown in Figure 4.4. The predicted demand for the time slot in area 1 and area 2 are assumed to be 266.7MW and 200MW respectively.

The vertical line in Figure 4.4 corresponds to 266.7MW and 200MW demands intersect the supply curve of each area. From Figure 4.4 it is clear that the y-axis of this intersection point is Rs105.6/MW for area 1 and Rs100/MW for area 2. The auction is cleared by pool operator with in-merit GENCOs as G_{11}, G_{21} in area 1 and G_{12} and G_{22} in area 2. Figure 4.4, shows that the allotted power of G_{11}, G_{21}, G_{12} and G_{22} are 100MW, 166.7MW, 100MW and 100MW respectively.
Figure 4.4: Auction clearing under single buyer model

The *gpf* value of each in-m merit GENCO depends on the allotted power of respective GENCO and total allotted power of all in-m merit GENCO. Using the concept given through equation (4.1) and the *gpf* values are calculated and are given in equation (4.23) and (4.24).

\[
GPM_1 = \begin{bmatrix} 0.375 & 0 \\ 0.625 & 0 \end{bmatrix} \quad (4.23)
\]

\[
GPM_2 = \begin{bmatrix} 0 & 0.5 \\ 0 & 0.5 \end{bmatrix} \quad (4.24)
\]

Rows of GPM\(_1\) and GPM\(_2\) corresponds to GENCOs in area 1 and area 2 respectively. While, the columns correspond to the area. Equation (4.23) shows that 37.5% and 62.5% of power demand in area 1 is met by GENCO 1 and GENCO 2 respectively. Thus, with a demand of 266.7MW, equation (4.23) shows that G\(_{11}\) and G\(_{21}\) generate power of 100 (i.e., \(0.375 \times 266.7\))MW and 166.7 (i.e., \(0.625 \times 266.7\))MW respectively to meet the same area demand by the ratio 0.375:0.625. The sum of participation factors is unity as per equation (4.2). Similarly, equation (4.24) shows that GENCO 3 and GENCO 4 meet 50% each of demand in area 2. Thus, with a demand of 200MW in area 2, G\(_{12}\) and G\(_{22}\) generate 100 (i.e., \(0.5 \times 200\))MW each by the ratio of 0.5:0.5. The sum of participation factor of area 2 GENCOs is unity as per equation (4.2).

However, during contract violation, all the willing GENCOs are made to meet the un-contracted demand based on the offer price submitted for un-contracted power auction. From Appendix IV, it is seen that the GENCOs willing to participate in LFC during contract violation in an area, G\(_{11}\) G\(_{21}\) and G\(_{22}\) submit the offer price to meet allotted power to be Rs1750/MW, Rs1500/MW and Rs1800/MW respectively. With tie line bias control strategy,
for contract violation in an area, only same area GENCOs are made to participate to meet violated demand. Thus for a violation in area 1, $G_{11}$ and $G_{21}$ meet the un-contracted demand. Using the offer price in Appendix IV and equation (4.22), the epf ratio of these GENCOs is $0.462:0.538$, with the sum unity. Similarly, $G_{22}$ alone meets the violated demand in area 2. Thus, epf of $G_{22}$ is unity.

Now, the mathematical model of two area deregulated system under single buyer model is to be incorporated with these participation factors and is to be analysed to check whether LFC operates based on these factors.

### 4.4.2 Scheduled GENCO power under single buyer model incorporating gpf and epf

This section analyses the performance of two area LFC system under single buyer model incorporating gpf and epf values. The system is analysed with p.u. values thus all the power values are converted to corresponding p.u. values using base value of 266.7MW in area 1 and 200MW in area 2. The GENCOs and TRANSCO contracted power is determined using equation (3.4) and is furnished in Table 4.1.

Table 4.1: GENCOs and TRANSCO contracted powers (p.u.) under single buyer model

<table>
<thead>
<tr>
<th></th>
<th>$PG_{11}$</th>
<th>$PG_{21}$</th>
<th>$PG_{12}$</th>
<th>$PG_{22}$</th>
<th>$P_{TRANSCO12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 1</td>
<td>0.375</td>
<td>0.625</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Area 2</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>0.375</td>
<td>0.625</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.1 shows that GENCO 1 ($G_{11}$) and GENCO 2 ($G_{21}$) meet demand of 1 p.u. in area 1. Similarly, GENCOs in area 2 meet 1 p.u. demand in area 2. Since, same area GENCOs meet its demand, TRANSCO power is zero.

As explained in section 3.4.2, during a contract violation in any area, the willing GENCOs participating in second round auction are made to compensate for the demand violation. Appendix IV shows that during violation in area 1, GENCO 1 and GENCO 2 are willing to compensate for the violated same area demand. Using values given in Appendix IV and equation (4.22) GENCO 1 and GENCO 2 contribute for the violated demand in the ratio $0.462:0.538$. Similarly, for a contract violation in area 2, GENCO 4 alone contributes for the violated demand. Thus, the epf value is unity. Since, same area GENCO contribute for the un-contracted power, the TRANSCO power remains same. The GENCOs and TRANSCO power during contract violation is determined using equation (3.27) and is furnished in Table 4.2.
It is clear from Table 4.2 that during contract violation in area 1, output power of GENCO 1 (G\textsubscript{11}) and GENCO 2 (G\textsubscript{21}) is increased from 0.375 p.u. to \textbf{0.3796} (i.e., 0.375+0.462×0.01) p.u. and from 0.625 p.u. to \textbf{0.6304} (i.e., 0.625+0.538×0.01) p.u.

Table 4.2: GENCOs and TRANSCO powers (p.u.) during violation of 0.01 p.u. incorporating tie line bias control under single buyer model

<table>
<thead>
<tr>
<th></th>
<th>Contracted power</th>
<th>Violation in area 1</th>
<th>Violation in area 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG\textsubscript{11}</td>
<td>0.375</td>
<td>\textbf{0.3796}</td>
<td>0.375</td>
</tr>
<tr>
<td>PG\textsubscript{21}</td>
<td>0.625</td>
<td>\textbf{0.6304}</td>
<td>0.625</td>
</tr>
<tr>
<td>PG\textsubscript{12}</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PG\textsubscript{22}</td>
<td>0.5</td>
<td>0.5</td>
<td>\textbf{0.51}</td>
</tr>
<tr>
<td>P\textsubscript{TRANSCO12}</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Similarly, for a violation in area 2, power output of GENCO 4 (G\textsubscript{22}) is increased from 0.5 p.u. to \textbf{0.51} (i.e., 0.5+1×0.01) p.u.

For a contract violation in each area, only same area GENCOs meets the un-contracted power and hence, TRANSCO power is unchanged.

### 4.4.3 Simulation result under single buyer model incorporating \textit{gpf} and \textit{epf}

To analyse the performance of LFC incorporating \textit{gpf} and \textit{epf}, the mathematical model (obtained by combining Figure 3.7 and Figure 3.8) of considered two area deregulated system under single buyer model is developed in MATLAB/Simulink, using the system parameters furnished in Appendix V. The calculated \textit{gpf} and \textit{epf} values are then incorporated in this complete mathematical model. The system is simulated and the GENCOs and TRANSCO power responses are shown in Figure 4.5.

![Figure 4.5: GENCOs and TRANSCO power responses under single buyer model](image-url)
From Figure 4.5 it is seen that $G_{11}$, $G_{21}$, $G_{12}$ and $G_{22}$ generates 0.375 p.u., 0.625 p.u., 0.5 p.u. and 0.5 p.u. respectively. The TRANSCO power from area 1 to area 2 is zero. The simulated values shown in Figure 4.5 matches well with the calculated values furnished in Table 4.1.

To analyse the performance of LFC based on $epf$ values, it is required to introduce a contract violation in the system. A contract violation of 0.01 p.u. is created in area 1 at 350s and the GENCOs and TRANSCO responses are shown in Figure 4.6.

![Figure 4.6: GENCOs and TRANSCO powers and frequency responses during violation of 0.01 p.u. in area 1 incorporating tie line bias control under single buyer model](image)

From Figure 4.6, it is seen that the output power of GENCO 1 ($G_{11}$) and GENCO 2 ($G_{21}$) is increased from 0.375 p.u. to 0.3796 p.u. and 0.625 p.u. to 0.6304 p.u. respectively. On the same hand, the generation of neighbouring area GENCOs remains same. Since the violated power is met by the GENCOs in same area, TRANSCO power remains same. The obtained values match with the tabulated values shown in Table 4.2. It is also seen from Figure 4.6 that area frequency deviations are made zero.

Again, a contract violation of 0.01 p.u. is created in area 2 at 350s and corresponding responses of GENCOs and TRANSCO is shown in Figure 4.7.

From Figure 4.7, it is seen that the power output of GENCO 4 ($G_{22}$) is increased from 0.5 p.u. to 0.51 p.u., while the power output of GENCO 3 ($G_{12}$) remains same. The violation in area 2 power is met by same area GENCO and hence TRANSCO power remains unaltered. The obtained values match with the tabulated values shown in Table 4.2. Figure 4.7 also shows that deviation in area frequencies settle at zero.
The performance of LFC to meet the unscheduled power can be viewed in better with the help of bar chart representation.

### 4.4.4 Bar chart representation of GENCOs and TRANSCO powers incorporating tie line bias control under single buyer model

This section presents operation of LFC in rescheduling power of willing GENCOs to meet unContracted power. The bar chart representation showing the change in GENCOs and TRANSCO powers and total GENCOs and TRANSCO powers are depicted in Figure 4.8, for a violation of 0.01 p.u. in area 1.
Figure 4.8 shows the GENCOs and TRANSCO power under single buyer model, incorporating tie line bias control during violation in area 1. Figure clearly shows that the strategy allows same area GENCOs contribute during the violation, whereas, the neighbouring area GENCOs do not contribute. Thus, GENCO 1 (G1) and GENCO 2 (G2) reschedule its generation from the contracted value. Since same area GENCOs participate, TRANSCO power change is zero.

The change and total GENCO and TRANSCO powers are depicted with the help of bar chart representation in Figure 4.9, for a violation of 0.01 p.u. in area 2.

![Bar chart representation of GENCOs and TRANSCO power responses during violation of 0.01 p.u. in area 2 incorporating tie line bias control under single buyer model](image)

Figure 4.9: Bar chart representation of GENCOs and TRANSCO power responses during violation of 0.01 p.u. in area 2 incorporating tie line bias control under single buyer model

Figure 4.9 presents powers of GENCOs and TRANSCO incorporating tie line bias control during a contract violation in area 2 under single buyer model. It is evident from figure that tie line bias control allows only same area GENCOs to meet the violated power. Hence, GENCO 3 (G3) and GENCO 4 (G4) are expected to participate during the period. However, GENCO 3 (G3) being not willing to participate, the change in power is zero. Hence, under this condition, only GENCO 4 (G4) participates, and hence, its power increases from the contract value. Tie line bias control allows only same area GENCOs to participate and hence the TRANSCO power is unaltered.

Figure 4.8 and Figure 4.9 shows that the willing GENCOs in respective area of violation shares for the violated power based on the ratio as calculated by $epf$. 

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4.5 ANALYSIS OF LFC UNDER BILATERAL MODEL INCORPORATING cpf AND epf

This section presents calculation of contract (cpf) and violation (epf) participation factor. The considered two area deregulated system is analysed with these factors to verify the operation of LFC based on cpf and epf.

4.5.1 Simulation for calculation of cpf and epf

In bilateral model, contracted power of each GENCO is obtained from the agreement made between them and DISCOs. Thus, the contract participation factor is not based on auction but on the contract. For the two area deregulated system shown in Figure 3.6 operating in bilateral model, it is assumed that each GENCO makes contract with four DISCOs with cpf values as given in equation (4.25).

\[
DPM = \begin{bmatrix}
0.4 & 0.1 & 0.4 & 0.4 \\
0.3 & 0.2 & 0.3 & 0.3 \\
0.2 & 0.3 & 0.2 & 0.2 \\
0.1 & 0.4 & 0.1 & 0.1
\end{bmatrix}
\quad (4.25)
\]

Column 1 of equation (4.25) shows that 40%, 30%, 20% and 10% of demand in DISCO 1 is met by GENCO 1, GENCO 2, GENCO 3 and GENCO 4 respectively. Similarly, it is clear from column 2 that 10%, 20%, 30% and 40% of demand in DISCO 2 is met by GENCO 1, GENCO 2, GENCO 3 and GENCO 4 respectively.

Also, during contract violation the willing GENCOs meet the un-contracted power based on the epf values that are also based on the contract made. It is assumed that GENCO 1, GENCO 2, GENCO 3 and GENCO 4 compensate for the un-contracted demand by 30%, 20%, 10% and 40% respectively.

Now, these participation factors are incorporated in the considered two area deregulated system so as to operate under bilateral model and the model is to be analysed to check whether LFC operates based on these factors.

4.5.2 Scheduled GENCO power under bilateral model incorporating cpf and epf

This section analyses the performance of two area LFC system under bilateral model incorporating cpf and epf values. With cpf values as per the contract, it is required to calculate the contracted power of each GENCO and TRANSCO.
Assuming a demand of 0.1 p.u., 0.2 p.u., 0.5 p.u. and 0.4 p.u. in DISCO 1, DISCO 2, DISCO 3 and DISCO 4 respectively, contracted power of GENCOs are calculated using equation (3.9) and is presented in Table 4.3.

Table 4.3: GENCOs and TRANSCO contracted powers (p.u.) under bilateral model

<table>
<thead>
<tr>
<th>DISCO</th>
<th>PG\textsubscript{11}</th>
<th>PG\textsubscript{21}</th>
<th>PG\textsubscript{12}</th>
<th>PG\textsubscript{22}</th>
<th>P\textsubscript{TRANSCO12}</th>
</tr>
</thead>
<tbody>
<tr>
<td>DISCO 1</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>DISCO 2</td>
<td>0.02</td>
<td>0.04</td>
<td>0.06</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>DISCO 3</td>
<td>0.2</td>
<td>0.15</td>
<td>0.1</td>
<td>0.05</td>
<td>\textbf{0.46}</td>
</tr>
<tr>
<td>DISCO 4</td>
<td>0.16</td>
<td>0.12</td>
<td>0.08</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>\textbf{0.42}</td>
<td>\textbf{0.34}</td>
<td>\textbf{0.26}</td>
<td>\textbf{0.18}</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 shows that GENCOs in area 1 meet 0.13 p.u. and 0.63 p.u. of demand in area 1 and area 2 respectively. Similarly, GENCO 3 and GENCO 4 meet 0.17 p.u. and 0.27 p.u. demand in area 1 and area 2 respectively. Meeting 0.63 p.u. of demand in area 2 by GENCOs in area 1, causes TRANSCO power to flow from area 1 to area 2. Similarly, 0.17 p.u. of demand in area 1 is met by GENCOs in area 2. This causes TRANSCO power to flow from area 2 to area 1. Thus the net power of 0.46 (i.e., 0.63 – 0.17) p.u. of power flows through TRANSCO from area 1 to area 2.

As explained in section 4.5.1, during a contract violation in any area, the un-contracted power is met by the willing GENCOs that make contract with DISCO. Section 4.5.1 assumes that GENCO 1 and GENCO 2 alone compensate for the violated demand in area 1 DISCOs in the ratio \textbf{0.6:0.4}. Similarly, for a contract violation in area 2 DISCOs, GENCO 3 and GENCO 4 alone contributes by the ratio \textbf{0.2:0.8}. Since, same area GENCO contribute for the un-contracted power, hence, the TRANSCO power remains same. The GENCOs and TRANSCO powers during contract violation are determined using equation (3.27) and is furnished in Table 4.4.

Table 4.4: GENCOs and TRANSCO powers (p.u.) during violation of 0.01 p.u. incorporating tie line bias control under bilateral model

<table>
<thead>
<tr>
<th>Contracted power</th>
<th>Violation in area 1</th>
<th>Violation in area 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG\textsubscript{11}</td>
<td>0.42</td>
<td>\textbf{0.426}</td>
</tr>
<tr>
<td>PG\textsubscript{21}</td>
<td>0.34</td>
<td>\textbf{0.344}</td>
</tr>
<tr>
<td>PG\textsubscript{12}</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>PG\textsubscript{22}</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>P\textsubscript{TRANSCO12}</td>
<td>0.46</td>
<td>0.46</td>
</tr>
</tbody>
</table>
Table 4.4 shows that during contract violation in area 1, output power of GENCO 1 is increased from 0.42 p.u. to **0.426** (i.e., 0.42+0.6×0.01) p.u. and from 0.34 p.u. to **0.344** (i.e., 0.34+0.4×0.01) p.u.. Similarly, for a violation in area 2, power output of GENCO 3 (G12) and GENCO 4 (G22) is increased from 0.26 p.u. and 0.18 p.u. to **0.262** (i.e., 0.26+0.2×0.01) p.u. and **0.188** (i.e., 0.18+0.8×0.01) p.u..

For a contract violation in each area, only same area GENCOs meet the un-contracted power and hence, TRANSCO power is maintained at 0.46 p.u..

### 4.5.3 Simulation result under bilateral model incorporating cpf and epf

To analyse the performance of LFC under bilateral model, the *cpf* and *epf* values are incorporated in the mathematical model (obtained by combining Figure 3.7 and Figure 3.9) of two area deregulated system under bilateral model is developed in MATLAB/Simulink, using the system parameters furnished in Appendix V. The system is simulated and the GENCOs and TRANSCO power responses are shown in Figure 4.10.

![Figure 4.10: GENCOs and TRANSCO power responses under bilateral model](image)

From Figure 4.10 it seen that GENCO 1 (G11), GENCO 2 (G21), GENCO 3 (G12) and GENCO 4 (G22) generates **0.42 p.u.**, **0.34 p.u.**, **0.26 p.u.** and **0.18 p.u.** respectively. The TRANSCO power through TRANSCO from area 1 to area 2 is **0.46 p.u.**. The simulated values shown in Figure 4.10 matches well with the calculated values furnished in Table 4.3.

To analyse the performance of two area LFC system under bilateral model based on *epf* values, it is required to introduce a contract violation in the system. A contract violation of 0.01 p.u. is created at 350s in area 1. During contract violation, the willing GENCOs are
made to meet the violated demand. The GENCOs and TRANSCO power responses for contract violation of 0.01 p.u., created at 350s in area 1 is shown in Figure 4.11.

Figure 4.11: GENCOs and TRANSCO powers and frequency responses during violation of 0.01 p.u. in area 1 incorporating tie line bias control under bilateral model

From Figure 4.11, it is seen that the output power of G\textsubscript{11} and G\textsubscript{21} is increased from 0.42 p.u. to \textbf{0.426 p.u.} and 0.34 p.u. to \textbf{0.344 p.u.} respectively. Since the violated power is met by the GENCOs in same area, TRANSCO power remains same. Figure 4.11 shows that during contract violation in area 1, GENCOs in the same area meet the un-contracted power based on the \textit{epf} values. The simulated GENCOs and TRANSCO power values match with the tabulated values shown in Table 4.4. It is also seen that deviation in area frequencies is brought to zero.

Again, a contract violation of 0.01 p.u. is created at 350s in area 2 and corresponding power responses of GENCOs and TRANSCO is shown in Figure 4.12.

From Figure 4.12, it is seen that the output power of G\textsubscript{12} and G\textsubscript{22} is increased from 0.26 p.u. and 0.18 p.u. to \textbf{0.262 p.u.} and \textbf{0.188 p.u.} respectively. Since the violated power is met by the GENCOs in same area, TRANSCO power remains same. The simulated GENCOs and TRANSCO power values match with the tabulated values shown in Table 4.4. The deviation in area frequencies are also brought to zero. This is clear from Figure 4.12.
Figure 4.12: GENCOs and TRANSCO powers and frequency responses during violation of 0.01 p.u. in area 2 incorporating tie line bias control under bilateral model.

The power responses of GENCOs and TRANSCO during contract violation can be easily viewed with the help of bar chart.

4.5.4 Bar chart representation of GENCOs and TRANSCO powers incorporating tie line bias control under bilateral model

This section gives the GENCOs and TRANSCO power responses as bar chart during contract violation. Figure 4.13 presents GENCOs and TRANSCO powers respectively during violation in area 1 incorporating tie line bias control under bilateral model.

Figure 4.13: Bar chart representation of GENCOs and TRANSCO power responses during violation of 0.01 p.u. in area 1 incorporating tie line bias control under bilateral model
For a violation in area 1, tie line bias allows only same area GENCO to meet the violated demand. Thus, GENCO 1 (G1) and GENCO 2 (G2) power increase. Conversely, neighbouring area GENCOs power change is zero. This is shown in Figure 4.13. Since, same area GENCOs participate in LFC, TRANSCO power change is zero, thus it remains equal to contract value.

The bar chart representation of change in GENCO and TRANSCO powers and total GENCO and TRANSCO powers are depicted in Figure 4.14, for a violation of 0.01p.u. in area 2.

Figure 4.14 shows that for a contract violation in area 2, GENCO 3 (G3) and GENCO 4 (G4) participate in meeting the violated power and hence the power generation is increased from the contracted value. The participating GENCO being in the same area of violation, the TRANSCO power is maintained at contracted value.

Figure 4.13 and Figure 4.14 shows that for a contract violation in an area, tie line bias control allows only same area willing GENCOs to participate in LFC. These willing GENCOs meet the un-contracted power based on the epf values decided by the bilateral contract made between the respective GENCOs and DISCOs.
4.6 ANALYSIS OF LFC UNDER POOLCO MODEL (WITH MARKET EQUILIBRIUM IN BOTH AREAS) INCORPORATING apf AND epf

The calculation of market (apf) and violation (epf) participation factor is illustrated in this section. The considered two area deregulated system under poolco model is analysed with the calculated participation factors to verify the effective operation of LFC based on apf and epf.

4.6.1 Simulation for calculation of apf and epf (with market equilibrium in both areas)

This section explains the formulation apf and violation epf for GENCOs of two area power system shown in Figure 3.6, operating under poolco model. To determine apf and epf, it is required to plot the supply and demand curve during a time window.

A MATLAB code is developed that accepts the offers and bids from individual GENCOs and DISCOs, plots the individual and combined supply and demand curves. The MCP is determined from the intersection of combined supply and demand curves. Using the data given in Appendix II, supply and demand curves are plotted using the developed code and is shown in Figure 4.15.

![Figure 4.15: Auction clearing under poolco model (with market equilibrium in both areas)](image)

Figure 4.15 shows that MCP obtained from the combined plot is Rs105.56/MW. As explained in section 4.2.3, ISO selects in-m merit players by extrapolating the MCP to supply and demand curves of individual areas. From Figure 4.15, the in-merit GENCOs and DISCOs in area 1 are G11, G21, D11, D21, while, in area 2 are G12, G22, D12 and D22. It is also clear that in-merit GENCOs G11, G21 is allotted with a power of 100MW, 166.7MW respectively, while the total demands in area 1 is 144.44MW. The in-merit GENCOs G12, G22 is allotted with a
power of 100MW, 111.12MW respectively, while the total demands in area 2 is 333.33MW. Using the equation (4.9) – (4.12), the \( apf \) values are calculated and are given in equation (4.26) and (4.27).

\[
APM_1 = \begin{bmatrix}
0.375 & 0.138 \\
0.625 & 0.229
\end{bmatrix} \quad (4.26)
\]

\[
APM_2 = \begin{bmatrix}
0 & 0.3 \\
0 & 0.333
\end{bmatrix} \quad (4.27)
\]

The rows of \( APM_1 \) and \( APM_2 \) corresponds to the corresponding area GENCOs, while, the columns corresponds to the areas. Equation (4.26) shows that GENCO 1 and GENCO 2 meet the demand of area 1 by 37.5% and 62.5% respectively. Also, the same GENCOs meet demand in area 2 by 13.8% and 22.9% respectively. Similarly, equation (4.27) shows that GENCO 3 and GENCO 4 meet demand in area 2 by 30% and 33.3% respectively. From equation (4.26) it is seen that \( G_{11} \) and \( G_{21} \) generate power of 54.165 (i.e., \( 0.375 \times 144.44 \)) MW and 90.275 (i.e., \( 0.625 \times 144.44 \)) MW respectively to meet the same area demand of 144.44MW by a ratio 0.375:0.625. The sum of participation factors is 1 as per equation (4.13). The remaining power of these GENCOs, \( G_{11} \) and \( G_{21} \) is 45.835 (i.e., 100–54.165) MW and 76.425 (i.e., 166.7–90.275) MW respectively flow to area 2 through the TRANSCO. The power demand of 333.33MW in area 2 is met by \( G_{11}, G_{21}, G_{12} \) and \( G_{22} \) with the power generation of 45.835MW, 76.425MW, 100MW and 111.12MW respectively by ratio of 0.138:0.23:0.3:0.333. The sum of participation factor of \( G_{11}, G_{21}, G_{12} \) and \( G_{22} \) that meets area 2 demand is as given in equation (4.15). The area 2 GENCOs do not contribute to the area 1 demand and hence the sum of participation of \( G_{12} \) and \( G_{22} \) is zero as per equation (4.14).

However, during contract violation, the participation of each GENCO willing to participate to meet the unscheduled power is decided from the offer prices submitted by the players. From Appendix IV, the willing GENCOs (\( G_{11}, G_{21} \) and \( G_{22} \)) offer price is Rs1750/MW, Rs1500/MW and Rs1800/MW respectively. During contract violation in area 1, incorporating tie line bias control, \( G_{11} \) and \( G_{21} \) meet the un-contracted demand by the \( epf \) ratio of 0.462:0.538 obtained from equation (4.22), making the sum unity. Similarly, during contract violation in area 2, \( G_{22} \) alone contribute to meet the unscheduled demand. Thus, \( epf \) of \( G_{22} \) is unity.

Now, these participation factors are to be incorporated in the mathematical model of considered two area deregulated system and is to be analysed to check whether LFC schedule GENCOs based on these factors.
4.6.2 Scheduled GENCO power under poolco model (with market equilibrium in both areas) incorporating \( apf \) and \( epf \)

This section analyses the performance of two area LFC system under poolco model incorporating \( apf \) and \( epf \) values. The system is analysed with p.u. values thus all the power values are converted to corresponding p.u. values using base value of 333.33MW. With thes base value and computed \( apf \) values, the GENCOs and TRANSCO contracted power is determined using equation (3.19) and is furnished in Table 4.5.

Table 4.5: GENCOs and TRANSCO powers (p.u.) under poolco model (with market equilibrium in both areas)

<table>
<thead>
<tr>
<th>Area 1</th>
<th>PG(_{11})</th>
<th>PG(_{21})</th>
<th>PG(_{12})</th>
<th>PG(_{22})</th>
<th>P(_{TRANSCO12})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 2</td>
<td>0.1623</td>
<td>0.2708</td>
<td>0</td>
<td>0</td>
<td>0.367</td>
</tr>
<tr>
<td>Total</td>
<td><strong>0.3003</strong></td>
<td><strong>0.4998</strong></td>
<td><strong>0.3</strong></td>
<td><strong>0.333</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5 shows GENCOs in area 1 meet 0.4331 p.u. and 0.367 p.u. of demand in area 1 and area 2 respectively. Similarly, GENCO 3 and GENCO 4 meet 0.6333 p.u. demand in area 2 respectively. Compensation of 0.367 p.u. demand in area 2 by area 1 GENCOs results in TRANSCO power flow. As explained in section 4.6.1, during a contract violation in any area, willing GENCOs that participate in second round auction compensate to contribute for the demand violation. With tie line bias control strategy, same area GENCOs compensate for the violated demand. From Appendix IV, it is clear that GENCO 1 and GENCO 2 compensate for the violated demand. Using equation (4.22) and values in Appendix IV, these GENCOs compensate in the ratio \( 0.462:0.538 \). Similarly, for a contract violation in area 2, GENCO 4 alone contributes for the violated demand. Since, same area GENCO contribute for the uncontracted power, hence, the TRANSCO power remains same. The GENCOs and TRANSCO power during contract violation is determined using equation (3.27) and is furnished in Table 4.6.

Table 4.6 shows that during contract violation in area 1, output power of GENCO 1 (G\(_{11}\)) and GENCO 2 (G\(_{21}\)) is increased from 0.3003 p.u. to \( 0.3049 \) (i.e., 0.3003+0.462×0.01) p.u. and 0.4998 p.u. to \( 0.5051 \) (i.e., 0.4998+0.538×0.01) p.u. respectively. The contract violation in area 1 is met by same area GENCOs and hence, TRANSCO power is same.
Table 4.6: GENCOs and TRANSCO powers (p.u.) during violation of 0.01 p.u. incorporating tie line bias control under poolco model (with market equilibrium in both areas)

<table>
<thead>
<tr>
<th></th>
<th>Contracted power</th>
<th>Violation in area 1</th>
<th>Violation in area 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG(_{11})</td>
<td>0.3003</td>
<td>0.3049</td>
<td>0.3003</td>
</tr>
<tr>
<td>PG(_{21})</td>
<td>0.4998</td>
<td>0.5051</td>
<td>0.4998</td>
</tr>
<tr>
<td>PG(_{12})</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>PG(_{22})</td>
<td>0.333</td>
<td>0.333</td>
<td>0.343</td>
</tr>
<tr>
<td>P(_{\text{TRANSCO12}})</td>
<td>0.367</td>
<td>0.367</td>
<td>0.367</td>
</tr>
</tbody>
</table>

During contract violation in area 2, output power of GENCO 4 (G\(_{22}\)) is increased from 0.333 p.u. to 0.343 (i.e., 0.333+1×0.01) p.u., while the power output of G\(_{12}\) remains same. The violation in area 2 is met by same area GENCO and hence TRANSCO power remains unaltered.

4.6.3 Simulation result under poolco model (with market equilibrium in both areas) incorporating apf and epf

To analyse the performance of LFC incorporating apf and epf, the mathematical model (obtained by combining Figure 3.7 and Figure 3.10) of considered two area deregulated system under poolco model is developed in MATLAB/Simulink, using the system parameters furnished in Appendix V. The calculated apf and epf values are then incorporated in this complete mathematical model. The system is simulated and the GENCOs and TRANSCO power responses are shown in Figure 4.16.

![Figure 4.16: GENCOs and TRANSCO power responses under poolco model (with market equilibrium in both areas)](image-url)
From Figure 4.16 it is seen that $G_{11}$, $G_{21}$, $G_{12}$ and $G_{22}$ generates 0.3003 p.u., 0.4998 p.u., 0.3 p.u. and 0.333 p.u. respectively. The TRANSCO power from area 1 to area 2 is 0.367 p.u. The simulated values shown in Figure 4.16 matches well with the calculated values furnished in Table 4.5.

To analyse the two area deregulated system under poolco model based on epf, a contract violation is to be created. A contract violation of 0.01 p.u. is created at 350s in area 1. The GENCOs and TRANSCO power responses for this case are shown in Figure 4.17.

![Figure 4.17: GENCOs and TRANSCO powers and frequency responses during violation of 0.01 p.u. in area 1 incorporating tie line bias control under poolco model (with market equilibrium in both areas)](image)

From Figure 4.17, it is seen that the output power of $G_{11}$ and $G_{21}$ is increased from 0.3003 p.u. to 0.3049 p.u. and 0.4998 p.u. to 0.5051 p.u. respectively. Since the violated power is met by the GENCOs in same area, TRANSCO power remains same. The power output of the participating GENCOs and TRANSCO are seen to be in tie with the values given in Column 3 of Table 4.6. Figure 4.17 also shows that frequency deviation in both areas are made to settle at zero.

Again, a contract violation of 0.01 p.u. is created at 350s in area 2 and corresponding power responses of GENCOs and TRANSCO are shown in Figure 4.18.

From Figure 4.18, it is seen that the power output of $G_{22}$ is increased from 0.333 p.u. to 0.343 p.u., while the power outputs of $G_{11}$ and $G_{12}$ remains same. The violation in area 2 power is met by same area GENCOs and hence TRANSCO power remains unaltered. These
GENCOs and TRANSCO powers seem to match with the values given in Table 4.6. The deviation in system frequencies are nullified as shown in Figure 4.18.

![Figure 4.18](image.png)

Figure 4.18: GENCOs and TRANSCO powers and frequency responses during violation of 0.01 p.u. in area 2 incorporating tie line bias control under poolco model (with market equilibrium in both areas)

The bar chart representation of GENCOs and TRANSCO power responses gives clear view of performance of LFC incorporating tie line bias control.

4.6.4 Bar chart representation of GENCOs and TRANSCO powers incorporating tie line bias control under poolco model (with market equilibrium in both areas)

The contribution of each GENCO and TRANSCO power variations can be easily represented in the form of bar chart. The GENCOs and TRANSCO powers in the considered two area system, operating under poolco model (with market equilibrium), for a contract violation in area 1 is presented in Figure 4.19.

Figure 4.19 gives the increase in power generation of willing GENCOs during violation. It is clear from figure that GENCO1 (G1) and GENCO 2 (G2) participate during violation in area 1 based on the $epf$ value. While, neighbouring area GENCOs do not contribute. Thus, the power output is rescheduled from contracted value for GENCO 1 (G1) and GENCO 2 (G2). Since, same area GENCOs take care of violated power, TRANSCO power remains unchanged.
The contracted power and power deviations of GENCOs and TRANSCO for a violation in area 2, incorporating tie line bias control is shown in Figure 4.20.

For a violation in area 2, tie line bias control allows only GENCO 3 (G3) and GENCO 4 (G4) to participate in LFC. Since, GENCO 3 (G3) is not willing to contribute; only GENCO 4 (G4) take part in LFC and its power is increases. This is seen from Figure 4.20. Thus, the power generation is changed from the contracted values in case of GENCO 3 (G3), while, power generation remains same for all other GENCOs. The participating GENCOs being in the same area, TRANSCO power remains same at contracted value.
Thus, it is clear from Figure 4.19 and Figure 4.20 that for a violation in area 1 or area 2, tie line bias control adopted in LFC reschedules same area willing GENCOs based on the computed $ep_f$ values.

4.7 ANALYSIS OF LFC UNDER POOLCO MODEL (WITH NO MARKET EQUILIBRIUM IN BOTH AREAS) INCORPORATING $ap_f$ AND $ep_f$

At any instant, if the total offered power in both the area is less than total bid power, there exists no intersection between the supply and demand curves. The trading of power is done for the entire offered power in each area. This section explains the formulation of $ap_f$ and $ep_f$ of GENCOs in two area power system with no market equilibrium in both areas.

4.7.1 Simulation for calculation of $ap_f$ and $ep_f$ (with no market equilibrium in both areas)

A MATLAB code is developed that accepts the offers and bids from individual GENCOs and DISCOs, plots the individual and combined supply and demand curves. Using the data given in Appendix III, supply and demand curves are plotted using the developed code and is shown in Figure 4.21.

![Figure 4.21: Auction clearing under poolco model (with no market equilibrium in both areas)](image)

Figure 4.21 shows that the total offered power is less than total bid power. The auction is cleared with the in-merit players as $G_{11}$, $G_{21}$ in area 1 and $G_{12}$, $G_{22}$ in area 2. It is also clear that $G_{11}$, $G_{21}$, $G_{12}$ and $G_{22}$ are allotted with a power of 150 (i.e., 100+50) MW, 50MW, 100MW and 130MW respectively. The total power demand in area 1 and area 2 is 200MW and 230MW respectively.
Using the equation (4.16) – (4.19), the \( apf \) values are calculated and the \( APM \) for the pools are given in equation (4.28) and (4.29).

\[
APM_1 = \begin{bmatrix}
0.75 & 0 \\
0.25 & 0
\end{bmatrix} \tag{4.28}
\]

\[
APM_2 = \begin{bmatrix}
0 & 0.435 \\
0 & 0.565
\end{bmatrix} \tag{4.29}
\]

The rows of equation (4.28) and (4.29) represents respective GENCOs, while, column corresponds to the areas. Equation (4.28) shows that GENCO 1 and GENCO 2 meets demand in area 1 by 75% and 25% respectively. Similarly, GENCO 3 and GENCO 4 meet the demand in area 2 by 43.5% and 56.5% respectively. From equation (4.28) it is seen that \( G_{11} \) generate 150 (i.e., \( 0.75 \times 200 \)) MW, while and \( G_{21} \) generate 50 (i.e., \( 0.25 \times 200 \)) MW respectively, to meet the demand of 200MW. These participation factors satisfy the equation (4.20). The entire power available in area 1 meet the demand in same area and thus, no power flows through the TRANSCO to area 2. Thus, the participation factor for \( G_{11} \) and \( G_{21} \) in area 2 is zero as per equation (4.18). The power demand of 230MW in area 2 is met by \( G_{12} \) and \( G_{22} \) having power generation of 100.05MW and 129.95MW respectively with ratio 0.435:0.565. This is evident from equation (4.29). These factors satisfy the condition given in (4.21). The GENCOs in area 2 do not contribute to the demand in area 1 and hence the sum of participation of \( G_{12} \) and \( G_{22} \) is zero as per equation (4.19).

During contract violation, the unscheduled demand is met by the willing GENCOs that submit their offers in the second phase auction. However, if none of the GENCOs are willing to participate in LFC during contract violation, \( epf \) becomes zero.

Now, these participation factors are incorporated in the considered two area deregulated system under poolco model and is to be analysed to check whether LFC operates based on these factors.

4.7.2 Scheduled GENCO power under poolco model (with no market equilibrium in both areas) incorporating \( apf \) and \( epf \)

This section analyses the performance of two area LFC system under poolco model incorpoating \( apf \) and \( epf \) values. The system is analysed with p.u. values, thus all the power values are converted to corresponding p.u. values using base value of 230MW. The GENCOs and TRANSCO contracted powers are determined using equation (3.19) and is furnished in Table 4.7.
Table 4.7: GENCOs and TRANSCO powers (p.u.) under poolco model (with no market equilibrium in both areas)

<table>
<thead>
<tr>
<th></th>
<th>PG$_{11}$</th>
<th>PG$_{21}$</th>
<th>PG$_{12}$</th>
<th>PG$_{22}$</th>
<th>P$_{\text{TRANSCO12}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 1</td>
<td>0.652</td>
<td>0.217</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Area 2</td>
<td>0</td>
<td>0</td>
<td>0.435</td>
<td>0.565</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>0.652</td>
<td>0.217</td>
<td>0.435</td>
<td>0.565</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.7 shows that GENCOs in area 1 meet 0.869 p.u. demand in same area. Similarly, GENCO 3 and GENCO 4 meet 1 p.u. demand in area 2 respectively. The demand in each area is met by GENCOs in same area and hence, TRANSCO power flow is zero.

As explained in section 4.7.1, during a contract violation in any area, the in-merit GENCOs with allotted power are made to compensate for the demand violation. During contract violation, the unscheduled demand is met by the un-allotted power of in-merit GENCOs. In case of no GENCOs willing to participate for the violated demand, the epf value is zero. This case is shown in Table 4.8.

Table 4.8: GENCOs and TRANSCO powers (p.u.) during violation incorporating tie line bias control under poolco model (with no market equilibrium in both areas)

<table>
<thead>
<tr>
<th></th>
<th>Contracted power</th>
<th>Violation in area 1</th>
<th>Violation in area 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG$_{11}$</td>
<td>0.652</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PG$_{21}$</td>
<td>0.217</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>PG$_{12}$</td>
<td>0.435</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>PG$_{22}$</td>
<td>0.565</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P$_{\text{TRANSCO12}}$</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.7.3 Simulation result under poolco model (with no market equilibrium in both areas) incorporating $apf$ and $epf$

To analyse the performance of LFC incorporating $apf$ and $epf$, the mathematical model (obtained by combining Figure 3.7 and Figure 3.10) of considered two area deregulated system under poolco model is developed in MATLAB/Simulink. The calculated $apf$ and $epf$ values are then incorporated in this complete mathematical model under poolco model. The system is simulated and the GENCOs and TRANSCO responses are shown in Figure 4.22.
Figure 4.22: GENCOs and TRANSCO power responses under poolco model (with no market equilibrium in both areas)

Figure 4.22 shows the power output of $G_{11}$, $G_{21}$, $G_{12}$ and $G_{22}$ as 0.652 p.u., 0.217 p.u., 0.435 p.u. and 0.565 p.u. respectively. These values match with the tabulated values shown in Table 4.7.

During contract violation, the unscheduled demand is met by willing GENCOs. However, Figure 4.15 shows that no un-allotted power is left with any of the GENCOs. Thus, during any contract violation, no GENCOs meet for the un-contracted power demand.

4.8 CONCLUSIONS

The complete mathematical model of two area deregulated power system explained in chapter 2 operates effectively only with suitable selection of market and violation participation factors under different market models. Based on the market procurement explained in chapter 3, a proper mathematical formulation of market and violation participations has been explained in detail and developed. Market conditions for different market models under different scenarios have been created. A MATLAB code has been developed that accepts offers and/or bids from GENCOs and/or DISCOs and sketches the supply and demand curves. From the curves obtained, MCP, MP, in-merit GENCO power, in-merit DISCO, allotted GENCO and DISCO power has been tabulated. From the tabulated allotted power of each GENCO, corresponding market and violation participation factors have been computed using the developed mathematical formulation. The effectiveness and accuracy of this mathematical formulation is to be tested by analysing the two area LFC system under different market model incorporating these factors. For this, the complete
mathematical model of two area power system operating under different market model, explained in chapter 2, is modelled in MATLAB/Simulink. The computed participation factors have been incorporated in this model and analysed to obtain the GENCOs and TRANSCO power. The obtained results are compared and found to match with the tabulated GENCOs and TRANSCO power using the formulated market and violation participation factors. Thus, it can be concluded that incorporating tie line bias control, allows LFC to reschedule the power generation of same area willing GENCOs to meet the violated demand.