MODEL MATCHING CONTROL OF TWO-AREA LFC

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Abstract— **Deregulation is the collection of restructured rules and economic incentives that governments set up to control and drive the electric power industry. There are crucial differences between the AGC operation in a vertically integrated industry and horizontally integrated industry. A reduced-order controller has been proposed to solve the automatic generation control problem in a deregulated power system that operates under deregulation based on the bilateral policy scheme. In the real world environment, access to all of the state variables of system is limited and measuring all of them is also impossible. So when we have fewer sensors available than the number of states or it may be undesirable, expensive, or impossible to directly measure all of the states, using a reduced-order controller was used. In this paper a new controller has been proposed to overcome the above difficulty. The proposed strategy has been tested on a two-area reheat thermal-hydro power system under De-Regulated environment and the results was compared with the optimal full-state feedback method in matlab/simulink environment. The results are shows that the proposed method improves the dynamic response of system and provides a control system that satisfied the load frequency control requirements.**

Keywords— *De-regulated power systems, GENCOs, DISCOs, LFC and model matching controller.*

I. Introduction:

The AGC regulator design techniques using modern optimal control theory enable the power engineers to design an optimal control system with respect to given performance criterion. Fosha and Elgerd [4] were the first to present their pioneering work on optimal AGC regulator design using this concept. Fosha and Elgerd [5] records the development of a state variable model of the megawatt-frequency control problem of multiarea electric energy systems. The model is in a mathematical form necessary for application of theorems of modem optimal control theory.

J. Nanda and M. L. Kothari [6] *et al.* highlights the design of automatic generation controllers through optimal control strategy, for an interconnected hydrothermal system using a new performance index that circumvents the need for a load demand estimator. The performance of the new optimal controller is found to be much superior to the one based on the conventional optimal control strategy used by Fosha and Elgerd.

The use of a new performance index for the design of an optimal controller reveals that the thermal area generation rate can be contained to safe permissible limits, by heavily penalizing the rate of change of thermal area generation and opening and closing of the thermal area valves. Moreover, the new controller also exhibits an improved performance of the hydro area in the regulation process.

Christie and Bose [7] have dealt with LFC (Load Frequency Control) issues in deregulated power system. It identifies the technical issues associated with load frequency control and also identifies technical solutions such as standards and algorithms, needed for the operation in this new restructured power system. The paper discusses the possible structures such as 'Free', 'Charged' and 'Bilateral' LFCs for providing real power control in deregulated environment. A comprehensive study on simulation and optimization in an AGC system after deregulation has been carried out by Donde and Pai [8]. The concept of DISCO participation matrix to simulate these bilateral contracts is introduced and reflected in the two-area block diagram. Trajectory sensitivities are used to obtain optimal parameters of the system using a gradient Newton algorithm.

A model of the interconnected power systems of Norway and Sweden is used by Bakken and Grande[9] to show how introduction of AGC might aid the system operator in handling the increased strain. However, the classical LFC based on the *Area Control Error* is difficult to implement in a deregulated environment. An alternative concept is thus introduced where selected units are automatically following load changes on the HVDC connections. This *rump following controller (RFC)* supported by manual control seems to be a promising option.

Manoranjan Parida, J. Nanda [10] deals with application of automatic generation control (AGC) to deregulated power system and makes a maiden attempt to provide a new practical AGC model to cater to the needs of a modern restructured hydrothermal power system. Several DISCO Participation Matrix (DPM) and Area Participation Factor (APF) have been tried out and dynamic responses for frequency, tie flow and generations are obtained to examine the performance of the system in deregulated environment considering integral controllers. The sensitivity of the optimal controller gains to DPM and APF has also been brought out.

For the first time, studies have been carried out for the selection of suitable values for governor speed regulation parameter R for the hydro and thermal plants in the deregulated mode. System studies reveal the satisfactory operation of the hydro-thermal system conforming to the requirements in the deregulated environment.

A. Demiroren, H.L. Zeynelgil [12] proposed a genetic algorithm (GA), which is used for optimization of integral gains and bias factors, is applied to automatic generation control (AGC) in three-area power system after deregulation. The conventional three-area AGC system is modified to take into account the effect of bilateral contracts on the dynamics. In the considered power system, each area contains two GENCOs; GENCOs at the first and the second areas include steam turbines and GENCOs at the third area include hydro turbines as generating units. This type of GA is chosen since the computational time is saved using this algorithm and it is more sensitive than simple GA.

In the practical environment, access to all of the state variables of system is limited and measuring all of them is also impossible. To solve this problem, the optimal output feedback method is proposed by Javad Sadeh, Elyas Rakhshani [13]. In the output feedback method only the measurable state variables within each control area is required to use for feedback. The optimal control law is determined by minimizing a performance index under the output feedback conditions leading to a coupled matrix equation. The proposed method is tested on a two area power system with different contracted scenarios. The results of the proposed controller are compared with the full-state feedback method. The results are shown that when the power demands changed, the output feedback method have a good ability to tracking of contracted and/or non-contracted demands.

II.   Modeling of AGC

Under the deregulated environments, the AGC is required to be innovated to be adapted to the competitive market systems with several types of the bidding strategies such as daily, hourly and adjustment bidding. The conventional AGC schemes adopt the algorithms to attain optimal generation allocation to the generator units. However, under deregulation, AGC is allowed to control the contract powers of IPPs rather than the outputs of generation units. If the power pool has some generator units to directly control, the AGC should control the outputs of those generator units. All IPPs participate in the electricity power bidding with providing unit prices or the incremental cost curves. Here, it should be noted that each IPP may have locally distributed generation stations.   This makes the bidding system complicate due to different penalty factors of generation units owned by an IPP.The AGC is mostly related to the adjustment bidding based on the market competition by the incremental cost curve or λ-curve.   The λ -curve may be an actual incremental cost curve as a *curve* arbitrarily designed by the IPP-side market manager for the market competition.

On the other hand, each IPP should have its own AGC to optimally allocate the contract power determined by the bidding system to the generator units under its control. The EMS may not cover the IPP-side AGC. However, the ACE can be actually corrected by the IPP-side AGC. Consequently, the central AGC should have a function to supervise the IPP-side AGC in order to check the mismatch between the actual generation and the contract power, frequency droop control, spinning reserve, etc.

In the restructured environment, GENCOs sell power to various DISCOs at competitive prices.   Thus, DISCOs have the liberty to choose the GENCOs for contracts. They may or may nothave contracts with the GENCOs in their own area. This makes various combinations of GENCO-DISCO contracts possible in practice. We introduce the concept of a "DISCO participationmatrix" (DPM) to make the visualization of contracts easier. DPM is a matrix with the number of rows equal to the number of GENCOs and the number of columns equal to the number of DISCOs in the system.

Each entry in this matrix can be thought of as a fraction of a total load contracted by a DISCO (column) toward a GENCO (row). Thus, the $i\,j$ th entry corresponds to the fraction of the total load power contracted by a DISCO 'j' from a GENCO 'i' . The sum of all the entries in a column in this matrix is unity. DPM shows the participation of a DISCO in a contract with a GENCO; hence the name "DISCO participation matrix." Consider a two-area system in which each area has one GENCO and two DISCOs in it. Let $GENCO_1$, $DISCO_1$, and $DISCO_2$ be in area I and $GENCO_2,DISCO_3$, and $DISCO_4$ be in area II as shown in Fig. 1.
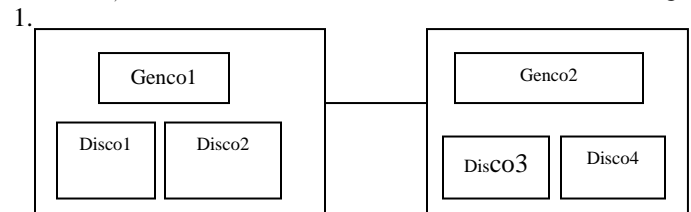

Fig. 1. Schematic of two area systems under De-regulation.

The corresponding DPM will become

$$\text{DPM}=\begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \end{bmatrix} \qquad (1)$$

Where *cpf* refers to "contract participation factor." and is like signals, that carry information as to which GENCO has to follow load demand by which DISCO.

Suppose that DISCO1 demands 0.1 pu MW power, out of which 0.8 pu MW is demanded from GENCO1, 0.2 pu MW from GENCO2,   Then column 1 entries in (1) are easily defined as

$$cpf_{11} = \frac{0.08}{0.1} = 0.8 \qquad\qquad cpf_{21} = \frac{0.02}{0.1} = 0.2$$

Other *cpf*s are defined similarly to obtain the entire DPM. It is noted that $\sum_i cpf_{ij} = 1$. The block diagonals of DPM correspond to local demands. Off diagonal blocks correspond to the demands of the DISCOs in one area to the GENCOs in another area. Whenever a load demanded by a DISCO changes, it is reflected as a local load in the area to which this DISCO belongs. This corresponds to the local loads ΔP_{L1} and ΔP_{L2} and should be reflected in the deregulated AGC system block diagram at the point of input to the power system block. As there are many GENCOs in each area, ACE signal has to be distributed among them in proportion to their participation in the AGC. Coefficients that distribute ACE to several GENCOs are termed as "ACE participation factors" (*apfs*). Note that $\sum_{j=1}^{m} apf_j = 1$ where *m* is the number of GENCOs. Unlike in the traditional AGC system, a DISCO asks/demands a *particular* GENCO or GENCOs for load power. These demands must be reflected in the dynamics of the system. Turbine and governor units must respond to this power demand. Thus, as a particular set of GENCOs are supposed to follow the load demanded by a DISCO, information signals must flow from a DISCO to a particular GENCO specifying corresponding demands. Here, we introduce the information signals which were absent in the traditional scenario.

III. **Modeling of Model Matching Controller.**

The main object of model matching is to select a suitable controller so that the transfer function of the closed loop system *can* approximate to one of a pre-specified reference model. It is known that perfect model matching is achievable only when the numerator of the given model contains all the unstable parts of the numerator of the plant. If the perfect model matching condition is not satisfied, the imperfect model matching case results. In the imperfect model matching case, one often tries to search for an approximate solution. This drawback will be overcome by the optimization approach presented here. Consider the perfect model matching control system with external disturbance *u(s),* shown in Fig.4.3. The plant being controlled is described by

$$\frac{y(s)}{u(s)} = \frac{B(s)}{A(s)} \qquad (1)$$

Where *u(s)* is the control input and *y(s)* is the output. It is assumed that *A(s)* and *B(s)* are coprime polynomials with

$$\deg(A(s)) \geq \deg(B(s)) \qquad (2)$$

The controller, composed of two inputs and one output, is expressed as

$$P(s)u(s) = -Q(s)y(s) + R(s)r(s) \qquad (3)$$

Where *P(s), Q(s),* and *R(s)* are design parameters to be determined such that the closed loop is stable and the transfer function from the command input *r(s)* to the output *y(s)* is equal to the prespecified stable model

$$M(s) = \frac{G(s)}{F(s)} \qquad (4)$$

This perfect model matching controller (4.17) could be thought of as a combination of feedback having the transfer function $Q(s)/P(s)$ and a feed forward with the transfer function $R(s)/P(s)$. It follows from (4.15) and (4.17) that the closed-loop transfer function relating *y(s)* to *r(s)* is given by

$$H(s) = \frac{y(s)}{r(s)} = \frac{B(s)R(s)}{A(s)P(s)+B(s)Q(s)} \qquad (5)$$

To achieve perfect model matching control, the closed-loop transfer function *H(s)* should equal *M(s),* that is,

$$\frac{B(s)R(s)}{A(s)P(s)+B(s)Q(s)} = \frac{G(s)}{F(s)} \qquad (6)$$
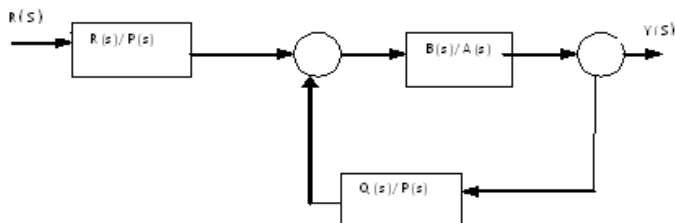

Fig. 2. Schematic of Model matching Controller.

Pade type approximation techniques have been widely used in the area of reduced order modeling. In the area of reduced order modeling, the objective is to find a reduced model R(s) that approximates a stable high order system G(s). The Pade approximation technique matches two sets of parameters called the time moments Ti and Markov parameters Mi, of G(s) with the corresponding parameters of R(s).

Time Moments

An irreducible rational function G(s) can be expanded as:

$$G(s) = \int_0^\infty (g(t)e^{-st})\, dt \qquad (7)$$

$$G(s) = \int_0^\infty (g(t)e^{-st})\, dt$$
$$- s \int_0^\infty tg(t)dt \qquad (8)$$
$$+ s^2 \int_0^\infty \frac{t^2}{2!} g(t)dt$$

Where g(t) is the impulse response of G(s).
Expanding G(s) into its power series expansion,

$$G(s) = c_0 + c_1 s + c_2 s^2 + \cdots = \sum_{i=0}^{\infty} c_i s^i \qquad (9)$$

From (4.4) the expression for the ith derivative of G(s) evaluated at s=0 as

$$\left\{ \frac{d^i}{ds^i} G(s) \right\}\Big|_{s=0} = (-1)^i \int_0^\infty t^i g(t)dt \qquad (10)$$
$$\triangleq (-1)^i T_i$$

Where T_i is defined as the ith Time Moment (TM) of G(s). it may be shown that

$$c_i = \frac{1}{i!} \frac{d^i}{ds^i} G(s) \Big|_{s=0} = \frac{(-1)^i}{i!} T_i \qquad (11)$$

c_i may be thus called the proportional Time Moment of G(s). for the state space triple (A,B,C). it may be shown that :

$$T_i = (-1)^i C A^{-(i+1)} B; \qquad i = 1,2,\ldots\infty \qquad (12)$$

Approximate Generalized Time Moments

Let K(s) be the high order controller transfer function obtained by the Synthesis equation. The time moments T_i; i=0,1,2, … , ∞ of K(s) are defined as

$$T_i = (-1)^i \frac{d^i}{ds^i} K(s) \Big|_{s=0} \qquad (13)$$

T_i are proportional to c_i where:

$$K(s) = \sum_{i=0}^{\infty} c_i \, s^i \qquad (14)$$

In the Classical Pade Approximate (CPA) technique, the reduced order transfer function equivalent of K(s) is chosen as

$$C(s) = \frac{b_m s^m + b_{m-1} s^{m-1} + \cdots + b_1 s + b_0}{s^n + a_{n-1} s^{n-1} + \cdots + a_1 s + a_0} ; \qquad (15)$$
$$n > m$$

Where n and m are the chosen orders of the denominator and numerator respectively. The denominator is assumed to be a monic polynomial. $a_i, i = 0,1,2 \ldots (n-1)$ and $b_i, i = 0,1,2 \ldots, m$ are the unknown parameter which are to be determined.

C(s) is chosen such that its power series expansion coefficients η_i

$$C(s) = \sum_{i=0}^{\infty} \eta s^i \qquad (16)$$

Coincide with the corresponding coefficients c_i of K(s), i=0,1,2,…,$(n_e - 1)$, where n_e is the number of expansion points. n_e has to be chosen depending on the number of unknown parameters of the controller as well as on the type of the expansion points (real or complex).

From (13), and (114) and (16), the CPA technique is mathematically equivalent to:

$$T_i \left\{ \frac{d^i}{ds^i} (K(s)) \right\} \Big|_{s=0} = \left\{ \frac{d^i}{ds^i} (C(s)) \right\} \Big|_{s=0} ; \qquad (17)$$
$$i \in [1, n_e]$$

This finally gives,

$$K(\delta_i) = C(\delta_i), \qquad i \in [1, n_e] \qquad (18)$$

Where δ_i are suitable non-zero general numbers (frequency) which are termed as expansion points and n_e is the number of expansion points taken.

Let n_e be distinct values of $t_1, t_2, \ldots, t_{n_e}$ such that ti is equivalent to $K(\delta_i); i \in [1, n_e]$, ti are ten defined as the *Approximate Generalized Time Moments* (AGTM), generalized because the relations in (4.20) are similar to the power expansions of K(s), C(s) about a non-zero general points δ_i and approximate because the exact differential operations $\frac{d^i}{ds^i} (K(s)) \Big|_{s=0}$ are replaced by the divided difference approximations, details of which are described in following section.

IV. **Simulation Results:**

A two area hydro-thermal system is considered to illustrate the behavior of the proposed AGC scheme for deregulated environment. In this section, the proposed model matching controller is applied to a two-area reheat thermal system. The comparison with the conventional PI controllers are given firstly in case 1. The effect of DPM is provided in case 2. The sampling time in simulink is set to be 40s, and step time is set to be 0.01s. Demand load change $\Delta L1$ and $\Delta L2$ are both chosen to be 0.01 p.u.

4.1 Scenario I: Without Deregulation

In this scenario simulations are performed for the two area reheat thermal-hydro system without any deregulation. Fig. 3.1. shows simulink model of a conventional AGC simulator for the two area hydrothermal system under traditional environment i.e. under regulated environment.
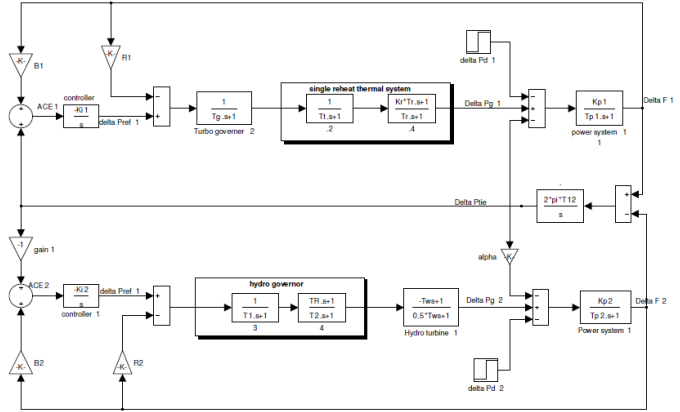

Fig.3 Simulink model of two area with I-controller without De-regulation.

In the above figure integral controllers are used to maintain the frequency of the generators to be constant. It's also called as conventional tie-line bias control.
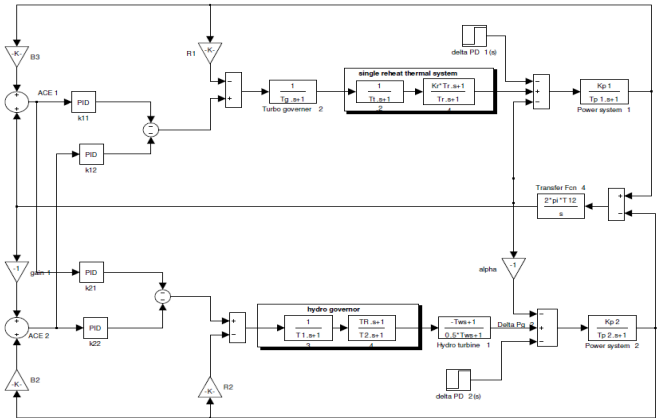

Fig.4.2 Simulink model of two area hydro thermal systems PI controller using Model Matching Controller without Deregulation.

From the proposed method model matching controller is designed for two area hydro thermal system as shown in Fig.5.2. The controller matrix K(s) is given by (4.49). The first step was the design of the model matching controller K(s), and the next step was to design the LQR controller with prescribed degree of stability for more improvement in dynamical responses. By using PSO the optimum values for the controller gains are obtained.

The obtained best value of the expansion point for $S_k = a_k + j b_k$ is as follows $S_k = -0.0519 - 0.2268i$ and the lower order model matching controller (PI) values are obtained as

79

$$K_{pi} = \begin{bmatrix} K_{p11} \\ K_{p12} \\ K_{p13} \\ K_{p14} \end{bmatrix} = \begin{bmatrix} 1.2410 \\ 1.2918 \\ -1.3030 \\ 1.1793 \end{bmatrix}$$

$$K_{ii} = \begin{bmatrix} K_{i11} \\ K_{i12} \\ K_{i13} \\ K_{i14} \end{bmatrix} = \begin{bmatrix} 0.5194 \\ 0.4730 \\ -0.3737 \\ 0.3355 \end{bmatrix}$$

Using the proposed method, the frequency deviation of each area and the tie-line power have a good dynamic response in comparing with initial system without controller. The results are shown in the following figures.
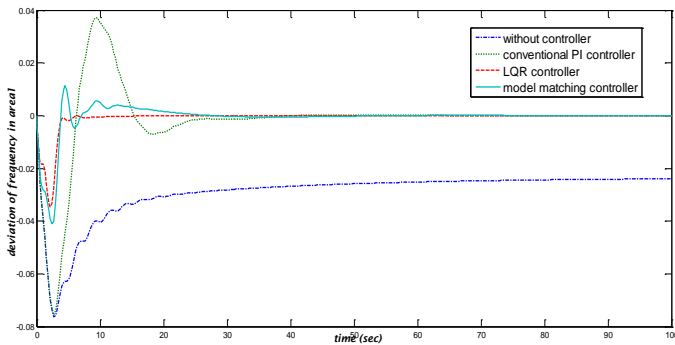
Fig.4.3 Comparison of frequency deviation in area1 without deregulation.
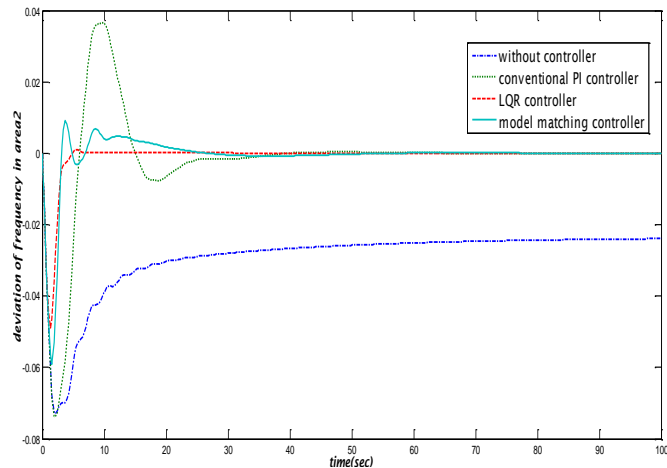
Fig.4.4 Comparison of frequency deviation in area2 without deregulation.
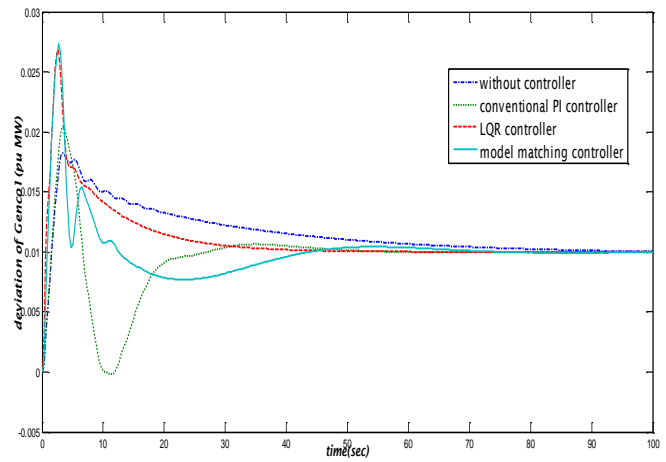

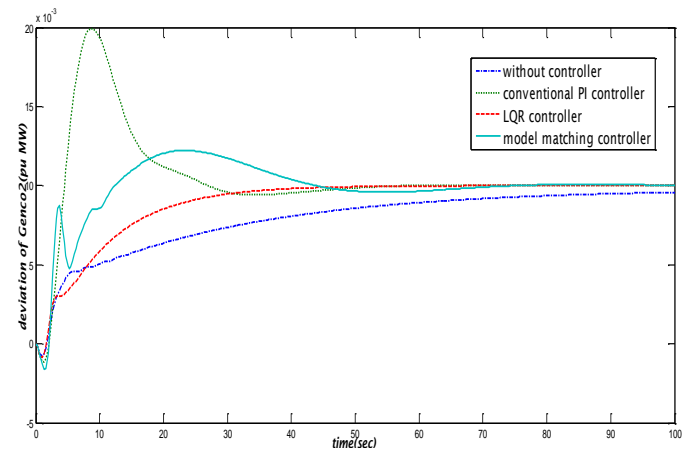Fig.4.5 Comparison of generated power deviation of Genco1 without deregulation.

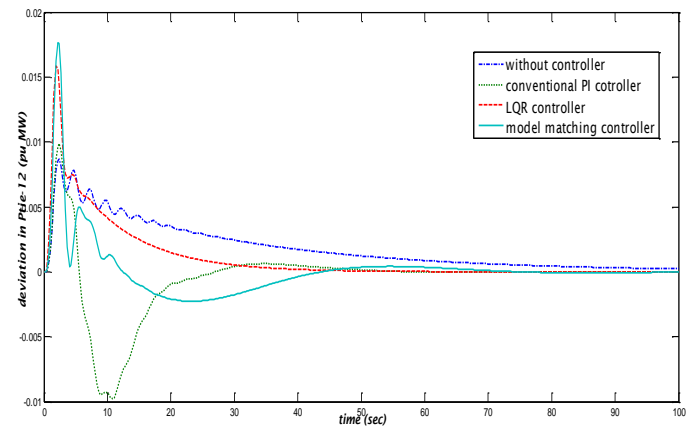Fig.4.6 Comparison of generated power deviation of Genco2 without deregulation.

Fig.4.7 Comparison of tie-line power deviation without deregulation.

4.2 Scenario II : **Under Deregulated Environment**

Area I comprises a reheat thermal system with one GENCO and Area2 comprising a hydro system with one GENCO. Figure 1.1 shows the new transfer function AGC model with single stage reheat turbine in thermal area and electric governor in hydro area are considered for deregulated environment. Areal has two DISCOs and Area2 has two DISCOs. A bias setting of $B_i = \beta_i$, is considered for both hydro and thermal areas.

Transactions based on free contracts:

Consider a case where all the DISCOs contract with the GENCOs for power as per the follows

$$\text{DPM} = \begin{bmatrix} 0.8 & 0.75 & 0 & 0.3 \\ 0.2 & 0.25 & 1 & 0.7 \end{bmatrix} \qquad (4.1)$$

It is assumed that each DISCO demands 0.1 pu MW power from GENCOs as defined by *cpfs* in DPM matrix and each GENCO participates in AGC as defined by *apfs*.
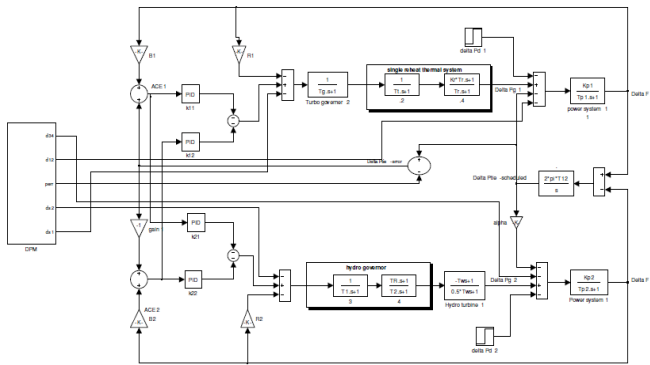

Fig. 4.8 Simulink model of two area hydro thermal system with PI controller using model matching method under deregulated environment.

The off diagonal blocks of the DPM correspond to the contract of a DISCO in one area with a GENCO in another area. The scheduled power on the tie line in the direction from area I to area II is

$$\Delta P_{tie1-2,scheduled} = \sum_{i=1}^{2} \sum_{j=3}^{4} cpf_{ij} \Delta P_{Lj} - \sum_{i=3}^{4} \sum_{j=1}^{2} cpf_{ij} \Delta P_{Lj} \dots\dots 4.2$$

Hence, $\Delta P_{tie1-2,scheduled}$ = -0.05 pu MW. Fig. 5.13 shows the actual power on the tie line. It is to be observed that it settles to 0.05 pu MW, which is the scheduled power on the tie line in the steady state. In the steady state, generation of a GENCO must match the demand of the DISCOs in contract with it. This desired generation of a GENCO in pu MW can be expressed in terms of *cpfs* and the total demand of DISCOs as

$$\Delta P_{mi} = \sum_{j} cpf_{ij} \Delta P_{Lj}$$

Where ΔP_{Lj} is the total demand of DISCO *j* and *cpfs* are given by DPM. In the two-area case,

$$\Delta P_{mi} = cpf_{i1} \Delta P_{L1} + cpf_{i2} \Delta P_{L2} + cpf_{i3} \Delta P_{L3} + cpf_{i4} \Delta P_{L4}$$

For the case under consideration, we have

$$\Delta P_{m1} = 0.8 \times \Delta P_{L1} + 0.75 \times \Delta P_{L2} + 0.3 \times \Delta P_{L4} = 0.185 \, pu \, MW$$

and similarly $\Delta P_{m1} = 0.215 \, pu \, MW$

As Fig. 3(c) shows, the actual generated powers of the GENCOs reach the desired values in the steady state.

The best value of the expansion point for $S_k = a_k + jb_k$ is obtained as

$S_k =$ -0.0206 - 0.3798i ,And the lower order model matching controller (PI) values are obtained as

$$K_{pi} = \begin{bmatrix} K_{p11} \\ K_{p12} \\ K_{p13} \\ K_{p14} \end{bmatrix} = \begin{bmatrix} 1.5170 \\ 0.8831 \\ -0.4942 \\ 0.5257 \end{bmatrix}$$

$$K_{ii} = \begin{bmatrix} K_{i11} \\ K_{i12} \\ K_{i13} \\ K_{i14} \end{bmatrix} = \begin{bmatrix} 0.5619 \\ 0.6095 \\ -0.4510 \\ 0.4126 \end{bmatrix}$$

Fig. 4.9-4.14 shows the results of this load change: area frequency deviations, actual power flow on the tie line (in a direction from area I to area II).
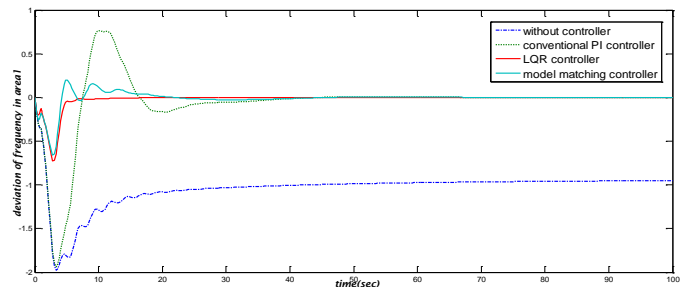

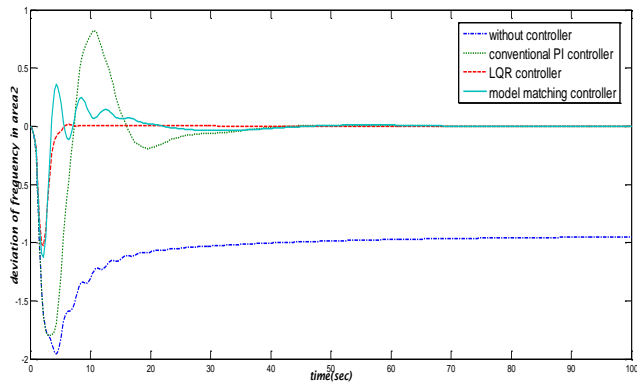Fig.4.9 Comparison of frequency deviation in area I under deregulated environment.

Fig.4.10 Comparison of frequency deviation in area II under deregulated environment.
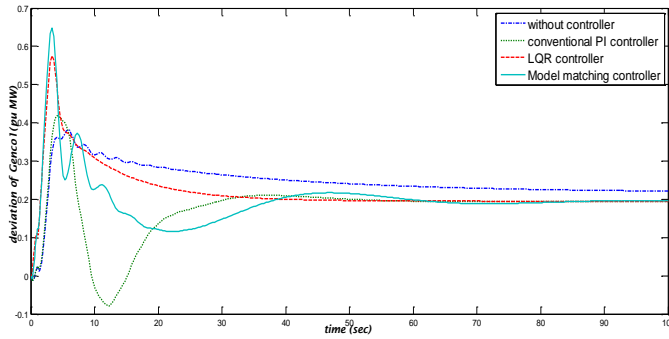

Fig4.11Comparison of generated power deviation of Genco1(thermal unit) under deregulated environment.
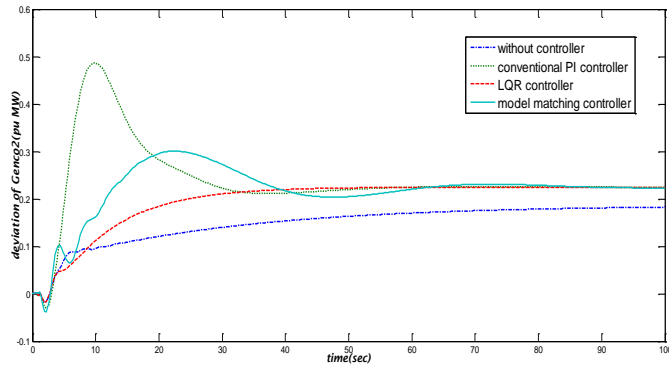

Fig.4.12 Comparison of generated power deviation of Genco2 (hydal unit) under deregulated environment.
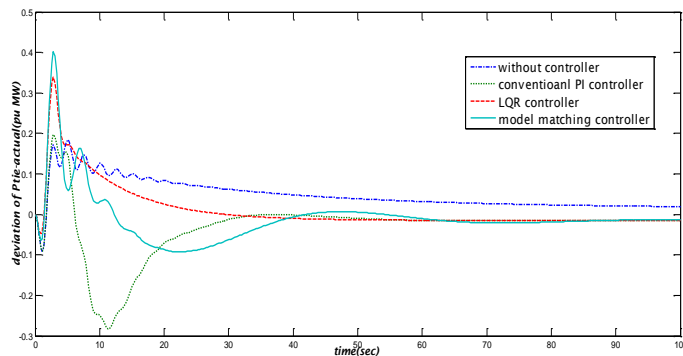

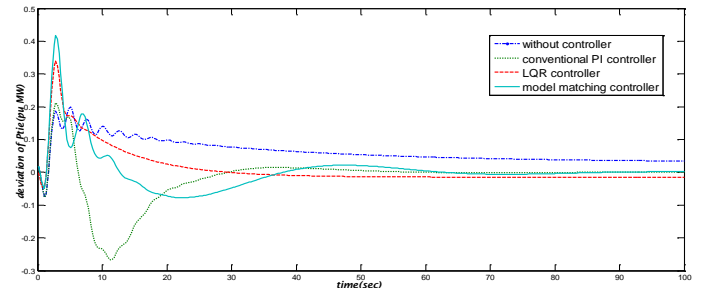Fig.4.13 Comparison of Actual tie-line (P$_{tie-actual}$) power deviation under deregulated environment.

Fig.4.14 Comparison of tie-line power deviation under deregulated environment.

V.   CONCLUSION

An attempt has been made for the first time to apply a model matching control method to optimize effectively several important parameters such as K$_{pi}$, K$_{Ii}$ for AGC of a two area reheat hydrothermal system under deregulated environment.   Results reveal that the controller using model matching method performs much better than conventional PI controller.

This work is presented and discussed Automatic Generation Control(AGC) before and after deregulation. The modified AGC scheme includes the contract data and measurements, which are continuous, regular and quiescent and hence, greatly improves control signals to unit dispatch and controllers. The proposed simulator is generic enough to simulate all possible types of load following contracts .

The simulation results show that the proposed model matching controller performance is comparable with the LQR. In a practical environment some of the state variable in AGC system such as output of governors, ACE or integration of ACE, are not measurable. Because of this, a reduced order controller design using model matching method is proposed for the purpose which works with only output feedback. And uses of this method reduce the peak deviations of frequencies, tie-line power, time error and inadvertent interchange.   It can be concluded that the application of model matching controller to AGC of interconnected power system will be provided a practical viewpoint compared to LQR design.

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82

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