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Frequency regulation Ancillary service dispatch in Restructured Electricity Market

R. Gnanadass, M. Prabavathi

Abstract—Ancillary services markets have been developed in many of the restructured power system regions through-out the world. Ancillary services are support services which are required to maintain reliability and support their primary function of delivering energy to customers. Ancillary services play an important role in restructured power market because they enable the commercial transactions of an electricity spot market to be realized. Such additional services are required for maintaining active and reactive power balance, variation in frequency and voltage with in allowable limits in event of emergency handling of power system such as black start capability etc. In this paper, the importance of frequency related ancillary services for Indian utility system is discussed and compared with the frequency regulation mechanism adopted in Indian power grids.

Index Terms—Unscheduled interchange price, Availability based tariff, automatic generation control, market clearing price, frequency control ancillary services.

I. Introduction

Over last decades, many electric power industries, throughout the world, have been changed their way of operation and business from vertically integrated structure to restructured power market. Among different issues in competitive power environments, ancillary services are one of the most important subjects which have essential role in power system operation and security. Power systems require ancillary services to ensure the system integrity and stability. Ancillary services are primarily real-power generator control capacity services. In a vertically integrated system, the ancillary services are an integral part of main electrical energy supply service and not dealt with separately. In competitive environment, the ancillary services are unbundled from the energy market and procured through competitive bidding. System operators have to purchase ancillary services from ancillary service providers. Different regions and countries around the world have adopted different approaches for managing the ancillary services. A de-tailed review of international experiences on ancillary services management is presented in [1-5]. An integrated market based approaches are proposed in [6] for procurement of ancillary services along with energy. In [7], an optimal power flow method is used for pricing and settling simultaneous provision of energy and ancillary services.

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In India also, ancillary services have developed along with the grid. The Central Electricity Regulatory Com-mission in India after detailed discussion with various system operators and load dispatch centers decided that ancillary services market was essential to assist the cur-rent Indian Power Scenario. CERC issued a staff paper on the Introduction of Ancillary Services in Indian electricity market that invited suggestions from all stakeholders [8]. Basically there are three types of Ancillary Services, viz. Frequency support ancillary services (FSAS), Voltage or Reactive power support ancillary services (VCAS) and Black start support services (BSAS). In a power system, the frequency deviations are mainly due to real power mismatch between generation and load, whereas volt-age variations are due to reactive power imbalance in the system. The system operator implements Automatic Generation control required for POOLCO based trans-action by utilizing different types of controllers in [9]. In competitive electricity markets, procurement of reactive power ancillary services is a complex issue for the independent system operator due to various factors that need to be considered [10]. Hernandez et al [11] have pro-posed a methodology to allocate reactive power ancillary service into a deregulated environment with centralized decision-making and cost-based. A novel reactive power market clearing algorithm is proposed for forward ancillary services market in [12]. In this paper, bidding structure of frequency control ancillary services is proposed. A model of price based automatic load frequency control is presented.

This paper is structured as follows. Section II describes the frequency related ancillary services. In Section III, Availability Based Tariff mechanism used in India has been described. Section IV discusses about the model of price based generation control. Modeling of power system suitable to frequency regulation is discussed in section V. The formulation of presented framework for bidding strategy problem is given in section VI. Section VII addresses the step by step algorithm. In Section VIII, the proposed approach is tested on Indian utility system with different case studies. In the last section conclusive remarks are given.

II. Frequency control ancillary service

A frequency regulation ancillary service is necessary to meet engineering control performance standards to protect the safe and reliable operation of the electric grid. This type of ancillary service is also sometimes referred to as regulation, frequency response, or automatic generation control.

This service is important to reliable grid operation since system frequency can fluctuate greatly with short-term load fluctuations. In the restructured power market, this service is provided by market participants and managed by the system operator. The mismatch between electrical generation and demand would cause the frequency to deviate from its nominal value. The system operator must maintain standard frequency and does so by utilizing generation resources that have automatic generation control (AGC) equipment installed. This makes those resources capable of raising or lowering of output instantaneously. Units that are capable of providing AGC are dispatched by the system operator, to protect system reliability. There are volumes of research articles which have been dis-cussed in the literature regarding Automatic Generation Control /Load Frequency Control of single area/multi area power system considering various control strategies. Kumar et al [13, 14] have developed a framework for price based operation to understand AGC implementation for bilateral and Pool Co structures. Zhong and Bhattacharya [15] have proposed a frequency linked price based bidding structure for the primary and the secondary regulation service in the pool market. Frequency linked UI mechanism for Indian power system have been discussed in [16, 17].

The pricing of ancillary services can be either cost-based or market-based. There are three essential models for pricing ancillary services: (1) bundle the services with other transmission services into a network tariff; (2) unbundle the services and procure them through contracts or bid solicitation; and (3) unbundle the ancillary services and price them competitively by allowing them to be bid into a day-ahead and/or real-time market for these services. In a market-based system, all units selected by the market operator for a particular ancillary service will receive the market clearing price for each unit of ancillary service provided. Where a market for ancillary services is not present or not yet fully developed, pricing of ancillary services should be cost-based to ensure sufficient competitive provision of these services. Pricing of ancillary services can be derived from that set of cost components that is relevant to each ancillary service, such as the cost of providing regulation, the cost of reactive power support, the cost of providing black start capability, the cost of providing spinning reserves, etc. In [18], a methodology of frequency control of AC network within an acceptable limit considering the cost of the control is proposed.

III. Frequency linked Availability Based Tariff (ABT) mechanism

In India, the increase in trading activities has led to increase in flow of power over the Interstate transmission system and Inter regional transmission system. The Power Grid corporation of India Limited has found the operation of regional grids in India to be very challenging. The regional grids had been operating in a very undisciplined and haphazard manner. There were large deviations in frequency from the rated frequency of 50.0 cycles per second (Hz). To deal with the problems faced by grid operators, a new tariff scheme ABT was introduced in the year 2002 [19]. Indian power engineers have introduced frequency linked tariff mechanism known as ABT in regional grids so as to impose the grid discipline and to regulate the wide fluctuations in frequency. Availability Based Tariff is a frequency based pricing mechanism applicable in India for un-scheduled electric power transactions. It concerns itself with the tariff structure for bulk power and is aimed at bringing about more responsibility and accountability in power generation and consumption through a scheme of incentives and disincentives. As per the notification, ABT is applicable to only central generating stations having more than one SEB/State/Union Territory as its beneficiary. The most significant aspect of ABT is the splitting of the existing monolithic energy charge structure into three components viz. capacity charges (fixed), energy charges (variable) and UI (unscheduled interchange) charges.

A. Capacity charge

It is a fixed cost and linked to availability of the generating plant. The payment of fixed charge to the generation company is linked to the availability of the plant. The total amount payable to the generator over a year towards the fixed cost depends on the average availability (capability to deliver MW) of the plant over the year.

B. Energy Charge

This component represents a variable cost (i.e) fuel cost of the power plant for generating energy as per the given schedule for the day. Hence energy charge is based on scheduled generation only but on actual generation.

C. Unscheduled Interchange

It is defined as difference between actual drawl and schedule. In case there are any deviations from schedule, the third component of ABT comes into picture. Third component is expected to bring about the desired grid discipline. Any deviation from schedule is to be paid through UI rate. This scheme encourages the re-dispatching of the generating units in real time based on prevailing UI charges to restore the frequency to nominal value of 50 Hz. If the frequency is above 50Hz, UI rate will be small and vice versa. As long as the actual generation /withdrawal are according to the given schedule, UI charge is zero. In case of over drawl, beneficiary has to pay UI charge according to the frequency dependent rate specified. In this paper, a case study has been done on a test system to illustrate the trading of power through UI mechanism [20, 21].

IV. Price based generation control

For satisfactory operation of a power system, the frequency should remain constant at its nominal value. The frequency of a system changes from its nominal value for any difference in the supply and demand. Balancing generation and load instantaneously and continuously is difficult because loads and generators are always fluctuating. Each generating unit is equipped with a speed governor mechanism. When incident is

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occurred such as sudden loss of generation or load, system will have enough primary control to maintain system frequency without interruption of load or generation.

The primary loop controls the frequency by self-regulating feature of the governor, but the frequency error could not be fully eliminated. Response of primary reserve is between 5 seconds to 30 seconds. The secondary control loop has a controller that can eliminate the frequency error. Response of Secondary reserve is between 30 second and 15 minutes in order to bring the frequency of the system back to nominal values. Action of Secondary control is to reduce Area Control Error when the load is different from the planning or any power imbalance happened due to any reason [22]. Grid Code (IEGC) specifies a Free Governor Mode of Operation (FGMO) for all generation units connected to the regional grid. According to IEGC, the droop of the governors should be set between 3 to 6 percent. A mathematical framework for the provision of ABT based frequency regulation service by a generator has been first investigated and reported in [23]. Feedback signal of this scheme, known as Generation control error, is the difference of marginal cost of generator responding to load change and UI price at the same instant. When a generator has a higher incremental cost than the UI rate, while supplying the extra load, it will only pick up the minimum amount as per the regulation of CERC and wait until the frequency goes below its threshold value for further supply of extra load. Therefore the response time deteriorates due to lack of proper remuneration. This scheme has such some short comings. To rectify the shortcomings of the above model, Saurabh Chanana et al [24] have developed a new algorithm for computing Generation Control Error instead of computing same for each generator. The same modified control scheme has been used in the present work. The block diagram of ABT based frequency control scheme of an area is shown in Fig.1. In the ABT based frequency control scheme, the primary control loop is the same as in the conventional frequency control but the secondary loop is changed to incorporate the UI price signal and called as ABT control loop.

V. Modeling of system

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, f_0 (50 Hz). When a load change of P_d happens in the system, it results in

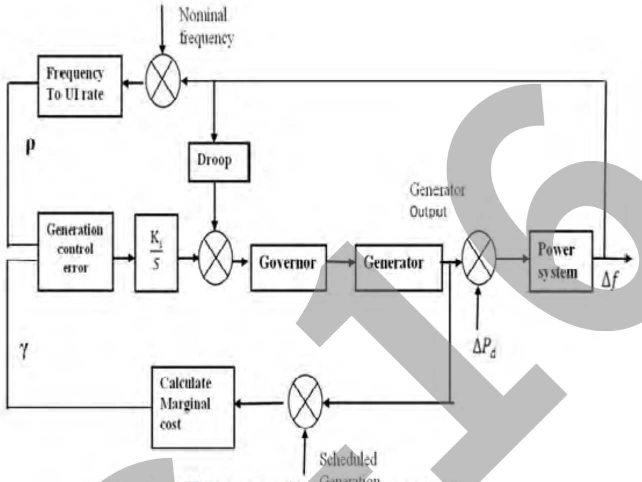

Fig. 1: ABT based frequency control

deviation in the supply frequency, f.

$$f = f + f_0 \quad (1)$$

UI frequency is 9000 Rs/MWh (max) when frequency (f) is 49.48 Hz or below and is minimum (zero), and when frequency is 50.2 Hz or above.

If $f > 50{:}2$ Hz, then

$$\text{UIrate} = 0{:}0 \text{ Rs/MWh} \quad (2)$$

If $f < 49{:}5$ Hz, then

$$\text{UIrate} = 9000 \text{ Rs/MWh} \quad (3)$$

If $50Hz < f < 50{:}2$ Hz

$$\text{UIrate} = 9675(50{:}2\ f) \text{ Rs/MWh} \quad (4)$$

If $49{:}8Hz < f < 50$ Hz

$$\text{UIrate} = 1935 + 14231{:}5\ (50\ f) \text{ Rs/MWh} \quad (5)$$

If $49{:}5Hz < f < 49{:}8$ Hz

$$\text{UIrate} = 4781{:}3 + 14062{:}3\ (49{:}8\ f) \text{ Rs/MWh} \quad (6)$$

At the frequency (f), the UI price signal (ρ) is calculated by using equations (2) to (6). This UI price signal (ρ) is compared with the incremental cost signal (γ) to generate the generator control error signal.

Incremental cost Signal (γ) can be calculated as,

$$= 2\ c\ P_g + b \quad (7)$$

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

$$P_g = \text{Scheduled generation} + \Delta P_g \quad (8)$$

where P_g is the change in turbine generator output. Further and signal is compared with following condition to generate generation control error (gce) for each generator which is as per the control scheme shown in Figure 1.

If $\gamma > \rho_0$; yes then go to (10)
No, then go to (15) (9)
If $\rho > \gamma$; yes then go to (11)
No, then go to (12) (10)

$$gce = \rho - \gamma; \quad (11)$$

If $\rho > \rho_0$; yes then go to(13)
No, then go to (14) (12)

$$gce = \rho - \rho_0; \quad (13)$$
$$gce = 0; \quad (14)$$

If $\rho < \gamma$; yes then go to (11)
No, then go to (16) (15)

If $\rho > \rho_0$; yes then go to(13)
No, then go to (14) (16)

VI. Mathematical model for power bidding

In a competitive electricity market, most of the participants can be allowed to bid their outputs and demands as blocks. The sales bid of suppliers and purchase bid of customers are expressed in the following way.

Suppose that a system consists of 'm' independent power suppliers. Each supplier is required to submit a block bid function. Each supplier has k_i $(i = 1, 2\ldots m)$ blocks of power which is given by the equations

$$S_i(q) = \begin{cases} p_{si1}, & a_{i0} \le q \le a_{i1}, \\ p_{si2}, & a_{i1} \le q \le a_{i2}, \\ p_{si3}, & a_{i2} \le q \le a_{i3}, \\ \vdots & \vdots \ddots \vdots \\ p_{sik_{i-1}i}, & a_{ik_{i-1}} \le q \le a_{ik_i}, \end{cases} \quad i = 1, 2, \cdots m \quad (17)$$

where p_{si1} denotes offering price of first block for the i[th] supplier between the power quantity a_{i0} and a_{i1}.

The electricity supply curve is upward sloping curve which can be obtained by summing of all net sales bids of suppliers. The cumulative blocks of power for all suppliers can be written as

$$S(q) = \begin{cases} p_{s1}, & a_0 \le q \le a_1, \\ p_{s2}, & a_1 \le q \le a_2, \\ p_{s3}, & a_2 \le q \le a_3, \\ \vdots & \vdots \ddots \vdots \\ p_{sk-1}, & a_{k-1} \le q \le a_k. \end{cases} \quad (18)$$

Where p_{s1} denotes offering price of first block for all suppliers between the power quantity a_0 and a_1.

Using Heaviside's unit step function, these equations are expressed as a single equation and given by the equation.

$$S(q) = p_{s1} + (p_{s2} - p_{s1})u_{a_1}(q) + (p_{s3} - p_{s2})u_{a_2}(q) + \cdots + (p_{sk} - p_{sk-1})u_{a_{k-1}}(q). \quad (19)$$

Similarly there are 'n' independent customers in a pool based electricity market and each customer has $l_j, (j = 1,2,\cdots,n)$ blocks of power and is given by the equations

$$D_j(q) = \begin{cases} p_{dj1}, & b_{j0} \le q \le b_{j1}, \\ p_{dj2}, & b_{j1} \le q \le b_{j2}, \\ p_{dj3}, & b_{j2} \le q \le b_{j3}, \\ \vdots & \vdots \ddots \vdots \\ p_{djl_j}, & b_{jl_{j-1}1} \le q \le b_{jl_j}, \end{cases} \quad j = 1, 2, \cdots n. \quad (20)$$

where p_{dj1} signifies the bidding price of first block for 'j[th]' customers between the power quantity b_{j0} and b_{j1}.

The electricity demand curve is downward sloping curve which can be obtained by summing up of all purchase bids of customers. The cumulative blocks of power for all customers can be written as

$$D(q) = \begin{cases} p_{d1}, & b_0 \le q \le b_1, \\ p_{d2}, & b_1 \le q \le b_2, \\ p_{d3}, & b_2 \le q \le b_3, \\ \vdots & \vdots \ddots \vdots \\ p_{dl}, & b_{l-1} \le q \le b_{lj} \end{cases} \quad (21)$$

where p_{d1} indicates the bidding price of first block for all customers between the power quantity b_0 and b_1.

Using Heaviside's unit step function these equations are expressed as a single equation and is given by

$$D(q) = p_{d1} + (p_{d2} - p_{d1})u_{b_1}(q) + (p_{d3} - p_{d2})u_{b_2}(q) + \cdots + (p_{dl} - p_{dl-1})u_{b_{l-1}}(q) \quad (22)$$

The MCP of the system is obtained by the intersection of the aggregated supply curve and the aggregated demand curve.

$$S(q) = D(q) \quad (23)$$

This is nothing but the solution of $F(q) = 0$ where $F(q) = S(q) - D(q)$.

VII. Solution algorithm

The main step of the proposed algorithm is described as follows.

Step 1: Read the supplier offers and bids of customer in each trading period

Step 2: Aggregate offers of suppliers in all areas. Step 3: Aggregate bids of customer in all areas.

Step 4: Determine MCP and MCV by matching the supply and demand curve with criteria discussed in section VI.

Step 5: Check energy flows in all the links within the transmission line capacity.

Step 6: Calculate dispatch and drawl schedule of all suppliers

and customers.
Step 7: Compute the frequency and UI price. Step 8: Compare demand and generation amount.
Step 9: If demand > generation and UI > MCP, dispatch instructions to ancillary services providers
Step 10: Read the regulation bids of ancillary service provider.
Step 11: Match the suppliers bid with demand bids and determine ancillary service clearing price.
Step 12: Again check out energy flows in all the links within the transmission limit.
Step 13: calculate dispatch schedule for generators.

VIII. Case studies and discussion

The proposed frequency regulation ancillary service has been tested on Indian utility 62 bus system. The 62 bus system consists of 89 lines and 19 generators. It has been divided into 3 control areas. The single line diagram of the test system shown in Fig.2 is illustrated using DSA. Number of Gencos and discos in 62 bus system is given in Table I.

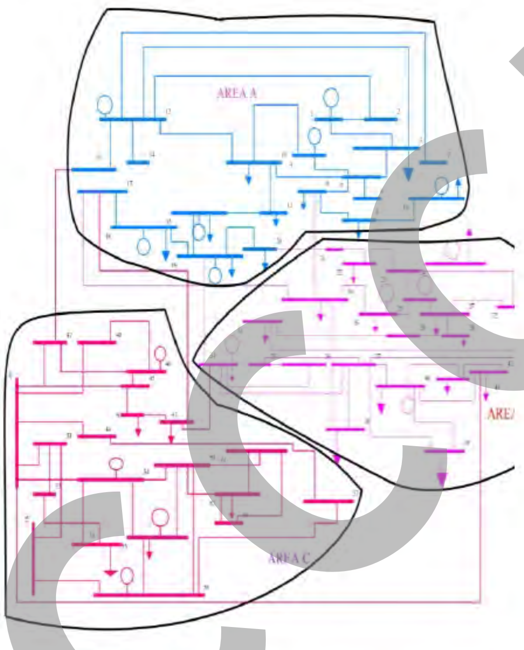

Fig. 2: Single line diagram of Indian utility 62-bus system

TABLE I: control areas in 62 bus power system

Control Area	Load(MW)	Market participants
Region 1	1600	Genco 1,2,3,4,5,6 Disco 1,2,3
Region 2	1000	Genco 7,8,9,10,11,12 Disco 4,5,6,7
Region 3	800	Genco 13,14,15,16,17,18,19 Disco 8,9,10

The following four case studies are carried out.
Case A: This part explains the energy transactions taking place between various entities in an Indian

Case B: In this part, frequency of the system at a particular trading period is discussed.
Case C: It deals with the procurement of frequency regulation ancillary services.
Case D: In this case, UI rate is compared with MCP for each trading period.

Case A:

To simulate the energy transactions, it is assumed that the Gencos and Discos both are participating in market. The Gencos' offers are aggregated in ascending order of price and the Discos' bids are aggregated in descending order of price in all areas. Market clearing price and market clearing volume can be calculated according to criteria discussed in section VI. By using Dynamic Security Assessment (DSA) tools, power flow in all links of transmission lines and inter area power flow are determined. It is found that power flow between these area is within the permitted transfer capability. Matching of supply and demand curve is given in Fig.3 at a particular trading period. The MCP and MCV is found to be 3900 Rs/MWh. The clearing quantity and requirement of each area is given in Table II. It can be inferred that after accommodating power exchange trades, there is a still deficit of electricity for three areas.

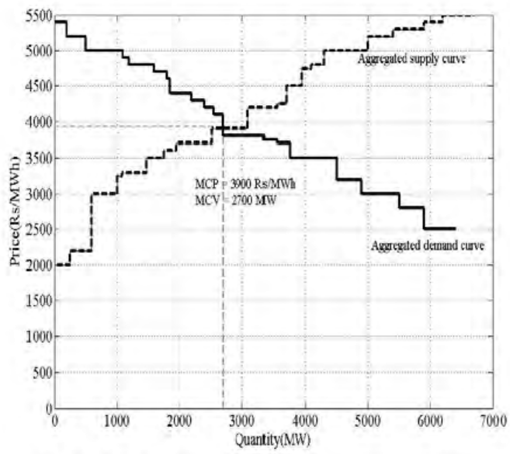

Fig. 3: Aggregated supply and demand curve

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TABLE II: Deficit details of area

Control Area	Clearing quantity (MW)	Deficit
Region 1	1220	380
Region 2	780	220
Region 3	700	100

Case B:

In this case, exchange of power in real time through UI mechanism has been examined. The deficit of states appear as over drawl (ie) withdrawal of power more than scheduled and surplus of states appear as under drawl(ie) withdrawal of power less than scheduled.

A model is required to observe the frequency deviations due to this over/under drawls. All models are created us-ing MATLAB-SIMULINK environment. The over/under drawls of areas is denoted as step load changes in order to determine the change in frequency. All generators shown in the model follow the Indian Electricity Grid Code (IEGC) guidelines regarding Free Governor Mode of Operation (FGMO). According to IEGC, the droop of the governors should be set between 3 to 6 percent. From the model, Pg1, Pg2 and Pg3 represent the change in generation output of three areas. In our case, all of the generating stations are not fully loaded and following the UI price signal. At that time region 1 was allowed for drawl of 1220 MW. However, region 1 was drawing 1600 MW. The frequency at that time is 49.71 Hz. This means region 1 was over drawing 380 MW at this frequency. The corresponding UI rate at this frequency is 6084 Rs/MWh and region 2 and region 3 were overdrawing 220 MW and 100 MW during this period. The response of the given system is given in Fig.4. Region 1 to Region 3 will have to Pay the prevailing UI charges to the pool at 6084 INR/MWh for their over drawls.

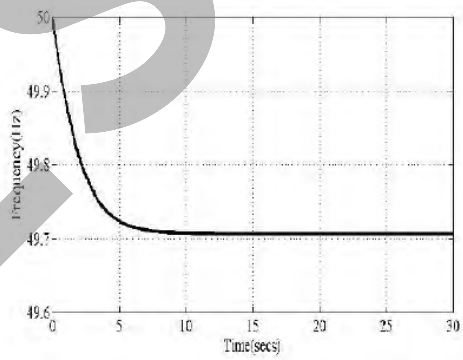
Case C:

Generally, a system operator is responsible for the procurement of all ancillary services. It is assumed that some of Gencos are participating in an ancillary service market. If the frequency of grid falls due to increase in the load in any area, ISO procures the quantity of power from Gencos, which are participating in frequency regulation and these Gencos will increase their generation and vice versa, if frequency of the grid increases.

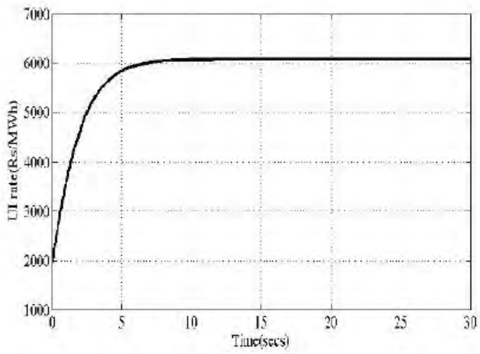
The power producers submit their bids of regulating reserves to the System Operator (with 10-15 minutes) through a secure network service. It is assumed that some of the Gencos' are not participating in ancillary service market. These regulation bids can be arranged by SO in ascending order by specified time period. Demand bids from areas are arranged in descending order of price. Then Matching of these bids determines the Ancillary service market Clearing Price (ASMCP) by considering the highest priced offer to intersect with the lowest priced bid of demand requirement. Then the sorted regulating reserves with the demanded load from are used to provide control decision. The clearing quantities are checked and resorted according the congestion condition and available capacity. The matching of ancillary service market participants bid is illustrated in Fig.5. The Ancillary service Market clearing price (ASMCP) is 4800 Rs/MWh. From this figure, it can be observed that pricing of ancillary service is less than UI rate. The UI price paid by areas at a particular period to the UI pool is around 6084 Rs/MWh. This price is higher than MCP of 4800 Rs/MWh in the day ahead market.

Case D:

In this part, hourly frequency linked UI rate is estimated and compared with market clearing price. For estimation of frequency and corresponding UI price for



(a) Frequency



(b) UI price

Fig. 4: Response of the system in each hour

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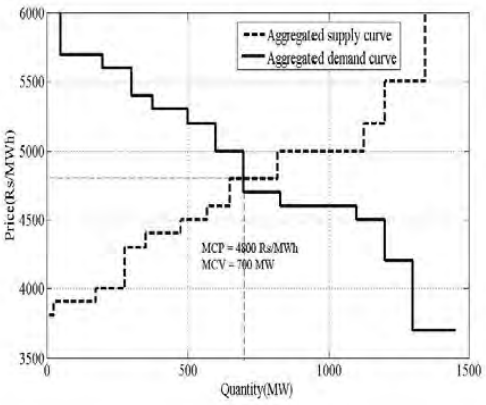

Fig. 5: Aggregated supply and demand curve

each hour, hourly load data is used. The daily load curve of Indian Utility 62 bus system is shown in Fig.6. For each hourly load, Surplus/deficit amount of electricity can be determined from its generation availability and demand requirement. The frequency estimated at each hour for a particular day by simulating test system with load changes. The fall in frequency translates into rise in UI price through UI mechanism. Then under ABT, frequency dependent UI price at each hour is assessed. Fig.7 shows frequency and UI rate curves for each hour. From this figure, it can be seen that if the frequency is low, UI rate will be high and vice versa. In this scenario, UI mechanism offers any generator with surplus generation an opportunity to provide for ancillary services. For each hour, Ancillary service market clearing price is also calculated. Fig.8 shows UI price and MCP for each trading period. From this, it can be observed that most of the hour market clearing price is less than UI price. In such situation, system operators must achieve a reliable equilibrium between power production and consumption and aiming at higher quality and efficiency levels.

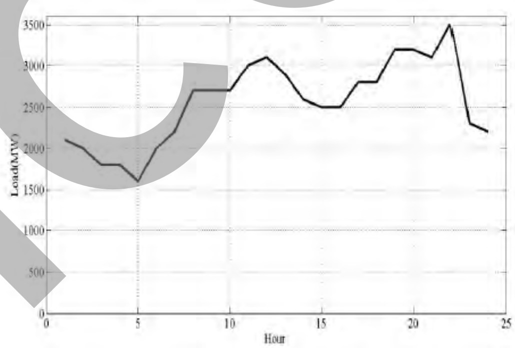

Fig. 6: daily load curve

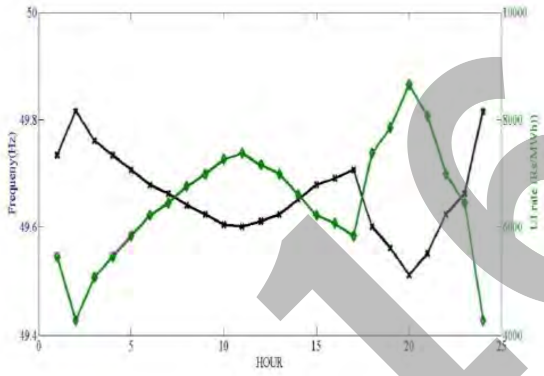

Fig. 7: change in system frequency and ui price

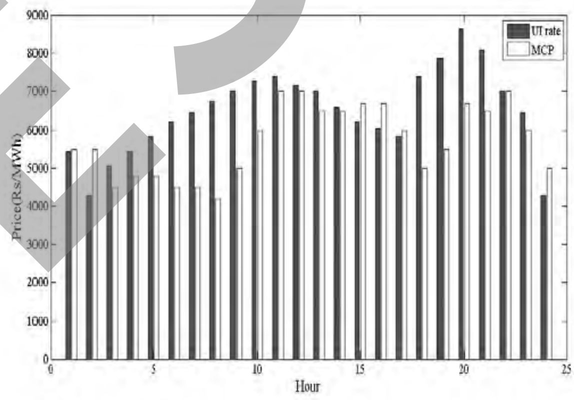

Fig. 8: UI rate and MCP at each trading period

IX. Conclusion

In this paper, sequential approach market model is proposed to determine the clearing price for energy and frequency regulation ancillary service. The model considers generation and transmission line constraints. Indian practical utility system has been simulated to evolve frequency deviations against overloads. An at-tempt has been made in this paper to develop price structure for the frequency-regulated ancillary systems. This paper presents a deterministic approach for solving the energy and ancillary services. The proposed method is demonstrated on Indian Utility 62 bus system.

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