# Retraction Notice

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**Comment:**

The paper is withdrawn from "Circuits and Systems" due to personal reasons from the corresponding author of this paper.

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Editor guiding this retraction: Prof. Mehdi Anwar and Prof. Gyungho Lee (EiC of CS)

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# ANFIS Controller for AGC in Restructured Power System

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## Abstract

**This paper investigates the ANFIS controller for an Automatic Generation Control (AGC) problem in a restructured power system. The intense participation of Gencos in restructured system leads to aggressiveness in frequency and tie-line responses which in turn affect the generation related ancillary services. For this reason, the ANFIS controller is designed to improve the dynamics, such as reducing the overshoot, minimizing settling time, reduce the steady state error of frequency and tie-line power deviations and maintain the balance between generation and demand. Five area control structure with Hydro-Thermal-Gas power generations are considered here as a test system. In each control area, the effects of the feasible contracts are treated as a set of new input signals in a modified traditional dynamical model. The key benefit of this strategy is its high insensitivity to large load changes and disturbances in the presence of plant parameter inconsistency and system nonlinearities such as Generation Rate Constraint (GRC) and Backlash. This newly developed scheme leads to a flexible controller with a simple structure that is easy to realize and consequently it can be constructive for the real world power system.**

## Keywords

**Automatic Generation Control, ANFIS Controller, Deregulated Power System, Generation Rate Constraint, Backlash**

## 1. Introduction

For a large interconnected power system, sudden load change causes the deviation of tie-line exchanges and the frequency fluctuations. Hence AGC is extremely important for supplying electric power with good quality. Nowa-

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days, the electric power industry is moving towards an open market, which means the consumers have an opportunity to buy power at competitive price among various suppliers. Deregulation is the collection of unbundled rules and economic incentives that governments set up to control and drive the electric power industry. Power system under open market scenario consists of generation companies (GENCOs), distribution companies (DISCOs), and transmission companies (TRANSCOs) and independent system operator (ISO). In deregulated environment, each component has to be modeled differently because each component plays an important role. There are crucial differences between the AGC operation in a vertically integrated industry (conventional case) and Deregulated power industry (new case). In the restructured power system after deregulation, operation, simulation and optimization have to be reformulated although basic approach to AGC has been kept the same. In this case, a DISCO can contract individually with any GENCO for power and these transactions are made under the supervision of ISO. DISCO Participation Matrix concept is introduced to narrate the contracts made between GENCOs and DISCOs. The information flow of the contracts is superimposed on the traditional AGC system. With increasing size and complexity of the restructured power systems, significant uncertainties and disturbances in power system control and operation may take place. It is desirable that the novel control strategies be developed to achieve AGC goals and maintain reliability of the electric power system in an adequate level. In this paper, the five area deregulated power system is formulated for unequal distribution of DISCOs and GENCOs and specifically focusing on the dynamics and trajectory sensitivities of frequency and tie line power flows.

The concept of a DISCO participation matrix (DPM) is proposed which helps the visualization and implementation of the contracts. The AGC is based on an error signal called Area Control Error (ACE) [1] which is a linear combination of net-interchange and frequency errors.

$$\mathrm{ACE} = \sum_j \left( \Delta P_{tie,i,j} + b_i \Delta f_i \right) \tag{1}$$

where $b_i$ is the frequency bias coefficient of the $i^{th}$ area, $\Delta f_i$ is the frequency error of the $i^{th}$ area, $\Delta P_{tie,i,j}$ is the tie line power flow error between $i^{th}$ area and $j^{th}$ area.

A lot of researchers have analysed about AGC in a deregulated power system over last decades. The conventional control strategy used in industry is to take the integral of ACE as the control signal [2]. It has been found [3] that the use of ACE as the control signal reduces the frequency and tie-line power error to zero in the steady state. These studies try to modify the conventional LFC system [4] [5] to take into account the effect of bilateral contracts on the dynamics [6] and improve the dynamical transient response of the system under competitive conditions. This paper proposes a control scheme that guarantees a minimum transient deviation and ensures zero steady state error [7] [8]. The stabilization of frequency oscillations in an interconnected power system [9] [10] becomes challenging when implementing in the future competitive environment. Consequently advanced economic, high efficiency and improved control schemes [11]-[13] are required to ensure the power system reliability. The conventional load-frequency controller may no longer be able to attenuate the large frequency oscillation due to the slow response of the governor [7]. Conventional controller is simple for implementation but takes more time and gives large frequency deviation [14] [15]. Fixed gain controllers are designed at nominal operating conditions and fail to provide best control performance over a wide range of operating conditions [16]-[18]. Subsequently, to keep system performance near its optimum, it is desirable to track the operating conditions and use updated parameters to compute the control. Adaptive controllers with self-adjusting gain settings have been proposed for LFC [19]-[21]. There has also been considerable research work attempting to propose better AGC systems based on neural network [19]-[23] fuzzy system theory [15] and reinforcement learning [24]. Recent study confirms that ANFIS approach has also been applied to hydrothermal system [25] [26].

All research during the earlier period in the area of AGC narrates interconnected two equal area thermal systems and petite attention has been paid to AGC of unequal multi area systems [27]. Most of ancient time works have been centred in the region of the design of governor secondary controllers, and design of governor primary control loop. Apparently no literature has been discussed about AGC performance subjected to simultaneous small step load perturbations in all area or the application of ANFIS technique to a multi-area power system. The escalation in size and convolution of electric power systems along with increase in power demand has necessitated the use of intelligent systems that combine knowledge, techniques and methodologies from various sources for the real-time control of power systems.

In this paper, an effort has been made to apply hybrid Neuro-Fuzzy (HNF) controller for the automatic load frequency control for the five area hydro-thermal-gas restructured power system in consideration with nonlinearities. The simulations are carried out in presence of the GRC's because ignoring GRC shows the way to non-realistic results.

## 2. System Investigated

In this multi source generating system, there are five control areas (**Figure 1**) in which each area has different combinations of GENCOs and DISCOs. Area 1 comprises of three GENCOs with thermal power system of reheat, hydro and gas turbines and two DISCOs, area 2 comprises of two GENCOs with hydro and thermal combination and one DISCO, area 3 consists of two GENCOs with gas and thermal (reheat turbine) combination and two DISCOs, area 4 includes two GENCOs of hydro-thermal combination with one DISCO and area 5 has two GENCOs of thermal-gas combination with two DISCOs. The plant parameters for five area deregulated power system is presented in **Table 1**. For restructured system having several GENCOs and DISCOs, any DISCO may contract with any GENCO in another control area independently through Bilateral Transaction. The independent system operator (ISO) observes those transactions. The main purpose of ISO is to control many ancillary services, one of which is AGC. The contracts of GENCOs and DISCOs described by "DISCO participation matrix" (DPM). The DPM for the n[th] area power system is as follows:

$$DPM = \begin{pmatrix} cpf_{11} & cpf_{12} & \cdots & cpf_{1n} \\ cpf_{21} & cpf_{22} & \cdots & cpf_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ cpf_{n1} & cpf_{n2} & \cdots & cpf_{nn} \end{pmatrix} \tag{2}$$

In DPM, the number of rows is equal to the number of GENCOs and the number of columns is equal to the number of DISCOs in the system. Any entry of this matrix is a fraction of total load power contracted by a DISCO towards a GENCO [24]. The sum of total entries in a column corresponds to one DISCO be equal to one (*i.e.*) $\sum_{j=1}^{n} cpf_{ij} = 1$.

$$AGPM = \begin{pmatrix} AGPM_{11} & AGPM_{12} & \cdots & AGPM_{1N} \\ AGPM_{21} & AGPM_{22} & \cdots & AGPM_{2N} \\ \vdots & \vdots & \cdots & \vdots \\ AGPM_{N1} & AGPM_{N2} & \cdots & AGPM_{NN} \end{pmatrix} \tag{3}$$

where, $AGPM_{ij} = \begin{pmatrix} gpf_{(s_i+1)(z_j+1)} & \cdots & gpf_{(s_i+1)(z_j+m_j)} \\ \vdots & \vdots & \vdots \\ gpf_{(s_i+n_i)(z_j+1)} & \cdots & gpf_{(s_i+n_i)(z_j+m_j)} \end{pmatrix}$

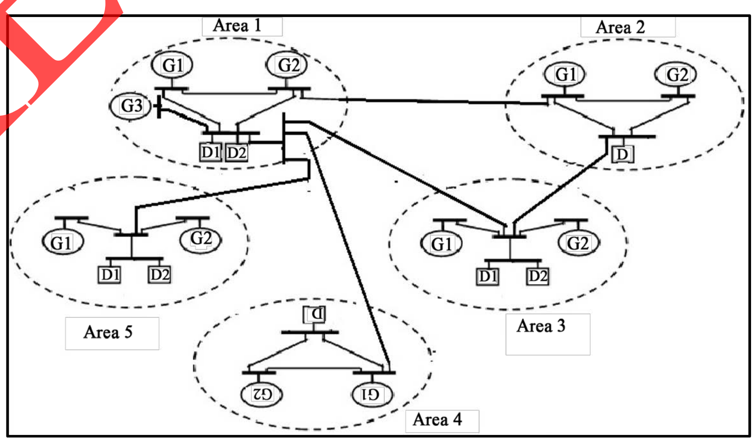


**Figure 1.** Schematic diagram of five control area restructured power system.

**Table 1.** Power system plant and control parameters.

| Area 1 | | | Area 2 | | Area 3 | | Area 4 | | Area 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Thermal-Hydro-Gas | | | Hydro-Thermal | | Thermal-Hydro | | Hydro-Thermal | | Thermal-Gas | |
| GENCO-1 | GENCO-2 | GENCO-3 | GENCO-1 | GENCO-2 | GENCO-1 | GENCO-2 | GENCO-1 | GENCO-2 | GENCO-1 | GENCO-2 |
| Thermal | Hydro | Gas | Thermal | Hydro | Thermal | Gas | Thermal | Hydro | Thermal | Gas |
| Tg = 0.06s | Tg = 0.2s | Tg = 0.049s | T1 = 0.06s | Tg = 0.2s | Tg = 0.06s | T1 = 0.049s | T1 = 0.06s | Tg = 0.2s | Tg = 0.06s | T1 = 0.049s |
| Tt = 0.3s | Tt = 0.55s | Tt = 0.2s | T3 = 10.2s | Tt = 28.149s | Tt = 10.2s | T3 = 1.1s | T3 = 10.2s | Tt = 28.149s | Tt = 10.2s | T3 = 1.1s |
| R = 0.3333 Hz/p.u.MW | Kr = 0.3113 | Kr = 0.5 | T2 = 0.3s | R = 0.29633 Hz/p.u.MW | Kr = 0.33 | T2 = 0.2s | T2 = 0.3s | R = 0.29633 Hz/p.u.MW | Kr = 0.33 | T2 = 0.2s |
| Tr = 10.2s | Tr = 10.6 s | Tr = 1.1s | Tw = 1s | Kg = 1 | Tr = 10s | Tw = 1.5s | Tw = 1s | Kg = 1 | Tr = 10s | Tw = 1.5s |
| | R = 0.32 Hz/p.u.MW | R = 0.33 Hz/p.u.MW | R = 0.32 Hz/p.u.MW | Kt = 1 | R = 0.2899 Hz/p.u.MW | R = 0.3077 Hz/p.u.MW | R = 0.32 Hz/p.u.MW | Kt = 1 | R = 0.2899 Hz/p.u.MW | R = 0.3077 Hz/p.u.MW |
| Kg = 1 | Kg = 1 | Kg = 1 | Kg = 1 | | Kg = 1 | Kg = 1 | Kg = 1 | | Kg = 1 | Kg = 1 |
| Kt = 1 | Kt = 1 | Kt = 1 | Kt = 1 | | Kt = 1 | Kt = 1 | Kt = 1 | | Kt = 1 | Kt = 1 |
| Kp = 20 Hz/p.u.MW Tp = 120s B = 0.532 p.u. MW/Hz Prated = 2000 MW (Nominal Load) Po = 1000 MW f = 60 Hz | | | Kp = 20 Hz/p.u. MW Tp = 120s B = 0.495 p.u. MW/Hz Prated = 2000 MW (NominalLoad) Po = 1000 MW f = 60 Hz | | Kp = 20 Hz/p.u. MW Tp = 120s B = 0.542 p.u.MW/Hz Prated = 2000 MW (Nominal Load) Po = 1000 MW f = 60 Hz | | Kp = 20 Hz/p.u. MW Tp = 120s B = 0.495p.u. MW/Hz Prated = 2000 MW (NominalLoad) Po = 1000 MW f = 60 Hz | | Kp = 20 Hz/p.u. MW Tp = 120s B = 0.542 p.u.MW/Hz Prated = 2000 MW (Nominal Load) Po = 1000 MW f = 60 Hz | |
| T12 = T13 = T23 = T14-T15 = 0.543 p.u/Hz | | | | | | | | | | |

For $i, j = 1, 2, \cdots, N$, and $s_i = \sum_{k=1}^{i-1} n_i$; $z_j = \sum_{k=1}^{j-1} m_j$; $s_1 = z_1 = 0$. Where, $n_i$ and $m_j$ are the number of GENCOs and DISCOs in area *i*. The $gpf_{ij}$ refer to generation participation factor and shows the participation aspect of GENCO*i* in total load following the requirement of DISCO*j* based on the possible contract.

In a power system having steam plants, power generation can change only at a specified maximum rate. The structure for $i^{th}$ area in the presence of nonlinearities is shown in **Figure 2**. A typical value of the generation rate constraint (GRC) for thermal unit is 3%/min, *i.e.*, GRC for the thermal system be $\Delta PGt(t) \leq 0.0005$ p.u.MW/s. Two limiters, bounded by ±0.0005 are employed within the AGC of the thermal system to prevent the excessive control action. Likewise, for hydro plant GRC of 270%/min. for raising generation and 360%/min. for lowering generation has been deemed. Thus, for Raising, $\Delta PGh(t) \leq 0.045$ p.u.MW/s for Lowering, $\Delta PGh(t) \leq 0.06$ p.u.MW/s.

The generation rate constraints for all the areas have been engaged keen on adding limiters to the turbines. Governor Dead band is none other than the total quantity of a sustained speed change when there is no resulting change. Though, the speed governor characteristics are nonlinear they are approximated for linear analysis. The limiting value of governor dead band is 0.06% [26]. One of the effects of governor dead band is to raise the obvious steady state speed regulation, R. Turbine-Governor Dead bands are found due to backlash in the linkage connecting the piston to the camshaft [23]. Backlash is the nonlinearity which causes governor dead band and tends to produce continuous sinusoidal oscillations with a natural period of about 2 secs.

## 3. ANFIS Controller

The Hybrid combination of neural and fuzzy is considered to be an adaptive network for this real time problem. The adaptive network simply transforms the neural network architecture with classical feed forward topology. This proposed network works similar to adaptive network simulator of Takagi-Sugeno's fuzzy controllers. This adaptive network is functionally comparable to a fuzzy inference system (FIS). ANFIS adjusts the entire parameters using back propagation gradient descent and least squares type of method for non-linear and linear parameters respectively for the set of input and output data [25].

Here, the multi layer perceptron model considered with 2-input, type-3 ANFIS with 9 rules. Three membership functions are associated with each input, so the input space is partitioned into 9 fuzzy subspaces, each one of them is governed by fuzzy if-then rules. The premise part of a rule defines a fuzzy subspace, while the resultant part states the output inside this fuzzy subspace.

*Layer* 1 is the input layer, neurons in this layer simply pass external crisp signals to next layer. *Layer* 2 is the fuzzification layer based on Gaussian membership function. *Layer* 3 is the rule layer, each neuron in this layer

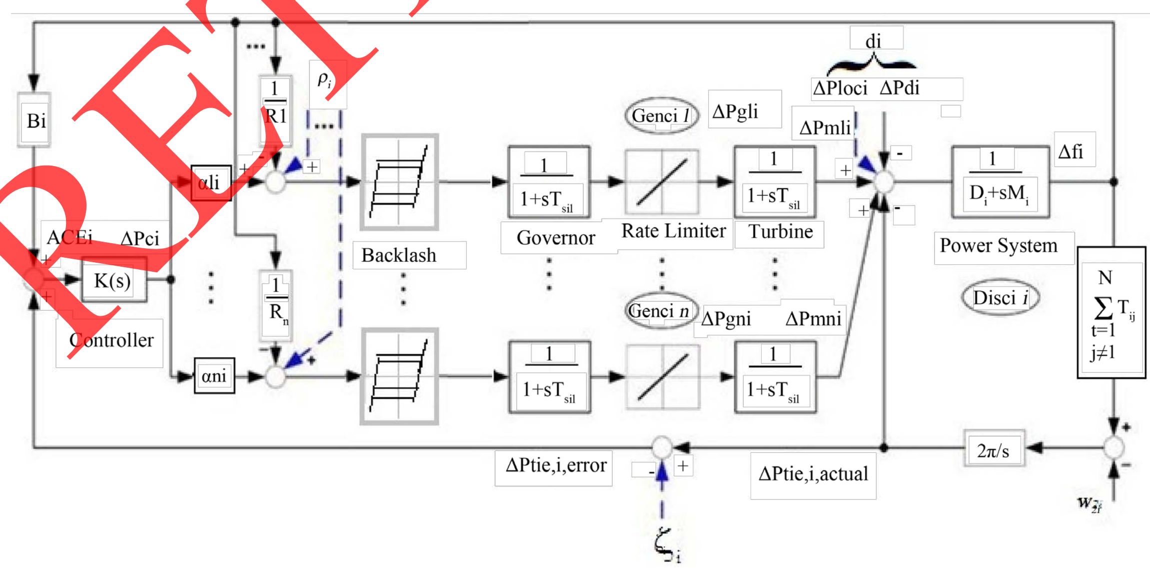


**Figure 2.** Control structure for $i^{th}$ area with nonlinearities.

corresponds to a single Sugeno-type fuzzy rule for calculating the firing strength. *Layer* 4 is the normalisation layer and each neuron receives inputs from all neurons in the rule layer and calculates the normalised firing strength as per the rule. *Layer* 5 is the defuzzification layer; each neuron in this layer is connected to the respective normalisation neuron, and also receives initial inputs, ACE and derivative of ACE.

The weighted average defuzzification method is employed here, it is framed by weighting each membership function in the output by its respective maximum membership value. *Layer* 6 is represented by a single summation neuron, in which neuron calculates the sum of outputs of all defuzzification neurons and produces the overall ANFIS output (*i.e.*,) stabilising signal for maintaining ACE as zero. The Multi Layer Perceptron (MLP) structure model of ANN is exercised for AGC of five unequal area Hydro-Thermal-Gas system.

### ANFIS Controller Design

This ANFIS controller make use of Sugeno-type fuzzy inference system (FIS) controller, with the parameters surrounded by the FIS determined by the neural-network back propagation method. The ANFIS controller is designed by taking ACE and its derivative (d(ACE)/dt) as the inputs. The output stabilizing signal is worked out by using the fuzzy membership functions. ANFIS-Editor is used for realizing the system and for putting into practice. The procedure for designing ANFIS controller in MATLAB Simulink is as follows:

1) Sketch the Simulink model with fuzzy controller and simulate it with the specified rule base and collect the training data while simulating the model.

2) The two inputs, *i.e.*, ACE and d(ACE)/dt and the output signal provides the training data.

3) Use anfisedit to generate the ANFIS. fis file.

4) Stack the training data composed in Step 2 and create the FIS with Gaussian membership function.

5) Train the collected data with generate FIS up to a particular number of Epochs.

6) Save the FIS. This FIS file is the Neuro-Fuzzy enhanced ANFIS file.

## 4. Simulation Results and Discussion

ANFIS controller has been implemented for AGC in deregulated environment taking into account the nonlinearities. The simulation study has been carried out for the three cases, namely Poolco Transactions, Bilateral Transactions and for the worst case, Contract violations. The results illustrate that ANFIS controller proves good dynamic performance in terms of settling time, overshoot and undershoot.

### 4.1. Case 1: Poolco Based Transactions

In this scenario, GENCOs take part only in the load pursuing the control of their areas. The transaction among DISCOs and available GENCOs is being simulated based on the following AGPM. The simulated values are presented in Table A1 and Table A2.

$$AGPM = \begin{pmatrix} 0 & 0 & 0.3 & 0 & 0.1 & 0.2 & 0 & 0.3 \\ 0.5 & 0 & 0 & 0.2 & 0 & 0.1 & 0.1 & 0 \\ 0 & 0.3 & 0 & 0 & 0.25 & 0.1 & 0 & 0 \\ 0.25 & 0.2 & 0.4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.3 & 0.1 & 0.25 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.2 & 0.2 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.35 & 0.15 & 0 & 0 & 0 \\ 0 & 0.3 & 0 & 0 & 0 & 0.4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 \\ 0.25 & 0 & 0 & 0 & 0 & 0 & 0.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.3 & 0.7 \end{pmatrix}$$

### 4.2. Case 2: Synthesis of Poolco and Bilateral Based Transactions

In this case, DISCOs have the liberty to deal with any of the GENCOs within or with other areas. The AGC assignment accomplished through the following AGPM. The inconsistency based on this transaction is listed in **Table A1** and **Table A2**.

$$AGPM = \begin{pmatrix} 0 & 0 & 0.3 & 0 & 0.1 & 0.2 & 0 & 0.3 \\ 0.5 & 0 & 0 & 0.2 & 0 & 0.1 & 0.1 & 0 \\ 0 & 0.3 & 0 & 0 & 0.25 & 0.1 & 0 & 0 \\ 0.25 & 0.2 & 0.4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.25 & 0.1 & 0.25 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.2 & 0.2 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.35 & 0.15 & 0 & 0 & 0 \\ 0 & 0.25 & 0 & 0 & 0 & 0.4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 \\ 0.25 & 0 & 0 & 0 & 0 & 0 & 0.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.3 & 0.7 \end{pmatrix}$$

### 4.3. Case 3: Contract Violation

In this scenario, Disco may defy the contracts by demanding more power than that stated in the contract. This excessive power is revealed as a located load of that area (un-contracted demand). This case has been carried out for various demand condition. The intention of this case is to test the effectiveness of the proposed controller against the uncertainties and sudden large load disturbances in the presence of nonlinearities. The response of frequency (**Figure 3** and **Figure 4**) and tie line power (**Figure 5** and **Figure 6**) depicts that very soon it reaches

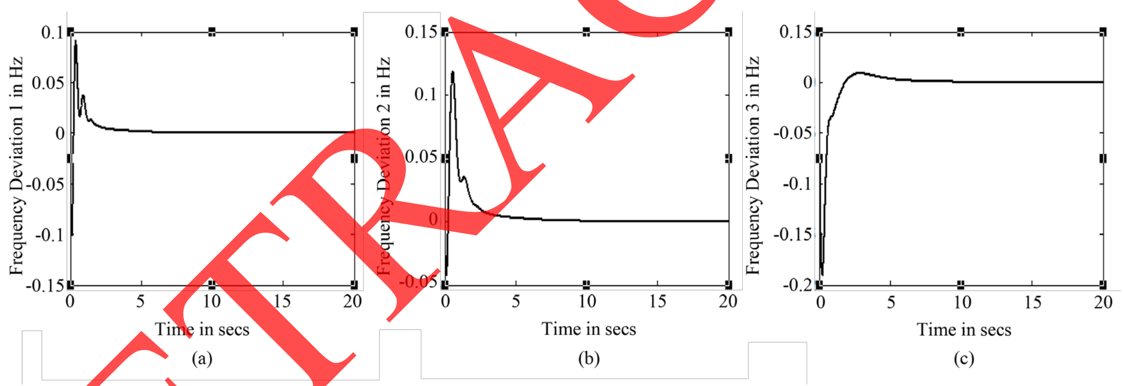


**Figure 3.** Frequency deviation for 10% rise in load (a) Area 1 (b) Area 2 (c) Area 3.

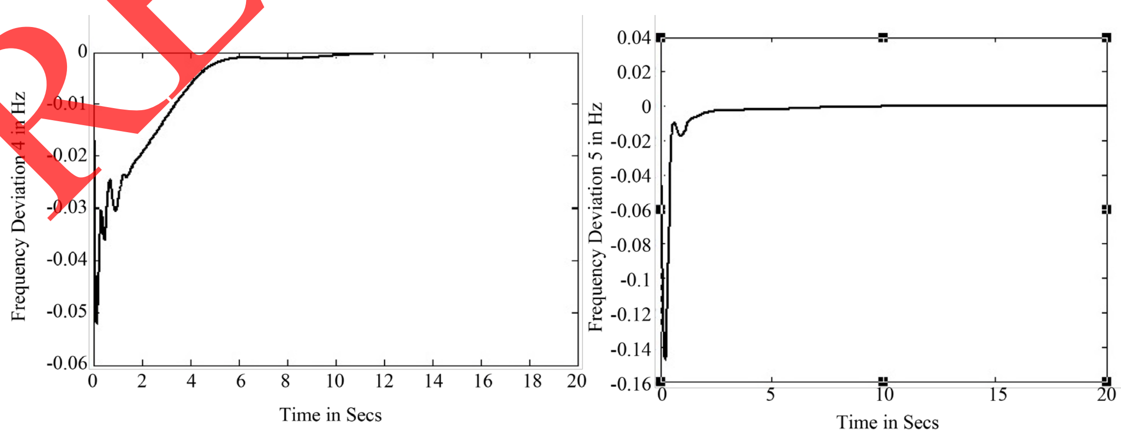


**Figure 4.** Frequency deviation for 10% rise in load (a) Area 4 (b) Area 5.

steady state stability for 10% rise in demand of discos in all the five areas which is shown in Figures 4-6. The figures depicts that the characteristics are almost spikes free and all settled quickly with smooth nature and having reduce overshoot and undershoot.

The Table 2 shows the comparison of GENCO power deviation for the three scenarios with theoretical and the simulated values by (10). The simulated values are almost same as that of the theoretical value which means that the proposed controller is a consistent and reliable one for AGC of deregulated power system. The results thus obtained through simulation depicts that the proposed controller holds better performance for all possible contracts and for wide range of load disturbances.

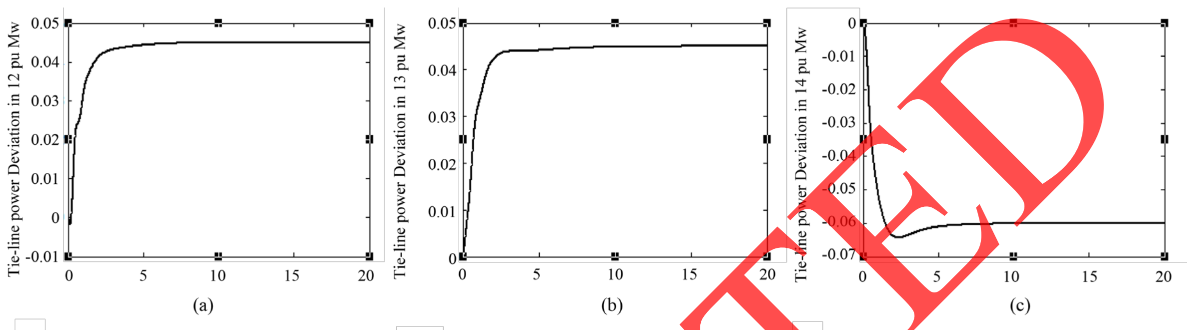


Figure 5. Tie line power deviation for 10% rise in load (a) Area 1 & 2 (b) Area 1 & 3 (c) Area 1 & 4.

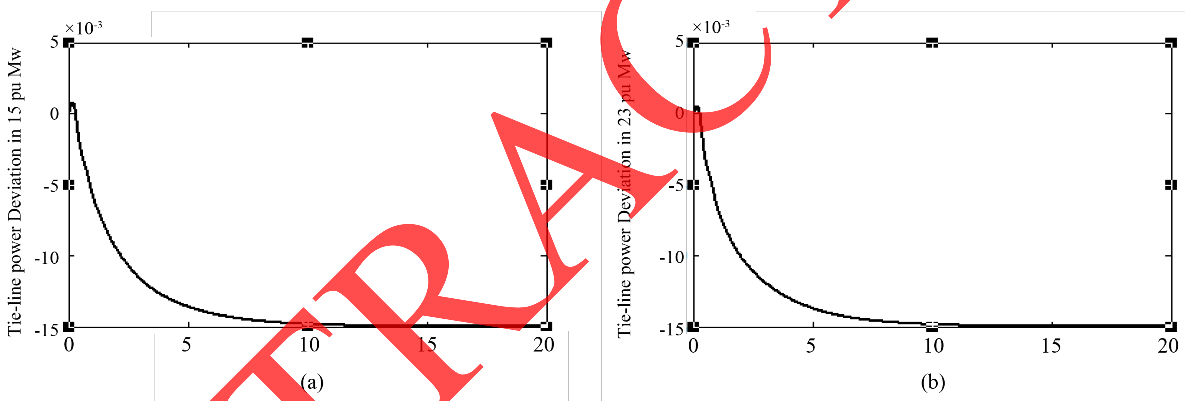


Figure 6. Tie line power deviation for 10% rise in load (a) Area 1 & 5 (b) Area 2 & 3.

Table 2. Actual power generated (pu MW).

| Area | Genco | Scenario | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| 1 | 1 | 0.1 | 0.09 | 0.107 |
| | 2 | 0.04 | 0.085 | 0.097 |
| | 3 | 0.075 | 0.09 | 0.11 |
| 2 | 1 | 0.042 | 0.065 | 0.075 |
| | 2 | 0.09 | 0.085 | 0.1 |
| 3 | 1 | 0.05 | 0.09 | 0.105 |
| | 2 | 0.06 | 0.06 | 0.068 |
| 4 | 1 | 0.125 | 0.05 | 0.07 |
| | 2 | 0.058 | 0.02 | 0.03 |
| 5 | 1 | 0.11 | 0.1 | 0.11 |
| | 2 | 0.045 | 0.065 | 0.0825 |

## 5. Conclusion

The various sources for generation are common for any real time grid in operation. It is a complex one to organize the different areas in a deregulated environment by means of frequency and tie line power flows. The conventional controllers for AGC are capable of coordinating but with large overshoots and settling time in its frequency and tie line power flows. As a result, an ANFIS controller is proposed for multi source generation for an AGC. This controller achieves reliability over tracking frequency and tie line power deviations for a wide range of load disturbances and system uncertainties for five interconnected areas. The proposed controller has proved its robust performance with reduced overshoot, undershoot and settling time with large load demands and uncertainities. The simulated result shows that ANFIS controller is best suitable for real time deregulated system for any number of interconnected areas.

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## Nomenclature

| | |
|---|---|
| $i$ | subscript referred to area |
| $F$ | area frequency |
| $P_{tie}$ | tie line power flow |
| $ACE$ | area control error |
| $cpf$ | contract participation factor |
| $gpf$ | generation participation factor |
| $K_P$ | subsystem equivalent gain constant |
| $T_P$ | subsystem equivalent time constant |
| $T_T$ | turbine time constant |
| $T_G$ | governor time constant |
| $B$ | frequency bias |
| $T_{ij}$ tie line | synchronizing coefficient between areas $i$ & $j$ |
| $Pd$ | area load disturbance |
| $P_{Lji}$ | contracted demand of DISCO$j$ in area $i$ |
| $P_{ULji}$ | un-contracted demand of DISCO$j$ in area $i$ |
| $P_{M,ji}$ | power generation of GENCO$j$ in area $i$ |
| $P_{Loc}$ | total local demand |
| $\eta$ | area interface |
| $\xi$ | scheduled power tie line power flow deviation |

## Appendix

**Table A1.** Tie line power deviation with respect to response characteristics.

| Area | Overshoots (MW) | | | Undershoot (MW) | | | Settling time (secs) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Scenario | | | Scenario | | | Scenario | | |
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| 1 - 2 | 0.052 | 0.0266 | 0.048 | −0.044 | −0.019 | −0.136 | 4 | 6 | 8 |
| 1 - 3 | 0.0037 | 0.1393 | 0.1092 | −0.012 | −0.006 | −0.007 | 5 | 7 | 4 |
| 1 - 4 | 0.052 | 0.6619 | 0.0523 | −0.044 | −0.085 | −0.156 | 6 | 8 | 9 |
| 1 - 5 | 0.0048 | 0.2393 | 0.112 | −0.014 | −0.007 | −0.009 | 4 | 7 | 8 |
| 2 - 3 | 0.0053 | 0.691 | 0.232 | −0.016 | −0.006 | −0.004 | 3 | 6 | 7 |

**Table A2.** Frequency deviation with respect to response characteristics.

| Area | Overshoots (MW) | | | Undershoot (MW) | | | Settling time (secs) | | | Computational time (secs) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Scenario | | | Scenario | | | Scenario | | | |
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | |
| 1 | 0.2386 | 0.1761 | 0.2146 | −0.367 | −0.394 | −0.489 | 4 | 8 | 9 | |
| 2 | 0.1092 | 0.0556 | 0.0414 | −0.07 | −0.222 | −0.131 | 4 | 9 | 8 | |
| 3 | 0.3671 | 0.2856 | 0.2489 | −0.246 | −0.328 | −0.327 | 6 | 8 | 10 | 0.15 |
| 4 | 0.1204 | 0.1932 | 0.3656 | −0.008 | −0.309 | −0.391 | 4 | 9 | 8 | |
| 5 | 0.0946 | 0.2969 | 0.4806 | −0.004 | −0.23 | −0.367 | 6 | 8 | 10 | |