Automatic Generation Control Scheme based on Dynamic Participation of Generators in Competitive Electricity Markets

Barjeev Tyagi and S. C. Srivastava

Abstract—In this paper a general model for multi-area AGC, suitable for deregulated electricity market has been proposed. A dynamic participation factor for Gencos and Discos based on their bid has also been proposed. To develop the model, control areas of different ratings and each area having number of Discos and Gencos with different response rate has been considered. Different types of transactions, possible in the deregulated markets, have also been considered to develop the model. The developed model has been tested on a 75-bus Indian power system, with PID and the fuzzy logic based controller.

I. INTRODUCTION

The objective of providing an Automatic Generation Control (AGC) has been to maintain the system frequency at nominal value and the power interchange between different areas at their scheduled values. Traditionally, power industries had adopted vertically integrated utility (VIU) structure. Maintenance of system frequency at the nominal value is the joint responsibility of all the generators owned by the utilities. Control area concept has been used to implement AGC scheme. The concepts of the conventional AGC are well discussed in [1], [2], [3] and [4]. In the restructured competitive electricity environment, vertically integrated utilities will no longer exist and the electricity market will involve several market players, such as generating companies (Gencos), distribution companies (Discos), transmission companies (Transcos) and system operator (SO). For stable and secure operation of the power system, SO has to provide number of ancillary services. One of the ancillary services is the ‘frequency regulation’. A Genco may or may not participate in the frequency control of the system. The load frequency control in a deregulated market will be a technical requirement for meeting various power transactions at an acceptable system frequency. A detailed discussion of load frequency control issues in power system operation after deregulation is reported in references [5] and [6].

In a competitive electricity environment, separate market, similar to spot market, is set up for supply of regulating power. This market is also called the frequency regulation market. Automatic generation control in a deregulated electricity market should be designed for different types of possible transactions [5] and [7], such as Poolco based transactions, bilateral transactions and combination of these two. AGC required for Poolco based transactions, implemented by the system operator (SO) may utilize different types of controller [7], [9], [6] and [10], [11], [12]. This paper proposes a general model for multi-area AGC, suitable for deregulated electricity market. The general model has been developed for control areas of different ratings, and each area having number of Discos and Gencos. Different types of transactions, possible in the deregulated markets, have also been considered to develop the model. Participation of any Genco or Disco in frequency regulation market depends on their bids. A dynamic participation factor for a Genco and a Disco has also been considered to develop the model. For each area, an optimally tuned Proportional Integral Derivative (PID) controller and a general-purpose fuzzy logic based controller has been used to test the developed model. The developed model, with PID controller and the fuzzy logic based controller, has been tested on a 75-bus Indian power system. The 75-bus system has been divided into four control areas. Bilateral transactions, Poolco based transactions and combination of the two have been considered for simulation studies.

II. PROPOSED MODEL OF AUTOMATIC GENERATION CONTROL

A competitive electricity market may have following transactions.

i. Poolco based transactions

ii. Bilateral transactions

The frequency regulation schemes for the two transactions are described below.

A. Poolco based transaction

In order to maintain the demand supply balance, the system operator (SO) accepts bids (volume and price) from power producers who are willing to quickly (within about 10-15 minutes) increase or decrease their level of production. Consumers also can submit bids to SO for increasing or decreasing their level of consumption. The up/down regulation bids can be arranged in ascending/descending order to form a staircase for each operating hour. When regulation is
needed, the SO activates the most favorable bid.

If the frequency is lower than nominal value, up regulation bids are activated by the SO in steps and the highest activated bid becomes the regulation price, uniformly paid to all the providers of upward regulation service. If frequency is higher than nominal, down regulation is activated by the SO in steps and the lowest activated bid price becomes the uniform price to be paid by all the down regulation service providers. Thus, the hourly regulating price is fixed as the price for the most expensive measure (regulating up) or least expensive measure (regulating down) utilized during the hour.

At the end of scheduling interval, the net energy balance of each entity is calculated and financial settlements are carried out.

**a. Participation of a Genco and Disco in Frequency Regulation Market**

Let there be n number of power producers and m number of consumers participating in the market. Assume that the bids submitted by the power producers and the consumers, for frequency regulation are \((p_{g}(1), c_{g}(1)), (p_{g}(2), c_{g}(2)), \ldots, (p_{g}(n), c_{g}(n))\) and \((p_{l}(1), c_{l}(1)), (p_{l}(2), c_{l}(2)), \ldots, (p_{l}(m), c_{l}(m))\), respectively.

where,
- \(p_{g}(i)\) is the price for regulating power quoted by the \(i^{th}\) Genco for upward regulation,
- \(c_{g}(i)\) is the capacity quoted by the \(i^{th}\) Genco for upward regulation, \(i=1, 2, \ldots, n\),
- \(p_{l}(j)\) is the price for regulating power quoted by the \(j^{th}\) Disco for upward regulation,
- \(c_{l}(j)\) is the capacity quoted by the \(j^{th}\) Disco for upward regulation, \(j=1, 2, \ldots, m\).

If \(T_{dem}\) is the total extra demand that arises in the hour of operation in any area for upward regulation, the participation factor of each Genco and Disco in that area can be calculated by minimizing the cost of regulating power.

Minimiz

\[
C_{reg} = \sum_{i=1}^{n} p_{g}(i)*c_{g}(i) + \sum_{j=1}^{m} p_{l}(j)*u_{load}(j)
\]

subject to a set of constraints

\[
gen(i) + u_{load}(j) = T_{dem}
\]

\[
gen(i) \leq c_{g}(i)
\]

\[
u_{load}(j) \leq c_{l}(j)
\]

where, \(c_{gen}(i)\) is the change in the power generated by the \(i^{th}\) Genco, \(u_{load}(j)\) is the load curtailed by the \(j^{th}\) Disco.

Although the price for the up regulating power is the maximum bid price selected to generate the power for frequency regulation, but the Gencos quoting the minimum price are allowed to generate the maximum power.

Participation factor of the \(i^{th}\) Genco for up regulation can be defined as,

\[
pfg(i) = \frac{gen(i)}{T_{dem}}
\]

and the participation factor of the \(j^{th}\) Disco for up regulation can be defined as,

\[
pfd(j) = \frac{load(j)}{T_{dem}}
\]

For down regulation, the participation factor of each Genco as well as Disco in any area can be calculated by maximizing the cost of the regulating power, defined as,

\[
C_{dreg} = \sum_{i=1}^{n} p_{g}(i)*r_{gen}(i) + \sum_{j=1}^{m} p_{l}(j)*u_{load}(j)
\]

subject to the following constraints

\[
r_{gen}(i) + u_{load}(j) = T_{dem}
\]

\[
r_{gen}(i) \leq c_{g}(i)
\]

\[
u_{load}(j) \leq c_{l}(j)
\]

where, \(r_{gen}(i)\) is the reduction in the power output of the \(i^{th}\) Genco, \(u_{load}(j)\) is the increase in the load by the \(j^{th}\) Disco, \(T_{dem}\) is the reduction in the total load demand in the area.

Participation factor of the \(i^{th}\) Genco for down regulation, thus, can be defined as,

\[
pfg(i) = \frac{r_{gen}(i)}{T_{dem}}
\]

and the participation factor of the \(j^{th}\) Disco for down regulation can be defined as,

\[
pfd(j) = \frac{u_{load}(j)}{T_{dem}}
\]

**B. Bilateral transactions**

A Disco (or buyer) in any of the areas and Genco (or seller) in the same or in a different area negotiate bilateral contracts with each other. These players of the electricity market are responsible for having a communication path to exchange contract data as well as measurements to perform the load following function. In such contracts, a Genco changes its power to follow the predicted load as long as it does not exceed the contracted value. The Disco is responsible to monitor its load demand and ensure that the load following requirements is met according to the contractual agreement.

In order to meet the bilateral transactions, Disco Participation Matrix (DPM) [9] has been used. Elements of this matrix represent the fraction of total the load contracted by a Disco towards a Genco. If a Disco \(j\) has a contract with Genco \(i\) to supply 10% of its load following demand, \(ij^{th}\) element of DPM will be 0.1 p.u. Elements of the \(j^{th}\) column of the DPM represents the total load following demand of \(j^{th}\) Disco shared by different Gencos, while the elements of \(i^{th}\) row of the DPM represents the contribution of Genco \(i\) towards the load following demand from different Discos. Let us consider a DPM given as,
From the $j^{th}$ column entries, it is clear that the total load following demand of $j^{th}$ Disco is shared by various Gencos such as $G1$-10%, $G3$-10%, $Gi$-10% and $Gn$-5%. Rest of the load following demand of $j^{th}$ Disco may be supplied through the Poolco transactions.

### C. Area control error (ACE) calculation

In a practical multi-area power system, a control area is interconnected to its neighboring areas with tie lines, all forming part of the overall power pool. If $P_{ij}$ is the tie line real power flow from an area-$i$ to another area-$j$ and $m$ is the total number of areas, the net tie line power flow from area-$i$ will be,

$$P_{tie-i} = \sum_{j=1}^{m} P_{ij}$$

In a conventional AGC formulation, $P_{tie-i}$ is generally maintained at a fixed value. However, in a deregulated electricity market, a Disco may have contracts with the Gencos in the same area as well as with the Gencos in other areas too. Hence, the scheduled tie-line power of any area will change as the demand of the Disco changes. Thus, the net scheduled steady state power flow on the tie line from an area-$i$ can be expressed as,

$$\Delta P_{i-new} = \Delta P_{tie-i} + \sum_{j=1}^{m} D_{ij} - \sum_{j=1}^{m} D_{ji}$$

where, $D_{ij}$ is the demand of Discos in area-$i$ from Gencos in area-$j$ and $D_{ji}$ is the demand of Discos in area-$i$ from Gencos in area-$j$. During the transient period, at any given time, the tie-line power error is given as,

$$\Delta P_{i-error} = \Delta P_{i-actual} - \Delta P_{i-new}$$

This error can be used to generate the Area Control Error (ACE) signal as,

$$ACE_i = B_i \Delta f_i + \Delta P_{i-error}$$

where, $B_i$ is the frequency bias factor and $\Delta f_i$ is the frequency deviation in area-$i$.

If $BC_{ii}$ and $BC_{ij}$ are the bilateral transaction signals from the Discos in the same area-$i$ and other area-$j$, respectively, then the overall block diagram of the proposed AGC for an $i^{th}$ area of $m$-area power system may be represented as shown in Fig. 1.

The Transfer Function of the model of the power system is given as, $\frac{K_{pi}}{1+sT_{pi}}$, where, $K_{pi}$ is the system gain and $T_{pi}$ is the time constant. $T_{i1}, T_{i2}, \ldots, T_{in}$ are the synchronizing power coefficients of the tie lines connecting to area-$i$.

### D. Controller design

An optimally tuned PID controller [7], [9], [14] and a fuzzy logic based AGC controller [12], [13] have been utilized to simulate the developed model. The optimal values of the proportional, integral and derivative parameters, $K_p$, $K_i$ and $K_d$ respectively, of the PID controller having the general structure $G_c(s) = K_p + \frac{K_i}{s} + K_d s$, has been determined using the least square minimization.

Conventional integral or PID controller, in general, has the following difficulties.

(i) In case of any change in system operating conditions, new gain values have to be computed.

(ii) In a multi-area system, tuning of PID controller, separately for each area, is required.

To evolve a simple and efficient method for optimal tuning of integral gain, a fuzzy logic based controller [13], having a general structure as shown in Fig. 2, has also been utilized to simulate the developed model.

### III. SYSTEM STUDIES

The proposed model of AGC described in previous section has been tested on 75-bus Indian power system [17]. Indian power system is in the process of restructuring. As a first step
in this process, generation, transmission and distribution are being separated. In the present work, a deregulated market scenario has been assumed in the 75-bus systems. A general purpose Governor-Turbine model has been used, which is taken from [18].

The 75-bus system consists of 95 lines and 15 generators. It has been divided into four control areas. Number of Gencos and Discos in the 75-bus system is given in TABLE I.

<table>
<thead>
<tr>
<th>Control Area</th>
<th>Area Rating (in MW)</th>
<th>Market Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area-1</td>
<td>460</td>
<td>Genco 1,2,3 Disco 1,2,3</td>
</tr>
<tr>
<td>Area-2</td>
<td>994</td>
<td>Genco 4,5,6,7,8 Disco 4, 5, 6</td>
</tr>
<tr>
<td>Area-3</td>
<td>400</td>
<td>Genco 9,10 Disco 7, 8, 9</td>
</tr>
<tr>
<td>Area-4</td>
<td>4470</td>
<td>Genco 11,12,13,14,15 Disco 10,11,12</td>
</tr>
</tbody>
</table>

The proposed scheme for multi-area AGC was simulated on the 75-bus system for the following types of transactions.

a. Poolco transaction

To simulate the Poolco transactions, it is assumed that the Gencos and Discos both are participating in the market. Gencos’ and Discos’ bids of area-1, 2, 3 and 4 were assumed as given in TABLES II to V, respectively.

Assume a step change in load demand of area-1 by 0.1087 pu (50MW), area-2 by 0.0503 pu (50 MW), area-3 by 0.125 pu (50MW) and area-4 by 0.0224 pu (100 MW) at time t = 0. To meet these changes in load demand, Gencos’ responses were obtained using MATLAB simulation with the PID and fuzzy controllers for the proposed multi-area AGC scheme. The change in load demand of any area is met by the Gencos in the same area, according to their Poolco transactions.

The results for all the four areas frequency deviations are shown in Fig. 3. This figure also compares the performance of the PID controller and the fuzzy controllers. The responses of the Gencos and Disco in all the areas, participating in the market, with the PID and the fuzzy controllers are also shown in Fig. 4 to 10, respectively.

TABLE II

<table>
<thead>
<tr>
<th>Gencos/Discos</th>
<th>Price (Rs./kWh)</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genco-1</td>
<td>4.9</td>
<td>15.0</td>
</tr>
<tr>
<td>Genco-2</td>
<td>4.75</td>
<td>30.0</td>
</tr>
<tr>
<td>Genco-3</td>
<td>5.1</td>
<td>25.0</td>
</tr>
<tr>
<td>Disco-1</td>
<td>4.8</td>
<td>10</td>
</tr>
<tr>
<td>Disco-2</td>
<td>5.2</td>
<td>10</td>
</tr>
<tr>
<td>Disco-3</td>
<td>5.9</td>
<td>10</td>
</tr>
</tbody>
</table>

TABLE III

<table>
<thead>
<tr>
<th>Gencos/Discos</th>
<th>Price (Rs./kWh)</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genco-4</td>
<td>5.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Genco-5</td>
<td>5.4</td>
<td>40.0</td>
</tr>
<tr>
<td>Genco-6</td>
<td>4.9</td>
<td>20.0</td>
</tr>
<tr>
<td>Genco-7</td>
<td>6.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Genco-8</td>
<td>4.7</td>
<td>25.0</td>
</tr>
<tr>
<td>Disco-4</td>
<td>5.5</td>
<td>10</td>
</tr>
<tr>
<td>Disco-5</td>
<td>4.8</td>
<td>5</td>
</tr>
<tr>
<td>Disco-6</td>
<td>5.1</td>
<td>5</td>
</tr>
</tbody>
</table>

TABLE IV

<table>
<thead>
<tr>
<th>Gencos/Discos</th>
<th>Price (Rs./kWh)</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genco-9</td>
<td>5.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Genco-10</td>
<td>4.8</td>
<td>35.0</td>
</tr>
<tr>
<td>Disco-7</td>
<td>5.1</td>
<td>10</td>
</tr>
<tr>
<td>Disco-8</td>
<td>5.2</td>
<td>10</td>
</tr>
<tr>
<td>Disco-9</td>
<td>5.9</td>
<td>10</td>
</tr>
</tbody>
</table>

TABLE V

<table>
<thead>
<tr>
<th>Gencos/Discos</th>
<th>Price (Rs./kWh)</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genco-11</td>
<td>4.6</td>
<td>25.0</td>
</tr>
<tr>
<td>Genco-12</td>
<td>5.8</td>
<td>25.0</td>
</tr>
<tr>
<td>Genco-13</td>
<td>5.1</td>
<td>50.0</td>
</tr>
<tr>
<td>Genco-14</td>
<td>5.5</td>
<td>25.0</td>
</tr>
<tr>
<td>Genco-15</td>
<td>4.7</td>
<td>25.0</td>
</tr>
<tr>
<td>Disco-10</td>
<td>5.5</td>
<td>10</td>
</tr>
<tr>
<td>Disco-11</td>
<td>4.9</td>
<td>10</td>
</tr>
<tr>
<td>Disco-12</td>
<td>5.3</td>
<td>10</td>
</tr>
</tbody>
</table>

The results for all the four areas frequency deviations are shown in Fig. 3. This figure also compares the performance of the PID controller and the fuzzy controllers. The responses of the Gencos and Disco in all the areas, participating in the market, with the PID and the fuzzy controllers are also shown in Fig. 4 to 10, respectively.
It is observed from these results that the response of Discos is similar with both the controllers, because SO sends the signal directly to the Discos and not through the controller. Gencos input signal comes through the area controller. It is clear from the results that the response of Gencos, participating in frequency control, is much faster with fuzzy based controller as compared to the PID controller. The frequency deviations in all the areas settle more quickly in case of fuzzy controller as compared to the PID controller.

b. Poolco and bilateral Transactions (mixed transactions)

For this case Gencos’ and Discos’ bids were assumed to be same as in the previous case. Different bilateral transactions were considered as given below.

- 10% of area-2 load demand changes to be provided by Genco-4 of the area-2 itself and 20% by the Genco-11 of area-4.
- In area-3 no bilateral transaction is considered.
- 10% of area-4 load demand changes to be provided by Genco-5 of the area-2 and 20% by the Genco 12 of area-4 itself.

Assume a step change (increase) in load demand of area-1 by 0.1087 pu (50MW), area-2 by 0.0503 pu (50 MW), area-3 by 0.125 pu (50MW) and area-4 by 0.0224 pu (100 MW) at time \( t = 0 \). The changes in load demand of all the areas are met according to their bilateral and Poolco transactions.

Frequency deviations in all the four areas are shown in Fig. 11. This figure also compares the performance of the PID and the fuzzy controllers. The response of the Gencos in all the areas, participating in the market, with the PID and the fuzzy controllers are also shown in Fig. 12 to 15, respectively. Change in the load demand of Discos selected for load curtailment, in the 75-bus system, is shown in Fig. 16.
A general model of automatic generation control scheme, suitable for a competitive electricity market, has been developed in this paper. The developed model is capable of incorporating the Poolco based transactions, bilateral transactions and combination of the two transactions in a deregulated electricity market environment. In multi-area AGC schemes, where different areas have different ratings, it is relatively difficult to find the optimum value of the PID controller gains for each area, while a properly designed fuzzy logic based controller can be effectively used in such cases. The proposed multi-area AGC scheme has been successfully tested on a 75-bus Indian power system. In all the cases simulated, the area frequency error got eliminated in the steady state and Gencos shared the increase in demand of Discos in the ratio of their participation factor. Results of the fuzzy logic based controller are compared with those obtained with an optimally tuned PID controller. For Poolco based transactions, the response of Gencos is faster with the fuzzy logic based controller as compared to the PID controller. Frequency deviations in all the areas settle down to zero more quickly with the fuzzy logic based controller as compared to the conventional PID controller.

IV. CONCLUSION

V. REFERENCES


VI. BIOGRAPHIES

Barjeev Tyagi (b’1964) received B. Tech. degree in Electrical Engineering from University of Roorkee (India) in 1987 and Ph. D. degree from IIT Kanpur in 2006. Presently, he is a faculty member in Electrical Engineering Department at Indian Institute of Technology, Roorkee (India). His research interests include control system, power system deregulation, power system optimization and control.

S. C. Srivastava (b’1955) received B. Tech. degree in Electrical Engineering from Banaras Hindu University, Varanasi (India) in 1976 and Ph. D. degree from Indian Institute of Technology, New Delhi, India. Presently he is a Professor in Electrical Engineering Department at Indian Institute of Technology, Kanpur, India. His research interests include energy management system, power system optimization, security analysis, voltage stability analysis and power system restructuring. He is a senior member of IEEE and Fellow of Institution of Engineers (India), IETE (India) and Indian National Academy of Engineers.