ANFIS controller based frequency linked availability based tariff mechanism for a restructured power system

Abhijith Pappachen\textsuperscript{1}, A Peer Fathima\textsuperscript{2*}, Stella Morris\textsuperscript{3}

\textsuperscript{1}Generation circle, Kerala State Electricity Board Ltd., Moolamattom, Kerala, India
\textsuperscript{2*} School of Electrical Engineering, VIT, Chennai, India - 600127
\textsuperscript{3} Department of Electrical & Electronic Engineering, Universiti Tunku Abdul Rahman, SungaiLong, Malaysia.

Email: peerfathima.a@vit.ac.in

Abstract: This paper proposes the frequency linked availability based tariff (ABT) mechanism along with ANFIS controller for extenuating the issues in load frequency control (LFC) for a four area deregulated/restructured power system. To scrutinize the effective performance of the proposed approach, the dynamic performance of the system is analyzed with single and bilateral contract considering the value of the marginal cost higher and lesser than the Unscheduled interchange (UI). For this analysis, UI rate chart from the Central Electricity Regulation Commission (CERC) is used. The simulation results confirm that the ANFIS controller performance is comparatively better than proportional controller in two different contract cases.

1. Introduction
Load frequency control (LFC) is one of the prominent issues in a deregulated power system operation and control for maintaining secure electric power to the consumers. Major objectives of the LFC in a restructured power system is (i) to maintain the expected power output and the nominal frequency must be in specified limits. (ii) to maintain the exchange of net power between control areas within its pre specified values [1-3].

In a competitive power market several market players like Generation companies (GENCO) distribution companies (DISCO), transmission companies (TRANS CO) and independent system operator (ISO) came into existence and main power transactions are carried out by these entities [3,5,9]. In this environment, DISCOs in one control area may undergo contract with GENCOs with its own control area or other areas. [5-7]. For secure and reliable operation of the entire system, ISO provide certain ancillary services [4]. Load following and LFC and are treated as the ancillary services for maintaining the frequency and prolonging the power system reliability and security.

The dynamic responses of the power system network are improved with the help of some control strategies such as fuzzy logic, AI based neural network, ant colony algorithm, genetic algorithm, particle swarm optimization algorithm are applied for controlling the output of the system [7,8,9]. These methodologies continuously tracking the fluctuations in the load and vary the governor setting points as soon as possible to move the system back to the normal stable operation [10-13].
The Indian power sector consists of a large combination of various types of power generations like thermal, hydro, nuclear and renewable power generations like solar, wind and tidal etc. Fossil fuel based thermal plants are donating the major part of the total power production. Entire Indian power system network are subdivided in to five interconnected regional grid systems. Before 2002, the regional grids are operating in a dissatisfactory manner. During peak hours frequency may violate drastically from the prescribed limits. Conventional tariff systems were not able to controlling the frequency violations caused by the regional grids. To overcome this situation, the frequency linked three part ABT based system is implemented in all the regional grids. It overcome the basic issues by providing incentives to the GENCOs for the production of excess power in the peak hours for meeting the excessive load demand and curtailed the power production during the off peak hours. And also it penalises heavily to the load centres for over drawls and pulling down the frequency from its nominal levels [14-18].

The present work proposes an ANFIS controller based ABT system for extenuating the various LFC issues in a restructured power sector. A conventional multi area hydro-thermal restructured power system incorporating frequency linked ABT blocks with ANFIS controller is developed by using MATLAB/Simulink. The developed scheme is tested in the regional grid Indian system system under two different contract scenarios.

2. Availability Based Tariff (ABT)
In 2002, a new tariff structure ABT is introduced in Indian power system. It replaces the conventional monolithic charge structure into a rational three-part tariff structure [17-21]. First part of the ABT is called the constant portion, which is connected to the available generating units, the second portion is the variable part, connected with the energy charge for schedule interchanges and the third portion is called frequency dependent part which is connected with unscheduled interchange. The UI behaves as a tool for controlling grid frequency and encourages the system to regain back to its normal frequency [20-23]. The three major components of ABT are discussed below.

2.1 fixed charge or capacity charge
The major parts of fixed charge are the interest and depreciation of the loan, maintenance cost, insurance, taxes etc. The total cost to be paid to the producing company during the year for the fixed cost will depend on mean availability of the unit in the same particular year.

2.2 Variable charge or energy charge
This charge comprises of the fuel cost or variable cost of the plant for the scheduled power generation. Energy charges or variable charges are payable by every consumer based on the scheduled energy and it is irrespective to the actual power generation.

2.3. Unscheduled interchange
If the system may violate the scheduled power exchange, the third portion of ABT came into picture. If frequency is higher than 50Hz, then the UI price is low and vice versa. In case of excess drawl, beneficiary unit or company has to remunerate the penalty as per the UI rate. As per CERC, UI rate chart are given in Fig.2. The deviation from the scheduled value is termed as UI pricing scheme in ABT [24-26].

3. Basic scheme for ABT based LFC
A framework for a ABT based frequency linked scheme for a single area LFC system is given in Fig. 1[16]. In this scheme, the primary control loop mechanisms with Free Governor Mode of Operation (FGMO) is used for suppressing the area frequency oscillations within few seconds and the control loop in secondary side (LFC or AGC) is also try to move back the system frequency to its nominal value within five to ten minutes. Due to the lack of generation, successful application of a system level
control procedure is not to be possible in the current Indian power system. In this paper, the UI pricing method of ABT is treated as a system level control mechanism, and generating stations are expected to work based on UI price signal in real-time. Feedback signal using in this method is called Generation Control Error (GCE) which is the deviation between incremental cost generating unit due to the variable load and cost for the UI at a particular period [19-20].

![Diagram of ABT based frequency control loop](image)

**Figure 1.** Basic structure of ABT based frequency control scheme.

The concept of ABT based frequency control loop is given in Fig.2. Here each Generating unit monitoring the UI cost $\rho$ and it is compared with the marginal price $\gamma$. The error or deviation signal is derived, from the change in present UI cost and its marginal price. The deviation signal, is called as GCE which is given as input to the controller. Because of ABT, the amount received by generating units for UI value are different from the amount to be paid for Schedule Interchange (SI). For all the cases the generating units will earn the profit.
4. System modeling

The schematic representation of a four area restructured power system with ABT based frequency control loop system is given in Fig. 4. It consists of four different control areas consisting GENCO and DISCO of one in each area. GENCO having Hydro plant is considered in area-1 and thermal GENCOs are considered in other three areas. In a restructured power system GENCOs can contract with DISCOs in the same or other area. This type of contract is termed as “Bilateral contract” and it is implemented through Independent System Operator (ISO) [3,4]. Various schemes of contract are explained in Distribution type Participation Matrix - (DPM) given as follows.

\[
DPM = \begin{bmatrix}
    cpf_{11} & cpf_{12} & \ldots & cpf_{1n} \\
    cpf_{21} & cpf_{22} & \ldots & cpf_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    cpf_{m1} & cpf_{m2} & \ldots & cpf_{mn}
\end{bmatrix}
\]

The total number of columns and rows in a DPM shows the number of DISCOs and GENCOs respectively and each factor in the DPM is represented as contract participation factor (cpf), which represents the fraction of total power contracted between DISCOs and GENCOs [4-6]. The addition of all the values in a column must be equal to one. ie.,

\[
\sum_{i=1}^{nGENCO} cpf_{ij} = 1; \quad \text{for } j = 1,2,\ldots nDISCO
\]

It is assumed that all generating units in each individual area are generating power at scheduled value and frequency of the grid frequency is considered as 50Hz. If a sudden load disturbance occurs in any area, the area frequency and tie-line power exchange must be altered, which indicates in the supply frequency deviation \( \Delta f \).

\[
S_1(f) = \Delta f + f^0
\]

If \( S_1(f) \) related to the frequency signal and \( S_2(\rho) \) mentioned in (INR/MWh) corresponds the UI price signal are the input signals for calculating the UI rate issued by CERC in the year of 2015 [25]. If \( S_1(f) > 50.2 \text{ Hz} \)
\[ S_2(\rho) = 0 \text{ Rs/MWhr} \quad (4) \]

If \( 50.0 \text{Hz} < S_1(f) \leq 50.2 \text{Hz} \)
\[ S_2(\rho) = 8250 \times \{ S_1(f) \} \text{ Rs/MWhr} \quad (5) \]

If \( 49.8 \text{Hz} < S_1(f) \leq 50.0 \text{Hz} \)
\[ S_2(\rho) = 1650 + 14250 \times \{ 50 - S_1(f) \} \text{ Rs/MWhr} \quad (6) \]

If \( 49.48 \text{Hz} < S_1(f) \leq 49.8 \text{Hz} \)
\[ S_2(\rho) = 4500 + 14062.5 \times \{ 49.8 - S_1(f) \} \text{ Rs/MWhr} \quad (7) \]

If \( S_1(f) \leq 49.48.2 \text{Hz} \)
\[ S_2(\rho) = 9000 \text{ Rs/MWhr} \quad (8) \]

In addition, with this, the incremental cost of the thermal units and hydro units are expressed as
\[ S_3(\rho) = a_i + b_i P_{gi} \text{ (Rs/MWhr)} \quad (9) \]

Where \( a \) and \( b \) are called as incremental cost co-efficient and \( P_{gi} \) is power output of hydro GENCO in \( i \)th area.

Similarly, IC in the case of hydro GENCO is expressed as
\[ S_4(\rho) = c_i + d_i P_{gi} \text{ (Rs/MWhr)} \quad (10) \]

Where \( c \) and \( d \) are called as co-efficient of incremental cost and \( P_{gi} \) is called power output of \( i \)th GENCO.
The UI based price signal $S_2(\rho)$ is now comparing with the other factor incremental cost based signal $S_4(\gamma)$ and produce the generation control error (GCE) signal. UI price at 50.0Hz is denoted as $\rho^0$ and it is calculated from the UI chart issued by CERC, India. Modified GCE control scheme flow chart is shown in Fig.3 [16]. The control scheme ensures that whenever a sudden variation in the load demand occurs each generating unit responds to change their generation based on the error signals received from GCE block for smoothening the frequency. To reduce the Generation Control Error (GCE) of generating units after a sudden load disturbance, ANFIS controller is used for minimizing the area frequency oscillations and tie-line power oscillations for enhancing the stability of the system. Detailed analysis of ANFIS controller is discussed below.
Figure 4. Simulated model of four area restructured power system with ABT mechanism
5. Concept of suggested ANFIS controller

ANFIS controller is the combination of artificial neural network (ANN) and fuzzy logic based adaptive type network having zero synaptic weight. Fig.5 shows the ANFIS structure including outputs and inputs. The concept is taken from the references [12-13].

![ANFIS structure](image)

Figure 5. ANFIS structure.

It is assumed that the FIS with Takagi-Sugeno’s controller having inputs x and y and an output z is considered here [27].

6. Simulated responses - Results and discussions

The suggested four area deregulated system model with ABT based ANFIS control scheme is shown in Fig.4. The parameter values of the test system are obtained from the regional Indian system which is shown in Appendix A. simulation procedures are performed under deregulated environment having three possible contract scenarios which are explained below

Case 1 – single contract

In this contract case, DISCOs in one area is contract with the same area GENCOs. Disturbance is created in all four areas. The values are assumed as $\Delta P_{L1} = \Delta P_{L2} = \Delta P_{L3} = \Delta P_{L4} = 0.1$pu and analysed using DPM (11):

$$DPM = \begin{bmatrix}
0.5 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.5 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 1.0 & 1.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.3 & 0.25 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.4 & 0.5 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.3 & 0.25 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 & 0.6 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 & 0.4
\end{bmatrix}$$

(11)

Power output ($\Delta P_{\text{GENCO-1}}$) of GENCO in each area is obtained by

$$\Delta P_{\text{GENCO-1}} = (0.5 \times 0.1) + (0.5 \times 0.1) + (0 \times 0.1) + (0 \times 0.1) + (0) + (0) + (0) = 0.1$$pu MW
Similarly, $\Delta P_{GENCO-2} = 0.1$ pu MW, $\Delta P_{GENCO-3} = 0.2$ pu MW, $\Delta P_{GENCO-4} = 0.055$ pu MW, $\Delta P_{GENCO-5} = 0.09$ pu MW, $\Delta P_{GENCO-6} = 0.055$ pu MW, $\Delta P_{GENCO-7} = 0.011$ pu MW, $\Delta P_{GENCO-8} = 0.09$ pu MW are calculated [3].

![Graphs showing frequency deviation responses of all the control areas under unilateral contract scenario](image-url)
Figure 7. Power output deviations of all the control area of the system under single contract scheme

Figure 8. UI rate and frequency of area-1 under unilateral contract scenario

Table 1. Frequency deviation of all the areas with controllers under unilateral contract

|                | P controller | ANFIS controller |
|----------------|--------------|------------------|
|                | POS          | PUS              | Ts   | POS          | PUS              | Ts   |
| Frequency deviation (pu Hz) |              |                  |      |              |                  |      |
| $\Delta F_1$  | 0.437        | -0.917           | 7    | 0.301        | -0.732           | 5.4  |
| $\Delta F_2$  | 0.200        | -0.195           | 14   | 0.075        | -0.896           | 11   |
| $\Delta F_3$  | 0.254        | -0.233           | 16   | 0.128        | -0.188           | 12   |
| $\Delta F_4$  | 0.183        | -0.185           | 12   | 0.132        | -0.171           | 11   |
Table 2. GENCOs output deviations with controllers under unilateral contract

| Controller | P controller | ANFIS controller |
|------------|-------------|-----------------|
|            | POS         | PUS  | Ts   | POS   | PUS  | Ts   |
| $GENCO_1$  | 0.371       | 0.038 | 11   | 0.328 | 0.081 | 8    |
| $GENCO_2$  | 0.356       | 0.023 | 10   | 0.322 | 0.081 | 8    |
| $GENCO_3$  | 0.282       | 0.021 | 12   | 0.225 | 0.125 | 9    |
| $GENCO_4$  | 0.0162      | -0.005 | 14   | 0.014 | -0.002 | 10 |
| $GENCO_5$  | 0.140       | 0.041 | 15   | 0.135 | 0.063 | 11   |
| $GENCO_6$  | 0.108       | 0.009 | 16   | 0.104 | 0.031 | 12   |
| $GENCO_7$  | 0.138       | 0.046 | 11   | 0.118 | 0.080 | 9    |
| $GENCO_8$  | 0.018       | 0.00  | 8    | 0.014 | -0.005 | 6   |

Frequency deviations and GENCOs power output deviations of the proposed ABT based multi area deregulated power system with Proportional and ANFIS controllers under unilateral contract are shown in Figs. 6 and 10. UI rate and frequency of area-1 under unilateral contract scenario is shown in Fig.8. Detailed time domain analysis based on the performance indices peak undershoot (PUS), peak overshoot (POS) and settling time (Ts) of frequencies and GENCOs output deviations for the Proportional and ANFIS controllers are given in Table 1 and 2. From all these results, it should be clear that ABT system with ANFIS controller reduces the frequency and GENCOs power output deviations better than the P controller.

Case 2- Bilateral contract

In bilateral contract case, system DISCOs are having the chance to collaborate with any one of the GENCOs in the same control area or other areas. The disturbance on DISCO is considered as $\Delta P_{L1} = \Delta P_{L2} = \Delta P_{L3} = \Delta P_{L4} = 0.1 pu$ Corresponding DPM is given below

$$DPM = \begin{bmatrix}
0.2 & 0.3 & 0.1 & 0.1 & 0.1 & 0.0 & 0.0 \\
0.4 & 0.3 & 0.1 & 0.2 & 0.1 & 0.1 & 0.0 \\
0.1 & 0.1 & 0.3 & 0.2 & 0.1 & 0.0 & 0.0 \\
0.1 & 0.1 & 0.1 & 0.2 & 0.2 & 0.1 & 0.1 \\
0.1 & 0.1 & 0.1 & 0.1 & 0.2 & 0.2 & 0.1 \\
0.1 & 0.1 & 0.1 & 0.1 & 0.2 & 0.2 & 0.1 \\
0.0 & 0.0 & 0.1 & 0.1 & 0.1 & 0.0 & 0.3 \\
0.0 & 0.0 & 0.1 & 0.1 & 0.1 & 0.3 & 0.3 
\end{bmatrix}$$
During steady state, output of the GENCOs are obtained. The values are: $\Delta P_{\text{GENCO-4}} = 0.09$ pu, $\Delta P_{\text{GENCO-2}} = 0.12$ pu MW, $\Delta P_{\text{GENCO-3}} = 0.1$ pu MW, $\Delta P_{\text{GENCO-4}} = 0.1$ pu MW, $\Delta P_{\text{GENCO-5}} = 0.1$ pu MW, $\Delta P_{\text{GENCO-6}} = 0.11$ pu MW, $\Delta P_{\text{GENCO-7}} = 0.08$ pu MW, $\Delta P_{\text{GENCO-8}} = 0.1$ pu MW.

![Graphs](image1.png)

**Figure 9.** Frequency deviation responses of all the control areas under bilateral contract scenario
Figure 10. Power output deviations of all the control area of the system for bilateral contract scheme

Figure 11. UI rate and frequency of area-1 under bilateral contract scenario

Table 3. Frequency deviation of all the areas with controllers under bilateral contract

| Frequency deviation (pu Hz) | P controller | ANFIS controller |
|-----------------------------|--------------|------------------|
| ΔF₁                        | 0.521        | 0.321            |
| ΔF₂                        | 0.302        | 0.201            |
| ΔF₃                        | 0.205        | 0.146            |
| ΔF₄                        | 0.298        | 0.188            |
Table 4 Output power deviation of GENCOs with controllers under bilateral contract

| Controller | P controller | ANFIS controller |
|------------|--------------|------------------|
|            | POS | PUS | Ts | POS | PUS | Ts |
| GENCO_1    | 0.400 | -0.082 | 8 | 0.352 | 0.012 | 7 |
| GENCO_2    | 0.418 | -0.071 | 7 | 0.386 | 0.001 | 6 |
| GENCO_3    | 0.182 | 0.025 | 12 | 0.155 | 0.051 | 10 |
| GENCO_4    | 0.035 | -0.012 | 12 | 0.021 | -0.008 | 11 |
| GENCO_5    | 0.162 | 0.067 | 16 | 0.128 | 0.072 | 15 |
| GENCO_6    | 0.179 | 0.075 | 15 | 0.151 | 0.078 | 14 |
| GENCO_7    | 0.162 | 0.020 | 11 | 0.137 | 0.048 | 9 |
| GENCO_8    | 0.023 | -0.005 | 9 | 0.020 | -0.003 | 8 |

Frequency deviations and GENCOs power output deviations of the proposed ABT based multi area deregulated power system with Proportional and ANFIS controllers under bilateral contract are shown in Figs. 9 and 10. UI rate and frequency of area-1 under bilateral contract scenario is shown in Fig.11. Detailed time domain analysis based on performance indices such as peak undershoot (PUS), peak overshoot (POS) and frequency settling time (Ts) and tie-line power variations for Proportional and ANFIS controllers are given in Table 3. Time domain analysis of each GENCOs are also given in Table 4. From all these results, it should be clear that ABT system with ANFIS controller reduces the frequency and GENCOs power output deviations than other controllers.

7. Conclusion
This paper reveals that the frequency linked ABT mechanism with ANFIS controller can improve grid frequency and GENCOs power output deviations as compared to the existing manual UI based control structure. The ANFIS controller technique can effectively control all the GENCOs in each area and improves the performance of frequency. This helps in reducing the cost of unneeded exchange of power between generation companies and utilities. Time domain outputs shows that frequency linked ABT mechanism with ANFIS based controller provides better performance in view of performance indices such as undershoot, overshoot, settling time of frequency deviations and GENCO power deviations than conventional proportional controller.
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