CHAPTER 3

MODELLING OF LOAD FREQUENCY CONTROL IN DEREGULATED POWER SYSTEM

3.1 INTRODUCTION

Traditional electric power system [43] incorporating a vertical structure, has been regulated through federal and state agencies. After decades of government regulation, the state-owned monopoly utility has been criticized as inefficient [97]. Customers have to pay the expenses of utilities due to low efficiency operation and improper policies. The system has been under stress, struggling to meet the highly increasing demand with limited resources. With the aim to uplift social welfare, these systems around the world are currently undergoing major restructuring processes and are adapting the deregulated market operation [101]. The new paradigm promotes new sources of power generation, invites new players with multiple sources of power generation and thus leaving customers with choices on selecting the sources of supply [164]. A reliable service from more efficient system is necessary so as to optimize the system welfare. This requirement can be provided only through innovations, which is possible by incorporating competition in the system. The concept of auction is hence introduced through the incorporation of market in the restructured system so as to bring competition [145]. The auction procurement adopted decides players who are allowed to perform trading with their allotted power and market price. Each supplier generates the allotted power with the help of LFC. This chapter presents the structure of electric power system under new environment. It also discusses the different models in deregulated market holds with its operations. The need, operation and mathematical modelling of LFC under different market models are discussed and developed in this chapter.

3.2 DEREGULATED POWER SYSTEM

The reason for worldwide trend of electric utility industry to shift towards horizontal structure has been different for different countries like Sweden, Finland, UK, Norway, US, Italy, India, China and certain countries of South America. In developing countries like India and China, the issues have been high growth in demand coupled with irrational tariff policies and inefficient system management. In developed countries like Sweden and US, the idea has
been to provide electricity at lower prices [190] and offer consumers with greater choice in purchasing economic energy. The newly reformed power system incorporates independent utilities named as GENCOs, TRANSCOs, DISCOs, Retail companies (RETAILCOS) and ISO. The structure of deregulated power system incorporating all the mentioned companies is shown in Figure 3.1.

![Figure 3.1: Structure of deregulated power system](image)

The GENCO is the portion of the formerly vertical utility that is dedicated to the generation of electric energy. Typically unregulated GENCOs are able to change market based rates. GENCOs generally have relationships with retailers for marketing their generation resources.

The TRANSCO is the portion of the formerly vertical utility, dedicated to the operation of transmission systems. While TRANSCOs continue to be owned by utility companies, their operation is separated from other operations such as generation and retailer. The TRANSCOs must allow access to their transmission systems on an equal basis. This provides a playing field for all market participants as they move electric power among regions.

The DISCO is the portion of the formerly vertical utility, dedicated to the delivery of electric energy to consumers. The entity focuses on the operation of distribution lines and generally continues to be regulated.

RETAILCOS are dedicated for marketing generation services and other energy related services to retail customers. RETAILCOS, also known as Retail Electric Providers (REPs), may or may not generate electric energy themselves.

In deregulated market, power is rated as that of any other commodity. There exists a number of GENCOs willing to sell electrical energy. As shown in Figure 3.1, the customers
can directly avail power from these GENCOs on economic basis by paying them or purchase power from RETAILCO on payment. The RETAILCO purchases bulk power from GENCOs upon payment and provides required power to the consumers. This power is transferred through the transmission and distribution lines. Hence, wheeling charges are to be paid by the GENCOs and customers for using the TRANSCO and DISCO facility. The electric energy is to be transferred from GENCOs through TRANSCOs such that no congestion occurs. Hence, GENCOs engage in information exchange with TRANSCOs and DISCOs for power trading. Electricity prices and system reliabilities in deregulated system are centrally controlled and managed by the ISO. The electricity prices vary with generation biddings, customer demands, locations, choices on price, reliability and mainly the power market structures. Power market holds different models namely single buyer, bilateral and poolco. Every market has its own unique characteristics and specific features [94].

The ISO [106; 109], described as the ‘soul of the grid’ and as the ‘air traffic controllers’ of the electricity system, controls the access to and use of the transmission system by competing GENCOs and RETAILCOs. The role of ISO is to balance supply and demand in real time and to maintain system reliability and security. ISOs do not own any electricity transmission lines, nor hold any generating units and thus should be impartial. The ISO should advance the objectives outlined in many state proceedings and in the Central Energy Regulatory Commission’s (CERC) various proposed rules on pooling and transmission access. The relevant objectives of ISO include:

- **Reliability**: ISO has to ensure reliability by coordinating short-term operations, while supporting the competitive spot market.

- **Independence**: The ISO’s incentives and governance structure should be designed such that no subset of the market participants is allowed to control the criteria or operating procedures.

- **Non-Discrimination**: The ISO should provide access to all market participants without distinction with pricing of services.

- **Unbundling**: The services should be unbundled when possible for acquisition from the competitive market and for utilization by the market participants.

- **Efficiency**: The ISO’s operating procedures and service pricing should support an efficient and competitive electricity market.
• **Economic Dispatch:** The ISO should adjust the dispatch to meet transmission constraints and maintain the system balance. The dispatch should be adjusted so as to provide market players, the most highly valued use of the grid based on the preferences. The ISO determines the most economical use of transmission system from the offers and bids provided by the market players.

• **Efficient Pricing:** The attribute cost set by the ISO includes the direct power cost and congestion short term cost in transmission grid. The congestion cost, which differs by locations, comes into account when transmission constraints compel expensive plants to operate. Those causing the congestion at the margin should pay for it.

The key to success of new competitive structure lies in the careful specification of ISO's functions and responsibilities to support an efficient competitive market.

Even though the system structure under deregulated environment remains same as vertical system, the operation differs [154]. The operation of unbundled utilities in the competitive electric power system is performed in an open access policy. This makes the operation of competitive electric power market different from the vertical system.

The newly reformed structure makes use of a platform called ‘market’ to perform power trading. Market holds different models namely, single buyer, bilateral or poolco. The power trading performed in these models are explained in the following sections.

3.2.1 **Single buyer market model**

In single buyer model, power trading is performed for each pool separately via auction mechanism. The suppliers (GENCOs) are the only entities participating in single buyer market. The schematic of single buyer model is shown in Figure 3.2.

![Figure 3.2: Schematic of single buyer model](image-url)
The GENCOs and pool operator are the signatories in the pooling agreement that directs the operation of the single buyer market. Under this market model, GENCOs participate in the auction submitting the bids for a prescribed time window to the ISO, which is referred to as pool operator. Each GENCO can lodge different offers, known as multiunit auction [44, 123]. The bids are sorted in the increasing order of offered price by the pool operator. The operator then sketches the vertical line that corresponding to the predicted demand for the specified period. An intersection point between the supply and demand curves is obtained. The extrapolation of this point to the horizontal and vertical axis gives the Market Power (MP) and MCP for the corresponding time window respectively. The players lying to the left of the intersection point along the supply curve are chosen as the in-merit players. These players dispatch the allotted power for the time slot. Under a single buyer model, it is mandatory for all the GENCOs to participate in the auction conducted by the pool operator. This model does not accept bids from the power buyers and hence this auction mechanism is also called as single sided auction. This type of market clearing procedure is adopted in UK.

### 3.2.2 Bilateral market model

The competitive environment also allows establishing power contracts mutually between the GENCOs and the customers [88]. The amount and the price of electricity to be traded for a time slot are clearly specified in the contracts. This model allows the GENCOs to decide on the dispatch of their own generating units. The bilateral model can also accommodate voluntary power exchange. Thus, in a bilateral model the concept of self-dispatch is adopted. The schematic of bilateral model is shown in Figure 3.3.

![Bilateral model schematic](image)

**Figure 3.3:** Schematic of bilateral model

If the static and dynamic securities are not violated, the ISO simply dispatches all the requested transactions and charge for the services. However, if there is threat to system security, the ISO can curtail contracted power. Since the ISO does not have the generation capabilities to balance the system under deviations; the imbalances are paid at penalty price.
This market model offers more retail choices for the customers. Thus, this model is considered suitable from viewpoint of dynamic incentive to competition and for short-term and long-term stability in the supply. This type of transaction model is adopted in Norway.

3.2.3 Poolco market model

In poolco model, power trading is performed under central auction, administered by ISO [178]. There are two major entities participating in the pool market namely, suppliers (GENCOs) and the buyers (DISCOs). The schematic of poolco model is shown in Figure 3.4.

The pool model facilitates competition between GENCOs and DISCOs. The GENCOs, ISO and DISCOs are the signatories in the pooling agreement that directs the operation of the pool. Each player is allowed to submit one or more offers or bids for a time window. The ISO then sketches the supply and demand curves. To be more specific, ISO rank the GENCOs’ offers in increasing order by price, while the DISCOs’ bids in decreasing order by price. Simultaneously, every offer or bid repeats to be sorted according to its quantity with each offer and bid corresponding to 1 kWh electric power. i.e., the bid quantity of 5 kWh corresponds to participants equal to 5 virtual participants whose bidding quantity is 1 kWh each. Once the sketch is done, the intersection between the supply and demand curves is determined. The MCP (y axis intercept of intersection point) and MP (x axis intercept of intersection point) are obtained from the intersection between the supply and demand curves. The players lying to the left of MP along the respective curves are chosen as the in-merit players. The power trading is done between in-merit GENCOs and in-merit DISCOs. If there is no threat to system security, the ISO fix the market clearance as per the obtained. However, if such contracts affect system parameters, the ISO will ask the GENCOs and DISCOs to make alternative arrangements or pay an extra price for the transmission constraints. Poolco
model leaves the GENCOs with choice on submitting offers to ISO. This model accepts offers and bids from GENCOs and DISCOs respectively, and hence, it is also called as double sided auction. The Nordic and California model has the structure similar to poolco model.

The auction in a single buyer or poolco model is done to determine the real time price and MP either on short term (hourly, daily or monthly) or long term (yearly) basis. Example, California ISO conducts real-time spot market using offers and bids that are submitted up to 45 minutes prior to the start of each operating hour. This market is open to in-state and out-of-state participants. Every 10 minutes, the ISO adjusts generation by calling on the offers and bids to continuously match California’s demand for energy. Final schedules are compared with the metered quantity for each player with the demand. Any “un-instructed deviation” is settled at hourly average price [151].

Under single buyer or poolco model, if power trading is performed between the in-merit players at MCP, then it is called uniform price mechanism. However, if trading between the in-merit players is done at the offered or bid power, then the mechanism is called pay-as-bid. This work assumes the model to operate at uniform price auction [25].

### 3.2.4 Hybrid market model

There also exist combination of bilateral and poolco model known as hybrid market. In such type of model, a GENCO has the freedom to enter into both auction as well as direct contracts with the DISCOs. The schematic of a hybrid power system is shown in Figure 3.5.

![Figure 3.5: Schematic of hybrid model](image)

The hybrid model incorporating bilateral and poolco model is seen in US.

Under the new reformed environment, power suppliers behave so that their profit is maximized, while the consumers are supposed to benefit from lower rates as a result of
introduction of competitive market. However, the operation of restructured system is decided by the market based on competition and contract. Thus, ISO faces a major challenge to coordinate among the various market players and manage a secure and reliable flow of power. Security of an interconnected power system relies on the balance between total generation and total load demand plus associated system losses. Any abrupt small disturbance due to generation or load losses results in imbalance between electrical power supplied by the connected generators and load. This directly results in lowering of turbine speed and hence, deviation in system frequency. Sequentially, the scheduled power exchange between control areas deviate from their nominal values. This poses serious threat to reliable operation of power system. It is necessary to have an automatic system that manipulates the operation of fuel valve which in turn adjusts real power output of generating units to match with the demand. This is accomplished with the help of LFC [24].

LFC, one of the ancillary services, aims to maintaining the GENCOs and TRANSCOs power at scheduled value [120], thereby maintaining the system frequency within limits. In deregulated system, GENCO sends information to the governor of LFC to follow as per the allotted (in case of single buyer or poolco model) or contracted (in case of bilateral model) power as long as the demand stays at the contract value. Conversely, when the demand violates from the contracted value, the LFC reschedules the GENCO units to meet the uncontracted demand, thereby maintaining the system frequency within limit.

There exist crucial differences between the LFC operation in a vertically integrated industry and horizontally integrated industry. With restructuring of electric markets, LFC requirements should be expanded to include the planning functions necessary to insure the resources needed for LFC implementation. The operation, simulation and optimization of LFC in the reconstructed power system after deregulation have to be reformulated even though basic approach remains the same. To analyse the operation of LFC, it is required to consider a system for the study.

3.3 TWO AREA Deregulated Power SYSTEM

To analyse the operation of LFC, the work considers two area power system [173] under deregulated power system as shown in Figure 3.6. The two control areas shown in Figure 3.6 are connected by TRANSCO. Each area consists of two GENCOs and two DISCOs as in-merit player in each area.
The GENCOs in each area are assumed to have a hydro and a thermal unit [96]. Each DISCO can avail power from GENCOs within or outside the control area. To analyse the LFC for its operation, it is necessary to develop the mathematical model of the power system shown in Figure 3.6.

### 3.4 MATHEMATICAL MODEL OF LFC IN Deregulated Power System

The LFC under deregulated power system requires modification in its mathematical model. The mathematical model of two area LFC system under deregulated environment presented by J. Kumar et. al., 1997 [84] is adopted in this work and is depicted in Figure 3.7. The model incorporates hydro and thermal system with non-reheat turbine. The model is modified to take into account, the characteristics of single buyer, bilateral and poolco market model.

The mathematical model shown in Figure 3.7 assumes that all GENCOs in each area are modelled to have a hydro and thermal system with non-reheat turbine [43]. The frequency variation at each control area due to the effect of local load ($\Delta P_D$) is represented as $\Delta f_1$ and $\Delta f_2$ respectively. The primary control responds within short duration of occurrence of disturbance. However, the governor is characterised by its drooping characteristics that prevents the system frequency to catch back the nominal frequency. This is incorporated in the model by the parameter R. This calls for the necessity of secondary controller.
The primary frequency control that provides the natural self-governing response attenuates frequency deviations that are greater than the speed governor tolerance. The secondary frequency control re-establishes area frequency to the nominal value. This objective is accomplished with the incorporation of integral controller as secondary controller.

The two areas are connected by TRANSCO modelled using the synchronizing coefficient, T. The TRANSCO handles power that corresponds to difference between power export and import in an area and is represented as the scheduled power ($\Delta P_{\text{TRANSCO12scheduled}}$). However, a violation of $\Delta P_D$ causes TRANSCO power to deviate from the scheduled value. This deviation results in error and is defined in equation (3.1).

$$\Delta P_{\text{TRANSCO12error}} = \Delta P_{\text{TRANSCO12actual}} - \Delta P_{\text{TRANSCO12scheduled}}$$ (3.1)

To meet the objective of LFC to maintain system frequency a nominal value and TRANSCO power at contracted value, the input to the secondary controller includes system frequency deviation and TRANSCO power error that incorporates the area control error (ACE). With ACE as input to the secondary controller, LFC monitors the system frequency.
and TRANSCO power deviations as a result of variation in demand, determines the net generation change required and changes the set operation of the generators within the area.

Thus, LFC constitutes an important function on the power system operation that allows GENCOs to generate scheduled value of power during contracted condition and also allows willing GENCOs to reschedule for meeting the unscheduled power during contract violation. This requires modification of existing conventional LFC under vertical power system. The existing mathematical model of LFC is to be modified in order to incorporate participation of each GENCO during contract and violation.

The mathematical model of GENCO contract power is based on market participation factor that differs with market model.

### 3.4.1 Market participation factor

One of the objectives of LFC is to schedule GENCOs to generate contracted value of power during contracted condition. The contribution of each in-merit or contracted GENCO to meet the scheduled power is based on market model.

#### 3.4.1.1 Market participation factor under single buyer model

Under single buyer model the total predicted demand for a time window is met by in-merit GENCOs. These in-merit GENCOs are chosen as per the auction procurement explained in section 3.2.1. The contribution of \( i \)th GENCO of \( j \)th area, to meet the total predicted demand \( P_L \) is represented as GENCO participation factor \( gpf_{ij} \).

The \( gpf \) values of all GENCOs in \( j \)th area are represented by GENCO participation matrix \( (GPM) \) as given in equation (3.2).

\[
GPM_j = \begin{bmatrix}
gpf_{1j} \\
gpf_{2j} \\
\vdots \\
gpf_{nG_j j}
\end{bmatrix}
\]  

(3.2)

It is mandatory for all the GENCOs under single buyer model to take part in auction. This leaves \( gpf \) of all GENCOs with non-zero values. The \( GPM \) elements are such that their sum is unity, which means that all GENCOs contribute to the total demand.

\[
\sum_{i=1}^{nG_j} gpf_{ij} = 1
\]  

(3.3)
Where,

\( nGj \) is the number of GENCOs in area \( j \).

Based on \( gpf \), the scheduled power output of each GENCO is calculated using equation (3.4).

\[
P_{G_{i\text{-contract}}} = gpf_{ij} \times P_{lj}
\]  

(3.4)

**GPM** for two area power system shown in Figure 3.6 using equation (3.2) is as given in equations (3.5) and (3.6).

\[
GPM_1 = \begin{bmatrix} gpf_{11} \\ gpf_{21} \end{bmatrix}
\]  

(3.5)

\[
GPM_2 = \begin{bmatrix} gpf_{32} \\ gpf_{42} \end{bmatrix}
\]  

(3.6)

These \( gpf \) values satisfy the condition given in equation (3.3). The GENCOs of system shown in Figure 3.6 generates scheduled power based on these \( gpf \) values, furnished in equations (3.5) – (3.6) are represented in Figure 3.8.

![Figure 3.8: Mathematical model of market contracted power of GENCOs under single buyer model](image)

The mathematical model of system given in Figure 3.6, operating under single buyer model explained in section 3.2.1, is obtained by combining Figure 3.7 and Figure 3.8. Each area demand is met by same area GENCOs and therefore, TRANSCO power is zero in single buyer model.

### 3.4.1.2 Market participation factor under bilateral model

For the bilateral model explained in section 3.2.2, the demand of a DISCO is met by each GENCO based on \( cpf \). \( cpf \) forms the elements of **DPM** matrix as shown in equation (3.7).

\[
DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & \cdots & cpf_{1nD} \\ cpf_{21} & cpf_{22} & \cdots & cpf_{2nD} \\ \vdots & \vdots & \ddots & \vdots \\ cpf_{nD1} & cpf_{nD2} & \cdots & cpf_{nnD} \end{bmatrix}
\]  

(3.7)
Where,

\( n_G \) is the number of GENCOs
\( n_D \) is the number of DISCOs

\( cpf_{ij} \) represents participation factor of \( i^{th} \) GENCO to meet demand of \( j^{th} \) DISCO.

For each column of DPM, the sum of \( cpf \) elements is unity as given in equation (3.8).

\[
\sum_{i=1}^{n_G} cpf_{ij} = 1 \quad (3.8)
\]

Using the \( cpf \) values, the contracted power output of \( i^{th} \) GENCO is calculated using equation (3.9).

\[
P_{Gi-contract} = \sum_{j=1}^{n_D} cpf_{ij} \times P_{lj} \quad (3.9)
\]

Where,

\( n_D \) is the number of DISCOs

\( P_{lj} \) is the scheduled power demand

The power export (\( P_{exp i} \)) and import (\( P_{imp i} \)) from and to area \( i \) is given in equation (3.10) and (3.11) respectively.

\[
P_{exp i} = \sum_{d=1}^{S} \sum_{k=1}^{P} cpf_{kd} \times P_{ld} \quad (3.10)
\]

\[
P_{imp i} = \sum_{l=1}^{R} \sum_{d=1}^{Q} cpf_{ld} \times P_{ld} \quad (3.11)
\]

Where,

\( P \) is the number of GENCOs in area \( i \)
\( Q \) is the number of GENCOs in area \( j \)
\( R \) is the number of DISCOs in area \( i \)
\( S \) is the number of DISCOs in area \( j \)

The scheduled power deviation calculated from the power export and import is given in equation (3.12).

\[
\Delta P_{\text{TRANSCO}ij\text{scheduled}} = P_{\text{exp} i} - P_{\text{imp} i} \quad (3.12)
\]

The error in the TRANSCO power deviation is obtained from the difference between scheduled and actual power as given in equation (3.13).

\[
\Delta P_{\text{TRANSCO}ij\text{error}} = \Delta P_{\text{TRANSCO}ij\text{actual}} - \Delta P_{\text{TRANSCO}ij\text{scheduled}} \quad (3.13)
\]
DPM for the power system shown in Figure 3.6 is as given in equation (3.14).

\[
DPM = \begin{bmatrix}
cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\
cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\
cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\
cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44}
\end{bmatrix}
\]  

(3.14)

The \(cpf\) values are such that it satisfies the condition given in equation (3.8). The contracted power of each GENCO under bilateral model is based on these \(cpf\) values and is obtained using equation (3.9). The market contracted power model is represented in Figure 3.9.

Figure 3.9: Mathematical model of market contracted power of GENCOs under bilateral model

The complete mathematical model of power system given in Figure 3.6 under bilateral model explained in section 3.2.2, is obtained by combining Figure 3.7 with Figure 3.9.

3.4.1.3 Market participation factor under poolco model

The in-merit GENCOs shown in Figure 3.6 under poolco model explained in section 3.2.3 produce contracted power based on \(apf\). The \(apf\) values make the elements of Area Participation Matrix \((APM)\). The \(APM\) for \(j\)'th area is formulated as per equation (3.15).
Where, 

\[ A \] is the total number of area

\[ nGj \] is the number of GENCOs in the \( j^{th} \) area

In equation (3.15), \( apf_{iA} \) corresponds to the participation of \( i^{th} \) GENCO of \( j^{th} \) area, to meet the demand in area ‘A’.

For the system shown in Figure 3.6, the criterion for \( apf \) value depends on the direction of power flow through TRANSCO and is given in equation (3.16) – (3.18).

When the TRANSCO power flow is zero:

\[
\begin{align*}
\sum_{k=1}^{P} apf_{ki} &= \sum_{l=P+1}^{Q} apf_{lj} = 1 \\
\sum_{l=P+1}^{Q} apf_{li} &= \sum_{k=1}^{P} apf_{kj} = 0
\end{align*}
\] (3.16)

When the TRANSCO power flow is positive:

\[
\begin{align*}
\sum_{k=1}^{P} apf_{ki} &= \sum_{l=P+1}^{Q} apf_{lj} + \sum_{l=P+1}^{Q} apf_{li} \\
&= \sum_{m=1}^{nG} apf_{mj} = 1 \\
\sum_{l=P+1}^{Q} apf_{li} &= 0
\end{align*}
\] (3.17)

When the TRANSCO power flow is negative:

\[
\begin{align*}
\sum_{k=1}^{P} apf_{ki} + \sum_{l=P+1}^{Q} apf_{li} &= \sum_{m=1}^{nG} apf_{mi} \\
&= \sum_{l=P+1}^{Q} apf_{lj} = 1 \\
\sum_{k=1}^{P} apf_{kj} &= 0
\end{align*}
\] (3.18)

Where,

\( nG \) is the total number of winning GENCOs

\( P \) is the number of GENCOs in area \( i \)

\( Q \) is the number of GENCOs in area \( j \)
The power output of $i^{th}$ GENCO to satisfy the demand of area ‘$j$’ is calculated as per equation (3.19).

$$P_{Gi-\text{contract}} = \sum_{j=1}^{A} a p f_{ij} \times P_{Lj} \quad (3.19)$$

Where,

- $P_{Lj}$ is the demand in area ‘$j$’
- $A$ is the number of areas

For the poolco model, power export ($P_{\text{exp}i}$) and import ($P_{\text{imp}i}$) from and to area $i$ is given in equation (3.20) and (3.21).

$$P_{\text{exp}i} = \sum_{k=1}^{P} a p f_{kj} \times P_{Lj} \quad (3.20)$$

$$P_{\text{imp}i} = \sum_{l=P+1}^{Q} a p f_{li} \times P_{Li} \quad (3.21)$$

Where,

- $P_{Li}$ is the demand in area ‘$i$’
- $P_{Lj}$ is the demand in area ‘$j$’

The scheduled TRANSCO power deviation $\Delta P_{\text{TRANSCOij scheduled}}$ is given in equation (3.22).

$$\Delta P_{\text{TRANSCOij scheduled}} = P_{\text{exp}i} - P_{\text{imp}i} \quad (3.22)$$

The error in the TRANSCO power deviation is obtained from the difference between scheduled and actual power as given in equation (3.23).

$$\Delta P_{\text{TRANSCOij error}} = \Delta P_{\text{TRANSCOij actual}} - \Delta P_{\text{TRANSCOij scheduled}} \quad (3.23)$$

$APM_1$ and $APM_2$ for the power system shown in Figure 3.6 based on equation (3.15), is given in equation (3.24) and (3.25).

$$APM_1 = \begin{bmatrix} apf_{11} & apf_{12} \\ apf_{21} & apf_{22} \end{bmatrix} \quad (3.24)$$

$$APM_2 = \begin{bmatrix} apf_{31} & apf_{32} \\ apf_{41} & apf_{42} \end{bmatrix} \quad (3.25)$$

These $apf$ values satisfy the equation (3.17) or (3.18) or (3.19).

The contracted output power of each GENCO based on equations (3.19), (3.24) – (3.25) is represented in Figure 3.10.
Combining Figure 3.7 with Figure 3.10 yields the complete transfer function of the system shown in Figure 3.6, operating under poolco model.

### 3.4.2 Violation participation factor

The second objective of LFC is to make willing GENCOs to meet the un-contracted power during contract violation. The willing GENCOs are called for a second round of auction to meet the un-contracted power. Based on the offer price of these willing GENCOs, the participation factor, $epf$, is calculated.

The Economic Participation Matrix (EPM) for the GENCOs in $j^{th}$ area with $epf$ as its elements is given in equation (3.26).

$$EPM_j = \begin{bmatrix} epf_{1j} \\ epf_{2j} \\ \vdots \\ epf_{nGj} \end{bmatrix} \quad (3.26)$$

Where,

$nGj$ is the number of GENCOs in $j^{th}$ area.

Thus, the output power of willing in-merit GENCO increases from the contracted power during contract violation and is as given in equation (3.27).

$$p_{Gi-new} = p_{Gi-contract} + (epf_i \times \Delta P_D) \quad (3.27)$$
Where,

\( P_{Gi-new} \) represents power output of \( i \)th GENCO

\( \Delta P_D \) represents un-contracted power

The cost incurred in meeting the \( j \)th area / DISCO un-contracted power (\( \Delta P_{Dj} \)) by all willing GENCOs is given in equation (3.28).

\[
\text{cost} = \sum_{k=1}^{N} epf_k \times \Delta P_{Dj} \times \text{price}_{\text{off-un} \_k}
\]  

(3.28)

Where,

\( epf_k \) is the \( epf \) of \( k \)th GENCO

\( \text{price}_{\text{off-un} \_k} \) is the offer price of \( k \)th GENCO participating in second round auction

### 3.5 CONCLUSIONS

Introduction to deregulated power system with its characteristics and different models are explained in this chapter. The auction procurement adopted under different market models, to perform power trading for a prescribed time window are presented in detail. The need of LFC to regulate frequency and maintain TRANSCO power under restructured environment is included. The mathematical modelling of two area hydro thermal turbine governor system is explained. This model is then modified to incorporate the operation under different market models by introducing market and violation participation factor. These factors are inevitable for efficient operation of LFC to schedule the GENCOs at the contracted and violated power. The superior performance of LFC depends on proper values of market and violation participation factors. The formulation of these factors under different market models are explained in the following chapter.