A Mathematical Framework for Frequency Linked Availability Based Tariff Mechanism in India

Barjeev Tyagi and S.C.Srivastava

Abstract-- **Frequency linked availability based tariff (ABT) has been successfully implemented in India at the regional grid level. This has resulted in improved grid discipline in terms of maintaining system frequency close to its nominal value. This paper has provided a mathematical framework for this control mechanism. A multi area automatic generation control model has been modified to include the ABT features. The conceptualized model has been tested on an available data for the Northern Regional Electricity Board (NREB) system.**

Index Terms– **Frequency control, Availability based tariff, Unscheduled interchange, Multi- area control**

I. Introduction

IN a power system network, the system frequency is a continuously changing variable that is controlled by maintaining continuous balance between system demand and total generation. If demand is greater than generation, the frequency falls, while if the generation is greater than the demand, the frequency rises. The frequency control requirements can be managed by either changing the output of the generating units or by changing the demand. The concept of conventional Load Frequency Control (LFC) is discussed in references [1, 2 and 3].

In a competitive electricity market, for stable and secure operation of power system, System Operator (SO) has to provide number of ancillary services [12]. One of the ancillary services is the 'frequency regulation' or 'load following' based on the concept of Load Frequency Control. A detailed discussion on load frequency control issues in power system operation after deregulation is reported in reference [4]. LFC, implemented by the SO, normally utilize an integral controller [5,6 & 7]. A method to find the optimum parameter for this type of controller for a two-area system of identical rating has been proposed in [7]. In a practical power system, there may be more than two areas and each of the areas may have different ratings. The authors in [8] have proposed a general model for multi-area AGC. A master controller scheme for multi area, which controls the frequency in different areas, has been proposed in [13]. Chown and Wigdorowitz in [14] have proposed a methodology of frequency control, in an acceptable range, considering the cost of the control.

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The power generation scenario in India presents a rich and composite mixture of hydro, nuclear, thermal, wind and solar generation. The installed generation capacity in the country at present is about 110,000 MW, a major share of which is derived from fossil fuel based thermal power plants. Power generation in India has been largely state owned. There are total five regional grids in India namely Northern grid, Southern grid, Western grid, Eastern grid and North-Eastern grid. All the states are connected to these grids as per their geographical locations.

The regional grids had been operating in a very dissatisfactory manner for many years. There were large deviations in frequency from the rated value of 50 Hz. The earlier tariff mechanism did not provide any incentive for either backing down the generation during off peak hours (higher frequency) or for reducing the consumers' load / enhancing the generation during peak load hours (lower frequency). In fact, there were financial advantages in generating at higher output irrespective of the consumers' demand.

The frequency linked Availability Based Tariff (ABT) that has been introduced at the regional level, starting from July 2002, directly addresses these issues. Firstly, by giving incentives for enhancing the output of plants during peak load hours, it enables more consumer loads to be met. Secondly, backing down the generation during off peak hours from the plants is encouraged when frequency is high. Thirdly, during peak load hours, the consumers or states are discouraged from overdrawals and pulling down the frequency, as they have to pay for it at higher rate.

Although ABT has been successfully operating in the regional electricity grids for over two years, no mathematical framework has been suggested so far to explain its functioning. The present work provides a general-purpose model for frequency control scheme provided by the ABT. A conventional multi-area automatic generation control (AGC) scheme has been extended to include frequency linked ABT blocks. The proposed scheme suggests that if the generating stations/loads are responding to the Unscheduled Interchange (UI) price signal, the desired grid discipline can be maintained. The developed scheme has been tested on the Northern Regional Electricity Board (NREB) system [10]. The northern grid system has been divided into seven control areas, which represents the states connected to the grid. The performance studies have been carried out by using the MATLAB/SIMULINK to incorporate the UI price signal.

II. Availability Based Tariff (ABT)

Availability Based Tariff is a rational tariff structure for power supply from generating units. The most significant aspect of ABT is the splitting of the earlier monolithic charge structure into following three components.

1. Fixed charges or Capacity charges
2. Variable charges or Energy charges
3. Unscheduled Interchange (UI) charges

It is the last component that is largely responsible for bringing about the desired grid discipline. Splitting of tariff into three components is meant to act as an incentive for power trading which may emerge in a self-regulating power market regime. It is also expected to promote the concept of Economic Load Dispatch (ELD) among the power generators.

1 Capacity or Fixed Charges

The fixed cost elements are interest on loan, return of equity, depreciation, operation and maintenance expenses, insurance, taxes and interests on working capital. Fixed charges are payable to the generating station, by the intended beneficiaries of the generating facility (state electricity boards of the region in most cases). The payment of the fixed cost to the generating company is linked to the availability of the plant, that is its capability to deliver MWs on a day-to-day basis. The total amount payable to the generating company over a year towards the fixed cost would depend on the average availability (MW delivering capability) of the plant. In case the average availability achieved over the year is higher than the specified norms, the generating company would get the higher payment. But if it is lower, the payment would also be lower.

2 Variable or Energy Charges

The energy charge comprises of the variable cost (fuel cost) of the power plant for generating energy as per the given schedule for the day. The energy charge is not according to the actual generation or plant output, but is for the scheduled generation. In case there are deviations from the schedule, the energy charge payment would be for the scheduled generation only, and the excess generation would be paid for at a certain rate which would depend on the system conditions prevailing at that time. If the grid has surplus power at that time and frequency is above 50 Hz, the rate would be small, if grid has deficit power and frequency is below 50 Hz, the payment for extra generation would be at a higher rate.

3 Unscheduled Interchange (UI) Charges

In the earlier tariff mechanism, there was no incentive/disincentive for deviation from the generating/drawal schedule by an entity. The ABT regime stipulates that UI charges are payable under the following conditions:

- A generator generates more/less than the schedule causing grid frequency to deviate upwards/downwards from the nominal value (50 Hz).
- A beneficiary draws more/less than the schedule causing grid frequency to deviate downwards/upwards from the nominal value (50 Hz).

The incentives/disincentives imposed vary with the grid condition at the time of indiscipline and the magnitude increases with the severity of the frequency deviation caused.

The current UI price curve is shown in Fig. 1.

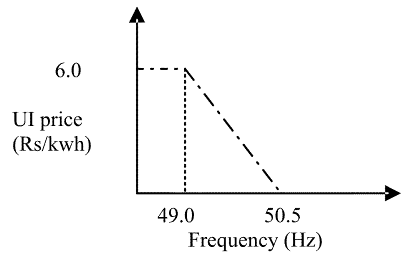

Fig 1. UI price

If frequency (f) is 49 Hz or below, UI price is maximum (600 paise per unit), and this price is minimum (zero paisa), when frequency is 50.5 Hz or above. If frequency is in between 49.0 Hz and 50.5 Hz, the UI price varies linearly, given by the following equation.

$$\text{UI rate} = 202 - 4*f \qquad (1)$$

Maximum value of ABT is fixed according to the cost of generation of the costliest generating unit (diesel generating plants).

III. Working Of The ABT Mechanism

All the generating stations in the region declare their expected output for the next day to the Regional Load Dispatch Center (RLDC). The RLDC breaks up and tabulates these output capability declarations according to the entitlements of each state and conveys the same to the State Load Dispatch Center (SLDCs). The SLDCs then carry out an exercise on how best they can meet the load of their consumers over the day and convey it to the RLDC. The RLDC compiles these declarations and determines the generation schedule for generating stations and drawal schedule for beneficiaries. These schedules are then issued by the RLDC to all the concerned and become the operational as well as the commercial datum.

These schedules are also used for determination of the amount payable as energy charges for the day. Deviations from the schedules are determined in 15-minutes time block (total 96 blocks in a day) by special metering, and priced as described above.

IV. Proposed Mathematical Model Of ABT Based Frequency Control Scheme

In an integrated power system, different control areas are connected to each other through the tie lines. Power interchange can take place between the two areas through these tie lines. In the conventional method of frequency control, if the load changes in any area, the generation of the same area is changed either manually or automatically to maintain the frequency at nominal value. In addition to maintaining the frequency at nominal value, area's net interchange should be as per schedule. In the process, the system frequency (which may have deviated from the nominal value due to the initial load - generation imbalance in the area) also returns to the nominal value, without the need for any corrective (secondary) action in the other control areas. The block diagram of a conventional frequency control scheme of an area-i is shown in Fig. -2 [1, 2].

Where,

- Δf is the frequency deviation
- ΔPd is the change in load demand
- ΔP_{tie} is the change in net tie line power interchange
- ΔP_v is the change in governor input
- B is the bias factor
- R is the governor droop
- grc is the generator rate constraint and limit
- Cn is the transfer function of a controller (normally PI controller is used)
- $Gg = 1/(1+sTg)$ is the governor transfer function with governor time constant Tg
- $Gt = 1/(1+sTt)$ is the turbine transfer Function with turbine time constant Tt
- $Gps = Kps/(1+sTps)$ is the power system transfer function with time constant Tps and gain Kps.

The conventional frequency control scheme has two control loops. First is the primary control loop, which controls the frequency by self-regulating feature of the governor, but frequency error cannot be fully eliminated. The secondary control loop has a controller that can fully eliminate the frequency error with the help of integral control. The input power (ΔP_v) to the governor can also be controlled manually to increase or decrease the plant output.

In the ABT based frequency control scheme the primary control loop is same as in the conventional frequency control, but the secondary loop is changed to incorporate the UI price signal. The block diagram of ABT based frequency control scheme of an area-i is shown in Fig. -3.

The complete block diagram can be divided into two control loops, Primary control loop and ABT control loop. The function of primary control loop is similar to the conventional frequency control and the function of the ABT control loop is explained below.

It is assumed that the generating plant of an area is generating at its scheduled output and the frequency of the grid is at the nominal value (50 Hz), when a load change of ΔPd occurs in the system. This results in deviation in the supply frequency. Actual frequency of the system is now

$$S1 = \text{Nominal Frequency} + \Delta f \quad (2)$$

At this frequency S1, the UI price signal S2 is calculated as given by equations (3) to (5) below, which is derived from Fig. 1.

if S1 > 50.5 Hz, then

$$S2 = 0.0 \text{ Rs/kwh} \quad (3)$$

if 49.0 Hz < S1 <50.5 Hz, then

$$S2 = (202.0 - 4.0*S1) \text{ Rs/kwh} \quad (4)$$

if S1 < 49.0 Hz, then

$$S2 = 6.0 \text{ Rs/kwh} \quad (5)$$

This UI price signal S2 is compared with the incremental cost signal (S4) to generate the signal S5. Signal S4 can be calculated as:

$$S4 = a*S3 + b \quad (6)$$

Where a and b are the incremental cost coefficients and depend on the type of the plant.

$$S3 = \text{Scheduled generation} + Kt*\Delta Pt \quad (7)$$

Where, ΔPt is the change in turbine power and Kt is a constant, which convert turbine power into electrical power (in p. u. its value is unity).

$$S5 = S2 - S4 = \text{UI price} - \text{Incremental cost of generation} \quad (8)$$

This signal S5 can be used to change the input power to the governor ΔPv.

$$\Delta Pv = K*S5 \quad (9)$$

Where, K is proportionality constant. In the present work, it is taken as unity.

V. THE TEST SYSTEM

The proposed ABT based frequency control scheme described in previous section has been developed and tested on the Northern Regional Electricity Board (NREB) system [4].

Indian power system is currently in the process of restructuring. As a first step in this process, generation, transmission and distribution are being separated. The concept of ABT has been introduced in India to bring more discipline in the grid. In the present work, it has been assumed that all the states connected to the northern grid are responding to the UI price signal. The northern grid system has been divided into seven control areas as shown in Table 1. A general purpose Governor-Turbine model has been used, which is taken from reference [9].

Table 1. Control areas of NREB system

Area	States	Area Rating in MW (P_R)	Incremental Cost (Rs/kwh)	
			Minimum	Maximum
1.	Uttar Pradesh & Uttaranchal	5420	0.999	2.257
2.	Haryana	1098	1.003	2.297
3.	Rajasthan	1827	1.024	2.502
4.	Punjab	3275	1.029	2.551
5.	Himachal Pradesh	412	All hydro plants	
6.	Jammu & Kashmir	407	3.554	6.00
7.	Delhi	679	1.007	2.339

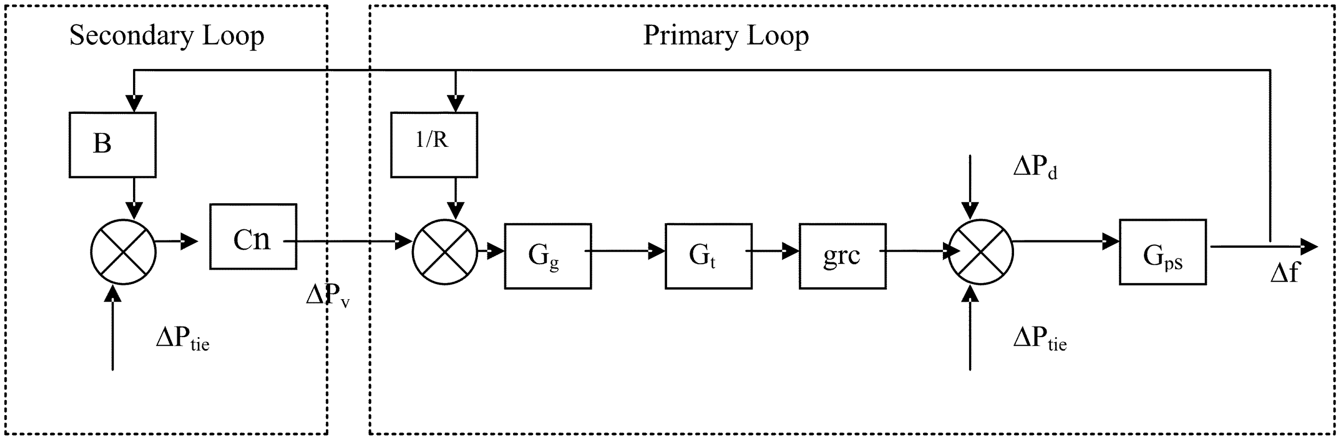

Fig. 2. Conventional frequency control scheme

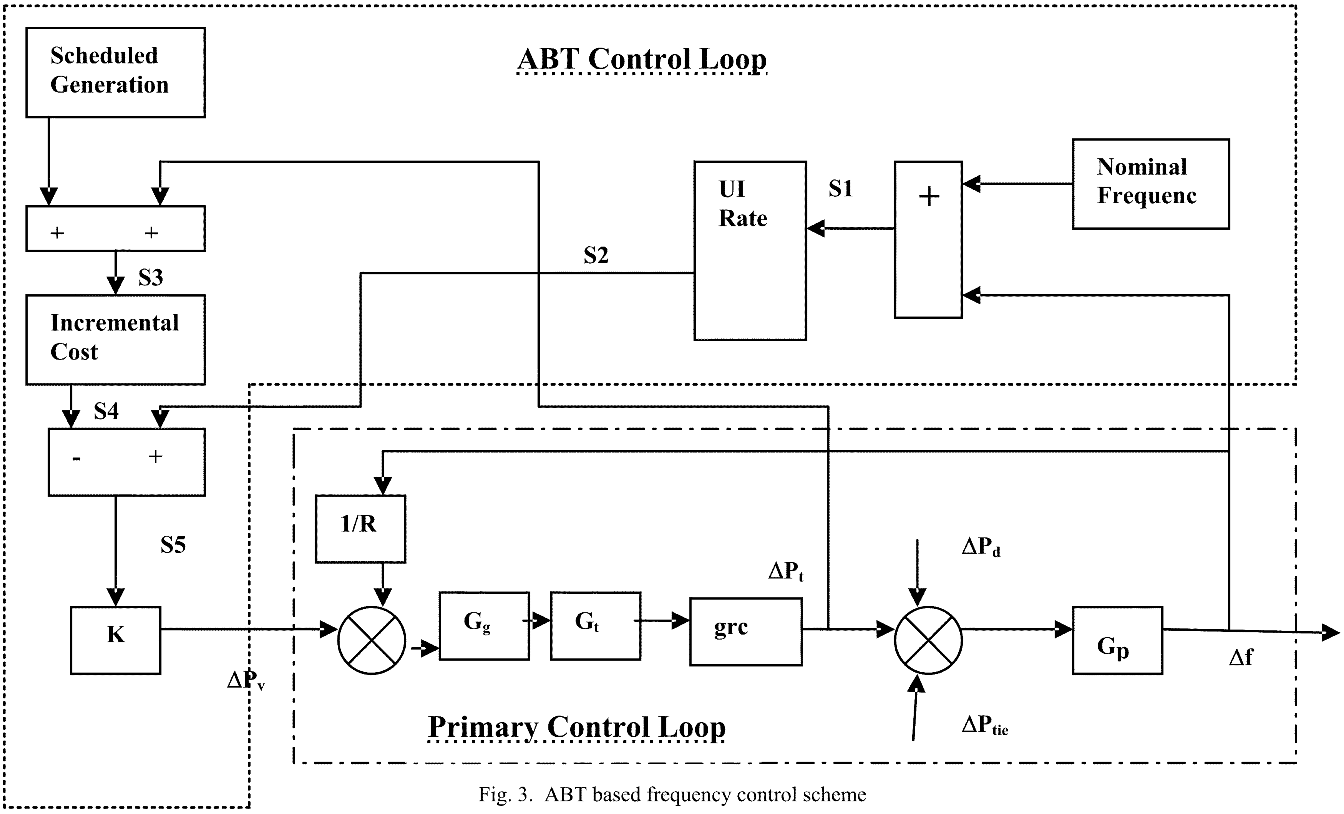

Fig. 3. ABT based frequency control scheme

The incremental cost of generation is assumed to be varying linearly between the minimum cost (at 0.1 pu output) and the maximum cost (at 0.98 pu output) for each generator. The cost of generation in different states, at 80% plant load factor, has been taken from reference [11].

VI. Simulation Results

The proposed ABT based frequency control scheme for the multi-area system was simulated on the northern grid system for the following cases.

Case-I: The first case assumes that when there are load changes in certain areas, the generator of the respective areas respond to change their output as per the ABT based scheme. To simulate the ABT based frequency control scheme, the change in demand of area-1, area-4 and area-7 were assumed to be 0.1 pu each, while the demand of other areas were assumed to be zero. To meet this demand, it is assumed that the generators of the same areas are responding to the UI price signal. It is also assumed that the incremental generation cost of area-1 is the lowest, that of the area-7 is the second lowest and for the area-4, it is maximum. A plot of the generation change in different areas is shown in Fig. 4 (a), which has been obtained by MATLAB simulation of the proposed scheme.

From Fig. 4(a), which shows the time variation of output of the generators of different areas, it is observed that the generation change is maximum in area-1, followed by that in areas 7 and 4, respectively. All other generators, except those in areas 1, 4 and 7 also change their output due to their governor actions. It is observed that the frequency of the grid is brought very close to the nominal frequency value at steady state. A typical plot of the frequency deviation of the grid is shown in Fig. 4(b).

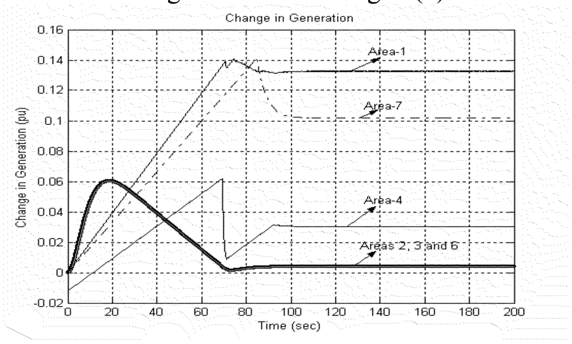

Fig. 4(a). Change in generation (case-I)

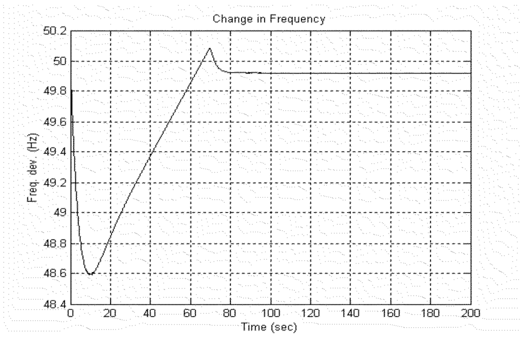

Fig. 4(b). Change in the grid frequency (case-I)

It is observed that as the frequency of the grid changes the ABT value also changes. The change in the ABT value is shown in Fig. 4(c).

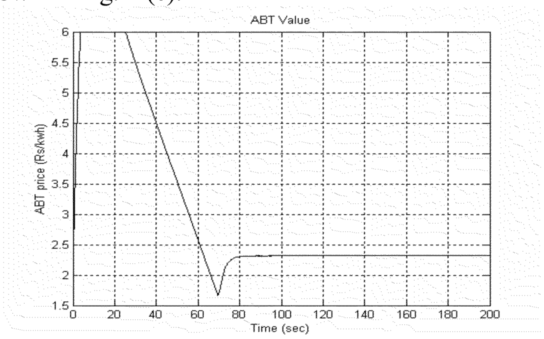

Fig. 4(c). ABT value (case-I)

Case-II: The second case assumes that when there is a load change in one area, the generators in the other areas respond to change their output. In this case, the change in demand of areas 1, 5 and 6 were assumed to be 0.1 pu each, while the change in demand of other areas were assumed to be zero. To meet this additional demand, it is assumed that the generators of the areas 2, 4 and 7 respond to the UI price signal. It is also assumed that the incremental cost of area-2 is the highest followed by that for areas 7 and 4, respectively. The change in the generation in different areas is shown in Fig. 5(a). From Fig. 5(a), it is observed that the generation change is maximum in area 2, followed by that in areas 7 and 4. All other generators except those in areas 2, 4 and 7 also change their output due to their governor actions. It is also observed that the frequency of the grid reaches close to the nominal value at steady state. A plot of the frequency deviation of the grid is shown in Fig. 5(b).

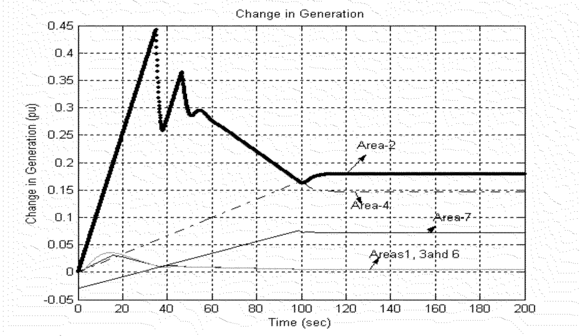

Fig. 5(a). Change in generation (case-II)

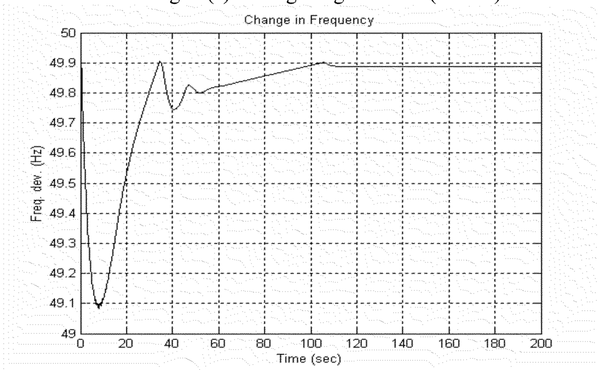

Fig. 5(b). Change in frequency (case-II)

The change in ABT value for this case is shown in Fig. 5(c).

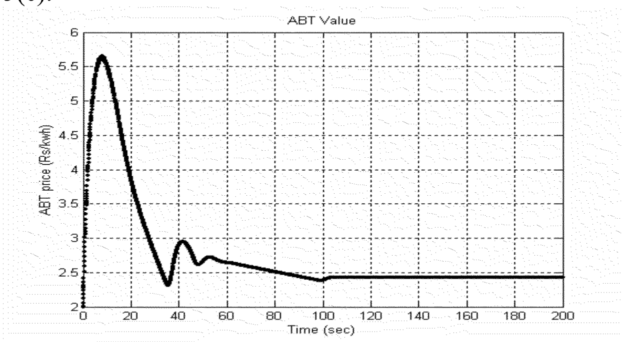

Fig. 5(c). ABT value (case-II)

In this case, the tie line power flows also change from the areas where generation is changing, to the areas where load is changing. The deviations in the tie line power flow from areas 2, 4 and 7 to area 1 are shown in Fig. 5(d).

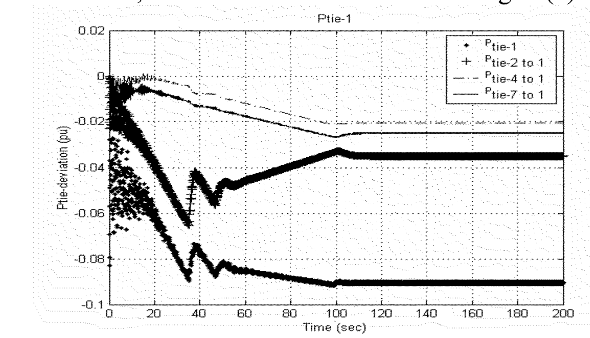

Fig. 5(d). Tie line power flow deviations (ΔP_{tie}) for case-II

VII. Conclusions

This paper has presented a control scheme representing ABT based frequency control mechanism. The simulation results obtained on the NREB system demonstrates that with the generators responding to the UI price signal, the frequency of the grid improves. Although the frequency deviation cannot be completely eliminated, it can be reduced to a very small value. The ABT mechanism is streamlining the operation of regional grids in India. There is now a defined scheduling procedure and the constituents are encouraged to follow the given schedules for generation and drawls.

The ABT based scheme introduces and encourages merit order dispatch in the Indian power sector. Generators need to ramp up and ramp down their output based on the declared generation schedules given by RLDC and the frequency at that time. It will promote competition, efficiency and economy leading to power trading which shall ultimately pave the way for a self-regulating power market.

The aim of the present work has been to demonstrate a mathematical model of the ABT based scheme. The incremental cost values have been assumed only to demonstrate the functioning of the proposed scheme. However, more realistic values can be used to compare the results with the actual changes being experienced in the grid.

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