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Deregulated AGC scheme using Dynamic Programming Controller

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Abstract

Action Dependent Heuristic Dynamic Programming (ADHDP) optimal controller for multi area Automatic Generation Control (AGC) scheme has been designed in this paper. A competitive environment has been considered in the interconnected power system. Conventional AGC model has been modified to include bilateral transactions taking place in energy market. The modified AGC model has been discretized to implement ADHDP. ADHDP is a powerful technique of Approximate Dynamic Programming, used for providing optimal solution by minimizing the given objective function. The proposed approach has been tested on two area AGC scheme for different cases. The results have been compared with the discrete full state feedback controller.

***Keywords**: Automatic generation control; bilateral contracts; deregulation; optimization; power system control.*

1. Introduction

A balance between power generation and load demand is necessary for successful operation of a power system. Any mismatch between generation and demand causes the deviations of frequency and net power exchange. AGC plays a key role in power system design/operation [1]. It is used to regains equilibrium between demand and generation on a load demand perturbation and maintains scheduled frequency and tie-line exchange [2-3]. Researchers discussed deregulated AGC in [4-7]. Deregulation is a process for improving efficiency in the operation of power system. In deregulated scenario generation, transmission and distribution works separately and comes under Genco (generation company), Disco (distribution company) and Transco (transmission company) and system operator (SO). In deregulated structure, a Disco can contract with a Genco for power transaction. The Disco-Genco contracts can be visualized using Disco participation matrix (DPM) [8].

A numbers of different approaches such as optimal, fuzzy and many more have been used to design a controller for AGC scheme [9-11]. One major drawback with state feedback approach is static feedback gain matrix. In ADHDP approach gain matrix is updated every time and gives optimal performance by minimizing the given objective function. The discrete model of the system has been used to design the controller. First, a quality function has been defined. Than this function has been optimized to determine the full state feedback gains. The designed controller has been successfully tested on a two area power system. The results obtained by ADHDP approach has been compared with the discrete state feedback controller.

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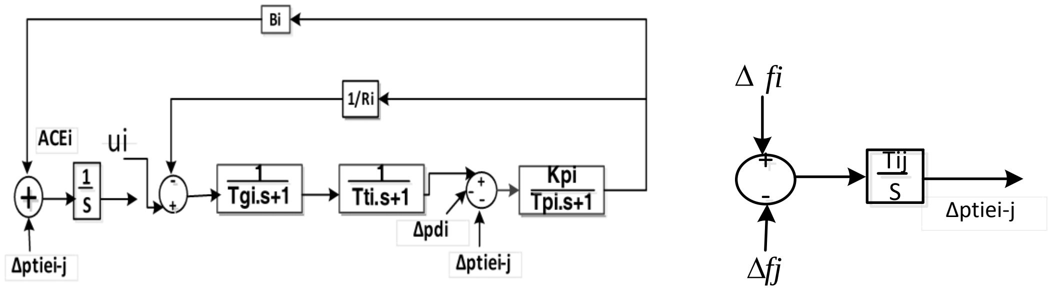
2. System Modeling

The block diagram of two area AGC scheme is shown in Figure 1.



(a) (b)

Figure 1. (a) Block Diagram of i^th Control Area. (b) Tie- Line Power

Followings are the different variables considered to model the system.

- State variables

$x_1 = \Delta f_1$, $x_2 = \Delta Pt_1$, $x_3 = \Delta Pg_1$, $x_4 = \Delta f_2$, $x_5 = \Delta Pt_2$ $x_6 = \Delta Pg_2$, $x_7 = \Delta Ptie_{(1,2)}$, $x_8 = \int ACE_1 dt$ $x_9 = \int ACE_2 dt$

- Control inputs: u_1 and u_2
- Disturbance inputs: $d_1 = \Delta Pd_1$ and $d_2 = \Delta Pd_2$

The state space representation of the considered two area interconnected power system can be written as,

$$\dot{x} = A_c x(t) + B_c u(t) + F_c d(t) \tag{1}$$

- State matrix A_c, control matrix B_c, and disturbance matrix F_c

$$A_c = \begin{bmatrix} -\frac{1}{Tp_1} & \frac{Kp_1}{Tp_1} & 0 & 0 & 0 & 0 & -\frac{Kp_1}{Tp_1} & 0 & 0 \\ 0 & -\frac{1}{Tt_1} & \frac{1}{Tt_1} & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{R_1 Tg_1} & 0 & -\frac{1}{Tg_1} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{Tp_2} & \frac{Kp_2}{Tp_2} & 0 & \frac{Kp_2}{Tp_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{Tt_2} & \frac{1}{Tt_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{R_2 Tg_2} & 0 & -\frac{1}{Tg_2} & 0 & 0 & 0 \\ 2\pi T^0 & 0 & 0 & -2\pi T^0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & B_2 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

$$B_c = \begin{bmatrix} 0 & 0 & \frac{1}{Tg_1} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{Tg_2} & 0 & 0 & 0 \end{bmatrix}^T$$

$$F_c = \begin{bmatrix} -\frac{Kp_1}{Tp_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{Kp_2}{Tp_2} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

This interconnected AGC scheme shown in Figure 1 is modified to deregulated AGC. In deregulated AGC scheme, tie-line power changes as per the demand of Discos and can be written as,

$$\Delta Ptiei_{\_schdule} = \Delta Ptie_i + \sum_{\substack{j=1 \\ i \neq j}}^{m} Dij - \sum_{\substack{j=1 \\ j \neq i}}^{m} Dji \tag{2}$$

where, Dij and Dji show the demand of Discos in *area-j* and *area-i* from Genco in *area-i*, and *area-j*. The mismatch between actual and scheduled tie-line exchange is known as tie-line power error,

$$\Delta Ptie_{i\_Error} = \Delta Ptie_{i\_Actual} - \Delta Ptie_{i\_Schdule} \tag{3}$$

Deviation in frequency and tie-line power error form ACE, which can be represented as

$$ACE_i = B_i \Delta f_i + \Delta Ptie_{i\_Error} \tag{4}$$

Deregulated AGC scheme of i^th area power system is shown in Figure 2. The mathematical modeling of AGC scheme in deregulated scenario is given as follows:

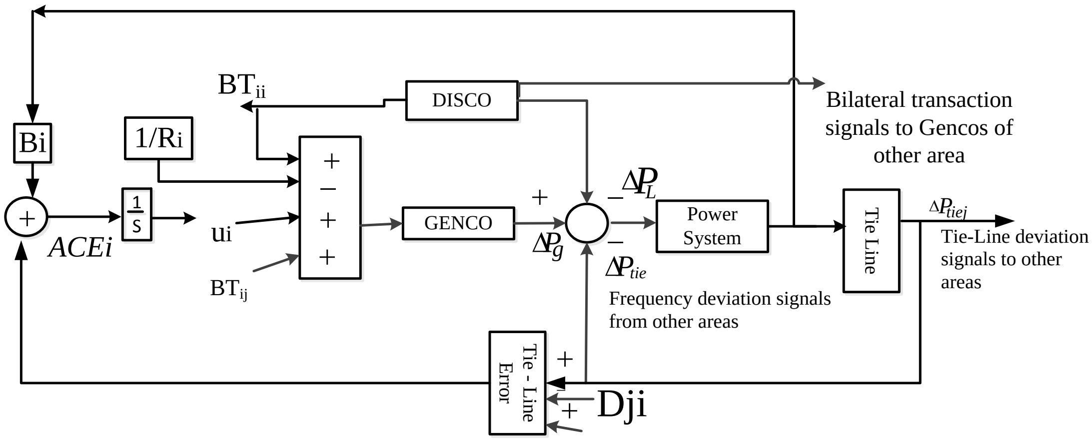


Figure 2. AGC Scheme of i^th area in Deregulated Scenario

- The state variables for the considered model of the system are

$$x = \left[\Delta w_1 \quad \Delta w_2 \quad \Delta P_{GV1} \quad \Delta P_{GV2} \quad \Delta P_{GV3} \quad \Delta P_{GV4} \quad \Delta P_{M1} \quad \Delta P_{M2} \quad \Delta P_{M3} \quad \Delta P_{M4} \quad \int ACE_1 dt \quad \int ACE_2 dt \quad \Delta P_{tie1-2}\right]$$

- Power demands vector: $P_L = [\Delta P_{L1} \quad \Delta P_{L2} \quad \Delta P_{L3} \quad \Delta P_{L4}]^T$,
- Control inputs: $u = [u_1 \quad u_2 \quad u_3 \quad u_4]^T$
- Uncontracted demands vector: $P_{uc} = [\Delta P_{uc1} \quad \Delta P_{uc2} \quad \Delta P_{uc3} \quad \Delta P_{uc4}]^T$

The state space characterization of the closed loop system shown in Figure 2 is,

$$\dot{x} = Ax + Bu + FP_L + \Gamma P_{UC} \tag{5}$$

The state matrix A, control matrix B and disturbances matrices F and Γ has the structure given below.

$$A=\begin{bmatrix}
-\frac{1}{T_{P1}} & 0 & \frac{K_{P1}}{T_{P1}} & \frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{K_{P1}}{T_{P1}} \\
0 & -\frac{1}{T_{P2}} & 0 & 0 & \frac{K_{P2}}{T_{P2}} & \frac{K_{P2}}{T_{P2}} & 0 & 0 & 0 & 0 & 0 & 0 & -a_{12}\frac{K_{P2}}{T_{P2}} \\
0 & 0 & -\frac{1}{T_{T1}} & 0 & 0 & 0 & \frac{1}{T_{T1}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\frac{1}{T_{T2}} & 0 & 0 & 0 & \frac{1}{T_{T2}} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -\frac{1}{T_{T3}} & 0 & 0 & 0 & \frac{1}{T_{T3}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{T4}} & 0 & 0 & 0 & \frac{1}{T_{T4}} & 0 & 0 & 0 \\
-\frac{1}{2\pi R_1 T_{G1}} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{G1}} & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{1}{2\pi R_2 T_{G2}} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{G2}} & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{1}{2\pi R_3 T_{G3}} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{G3}} & 0 & 0 & 0 & 0 \\
0 & -\frac{1}{2\pi R_4 T_{G4}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{G4}} & 0 & 0 & 0 \\
\frac{B_1}{2\pi} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & \frac{B_2}{2\pi} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
\frac{T_{12}}{2\pi} & -\frac{T_{12}}{2\pi} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

$$B=\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & \frac{apf_1}{T_{G1}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{apf_2}{T_{G2}} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{apf_3}{T_{G3}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{apf_4}{T_{G4}} & 0 & 0 & 0
\end{bmatrix}^T$$

$$\Gamma=\begin{bmatrix}
-\frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{K_{P2}}{T_{P2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{K_{P3}}{T_{P3}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{K_{P4}}{T_{P4}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}^T$$

$$F=\begin{bmatrix}
-\frac{K_{P1}}{T_{P1}} & -\frac{K_{P1}}{T_{P1}} & 0 & 0 \\
0 & 0 & -\frac{K_{P2}}{T_{P2}} & -\frac{K_{P2}}{T_{P2}} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\frac{cpf_{11}}{T_{G1}} & \frac{cpf_{12}}{T_{G1}} & \frac{cpf_{13}}{T_{G1}} & \frac{cpf_{14}}{T_{G1}} \\
\frac{cpf_{21}}{T_{G2}} & \frac{cpf_{22}}{T_{G2}} & \frac{cpf_{23}}{T_{G2}} & \frac{cpf_{24}}{T_{G2}} \\
\frac{cpf_{31}}{T_{G3}} & \frac{cpf_{32}}{T_{G3}} & \frac{cpf_{33}}{T_{G3}} & \frac{cpf_{34}}{T_{G3}} \\
\frac{cpf_{41}}{T_{G4}} & \frac{cpf_{42}}{T_{G4}} & \frac{cpf_{43}}{T_{G4}} & \frac{cpf_{44}}{T_{G4}} \\
cpf_{31}+cpf_{41} & cpf_{32}+cpf_{42} & -(cpf_{13}+cpf_{23}) & -(cpf_{14}+cpf_{24}) \\
-(cpf_{31}+cpf_{41}) & -(cpf_{32}+cpf_{42}) & cpf_{13}+cpf_{23} & cpf_{14}+cpf_{24} \\
0 & 0 & 0 & 0
\end{bmatrix}$$

The above given system has been discretized with sampling time T_s [12-13],

$$x_{k+1} = Ax_k + Bu_k + FP_{L_k} + \Gamma P_{uc_k} \tag{6}$$

where, k = discretization step.

3. Action Dependent Heuristic Dynamic Programming (ADHDP)

Discrete state feedback controller does not have desired dynamical characteristics due to risk of instability since feedback gain matrix is static. The aim of this paper is to design a dynamical feedback gain controller that minimize the cost and provide optimal solution. ADHDP is a useful technique of approximate dynamic programming (ADP), for feedback control of systems [14-19].

ADHDP is also known as Q- learning. It is used to estimate the quality function (Q-function or action value function) for any policy, optimal or non-optimal. In ADHDP, first the feedback policy, i.e. Lx_k evaluated and then updated by utilizing Q function. Watkins [20] defined the Q function which can be represented as,

$$Q(x_k, u_k) = r(x_k, u_k) + \gamma V(x_{k+1})$$

(2)where , $0 \le \gamma \le 1$ is the discount factor. $r(x_k, u_k)$ represents the instantaneous cost and $V(x_k)$ is the long term cost. For a linear system $V(x_k)$ is quadratic and can be represented as

$$\begin{aligned} V(x_k) &= \sum_{j=k}^{\infty} \gamma^{j-k} r(x_j, u_j) = \sum_{j=k}^{\infty} \gamma^{j-k} (x_j{}^T P x_j + u_j{}^T R u_i) \\ &= \sum_{i=0}^{\infty} \gamma^{i} (x_{i+k}^T P x_{i+k} + u_{i+k}^T R u_{i+k}) \end{aligned} \tag{8}$$

For a linear system with quadratic cost, Q function also becomes a quadratic function. γ is set to 1 for simplicity [16],

$$Q(x_k, u_k) = r(x_k, u_k) + V(x_{k+1}) = \begin{pmatrix} x_k^T & u_k^T \end{pmatrix} \begin{pmatrix} P & 0 \\ 0 & R \end{pmatrix} \begin{pmatrix} x_k \\ u_k \end{pmatrix} + x_{k+1}^T K x_{k+1} \tag{3}$$

$$\begin{aligned} &= \begin{pmatrix} x_k^T & u_k^T \end{pmatrix} G \begin{pmatrix} x_k \\ u_k \end{pmatrix} + (Ax_k + Bu_k)^T K (Ax_k + Bu_k) \\ &= \begin{pmatrix} x_k^T & u_k^T \end{pmatrix} \left[G + \begin{pmatrix} A^T \\ B^T \end{pmatrix} K \begin{pmatrix} A & B \end{pmatrix} \right] \begin{pmatrix} x_k \\ u_k \end{pmatrix} \\ &= \begin{pmatrix} x_k^T & u_k^T \end{pmatrix} H \begin{pmatrix} x_k \\ u_k \end{pmatrix} \end{aligned} \tag{4}$$

where, $G = \begin{pmatrix} P & 0 \\ 0 & R \end{pmatrix}$ is the block diagonal matrix with blocks P and R. $H = \left[G + \begin{pmatrix} A^T \\ B^T \end{pmatrix} K (A \quad B) \right]$ is the quadratic kernel matrix. Q function can be computed explicitly for a Linear Quadratic Regulator (LQR) problem which is quadratic in x_k and u_k and given as,

$$\begin{aligned} Q(x_k, u_k) &= \begin{pmatrix} x_k{}^T & u_k{}^T \end{pmatrix} \begin{bmatrix} H_{xx} & H_{xu} \\ H_{ux} & H_{uu} \end{bmatrix} \begin{pmatrix} x_k \\ u_k \end{pmatrix} \\ &= \begin{pmatrix} x_k{}^T & u_k{}^T \end{pmatrix} H_u \begin{pmatrix} x_k \\ u_k \end{pmatrix} \end{aligned} \tag{5}$$

where, H_u is a symmetric positive definite matrix, and the various sub matrices are given in eq. (12).

$$\begin{aligned} H_{xx} &= P + A^{'} K A \\ H_{ux} &= A^{'} K B \\ H_{xu} &= B^{'} K A \\ H_{uu} &= R + B^{'} K B \end{aligned} \tag{6}$$

The sub matrix H_{uu} is symmetric positive definite. By giving policy and cost function at any time, an improved policy can be determined as,

$$L_{k+1} x = \arg\min_{u} Q(x_k, u_k) \tag{7}$$

$$\frac{\partial}{\partial u_k} Q\left(x_k, u_k\right) = 0 \tag{8}$$

By placing $Q(x_k, u_k)$ value from eq. (11) in eq. (14), control action can be determined as

$$u_k = (-H_{uu})^{-1} H_{ux} x_k \tag{9}$$

where, $L_{k+1} = -(H_{uu})^{-1} H_{ux}$ is the minimizing policy for all *x*.

4. Results And Discussions

The performance of ADHDP controller is checked on deregulated two area AGC scheme which consists Disco_1, Disco_2, Genco_1 and Genco_2 in *area-1*. Similarly Disco_3, Disco_4, Genco_3 and Genco_4 are in *area-2*. The parameters given in Table 1 are used to model the AGC scheme.

Table 1. Two Area Power System Paramaters

$T_{G1} = T_{G2} = .08$ Governor time constt.	$T_{p1} = T_{p2} = 24$ Power system time constt.
$K_{p1} = K_{p2} = 120$ Power system gain constt.	$T_{T1} = T_{T2} = .3$ Turbine time constt.
$R_1 = R_2 = 2.4$ speed regulation	$B_1 = B_2 = .425$ Frequency bias constt.
$T_{12} = .0707$ synchronizing constant	

Two cases are considered in this paper. In first case load changes occur in *area-1* (Disco_1 and Disco_2) only. The second case is a contract violation case where Disco in *area-1* violates the contract.

A. Case 1

An increment of 0.2 pu in the load demands of Discos in *area-1* (.1 pu in Disco_1 and Disco_2 each) is considered in this case. A contract between Gencos and Discos of *area-1* to meet the power demand is established through the following DPM.

$$\begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

It is seen that Genco_1 and Genco_2 deliver the extra load demand of Disco_1 and Disco_2 in *area-1*. Genco_1 and Genco_2 regulate their generation to match the Disco_1 and Disco_2 demand. This desired change in the generation of a Genco can be expressed as,

$$\Delta P_{g_i} = \sum_j cpf_{i_j} \Delta P_{Lj} \tag{10}$$

where, ΔP_{Lj} = change in load demand of j^{th}, cpf_{ij} = contract participation factors given in DPM. For the considered case, eq. (16) can be expanded as

$$\Delta P_{gi} = cpf_{i1}\Delta P_{L1} + cpf_{i2}\Delta P_{L2} + cpf_{i3}\Delta P_{L3} + cpf_{i4}\Delta P_{L4} \tag{17}$$

On putting values in eq. (17) the change in generation of different Gencos of *area-1* and *area-2* can be determined and given as, $\Delta P_{g_1} = 0.5 \times \Delta P_{L1} + 0.5 \times \Delta P_{L2} = 0.1$pu, $\Delta P_{g_2} = 0.1$pu (*area-1*), $\Delta P_{g_3} = \Delta P_{g_4} = 0$pu (*area-2*).

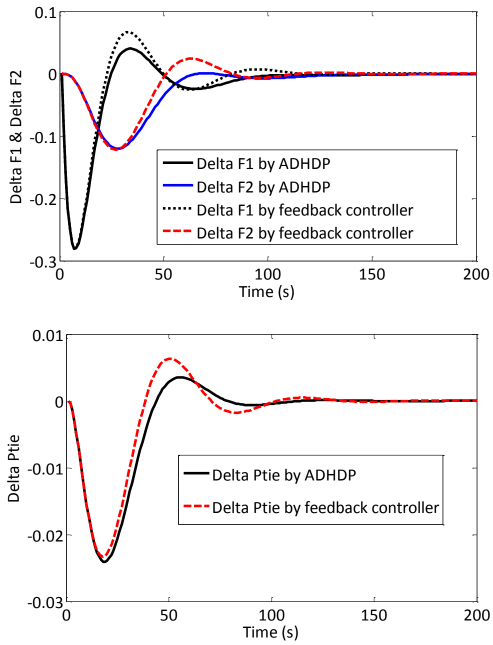


Figure 3. (a) Deviations in Frequency, (b) Deviations in Tie-line power.

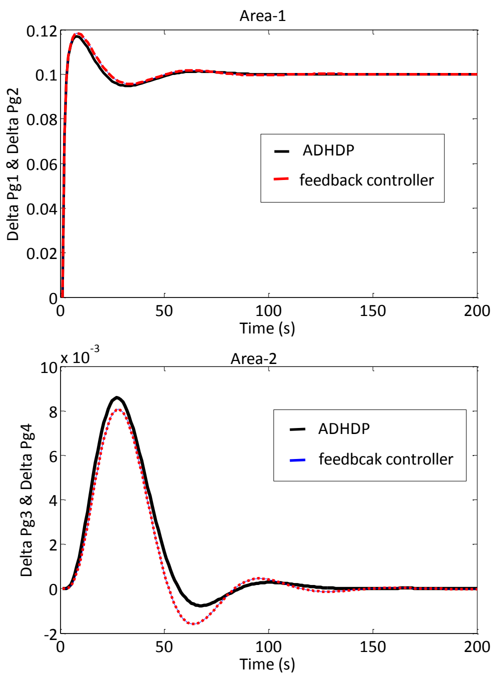


Figure 3. (c) Generations Change

The result of frequency deviations of *area-1* and *area-2* is given in Figure (3a). It is seen that at steady state deviations in frequency settle down to zero value. Figure (3b) shows that tie-line power also settled at zero value at steady state. Since the load in area-2 has not been disturbed, *area-2* frequency deviation has lower magnitude than *area-1* frequency deviation. The Gencos of *area-1* regulate their generation to meet up the load demand of Discos in *area-1* and settle down at the values 0.1 pu each as shown in Figure (3c). It is seen that ADHDP and state feedback controller perform well and settle various responses at steady state, however the transient responses prove that better and effective performance of ADHDP over state feedback controller.

B. Case 2

This case considers an increment of 0.2 pu load in *area-1* and *area-2* respectively. The following DPM shows the power transaction contract between Discos- Gencos of *area-1* and *area-2.*

$$\begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix}$$

At t=0, $Disco_1$ of *area-1* draws 0.1 pu more power and violates the contract. This extra power mismatches the generation and load equilibrium and forces the frequency to deviate from nominal value. To keep the frequency at nominal Gencos of same area i.e. *area-1* will supply this excess power. Therefore to simulate this case a total load of 0.3 pu and 0.2 pu have been considered in *area-1* and *area-2* respectively. Figure (4a) shows the frequency deviations in *area-1* and *area-2* which vanish and settle down to zero values that at steady state. The change in the tie-line power can be determined as,

$$\Delta P_{tie1-2,Schedule} = \sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\Delta PL_j - \sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\Delta PL_j \tag{11}$$

$\Delta P_{tie1-2,Schedule} = -0.05$ pu. Figure (4b) determines 0.05 pu power is exchanged form *area-2* to *area-1* to compensate the effect of extra load demand of $Disco_1$. Therefore deviations in tie-line power settle at the same values given by eq. (18), i.e. at -0.05 pu. The Gencos of *area-1* increase their generation to cop up with the extra demand of $Disco_1$ and settle down at new values, the extra demand of $Disco_1$ has not any affect on the Gencos of *area-2* as shown in Figure (4c). This uncontracted extra load of $Disco_1$ is shared by the Gencos of *area-1* only.

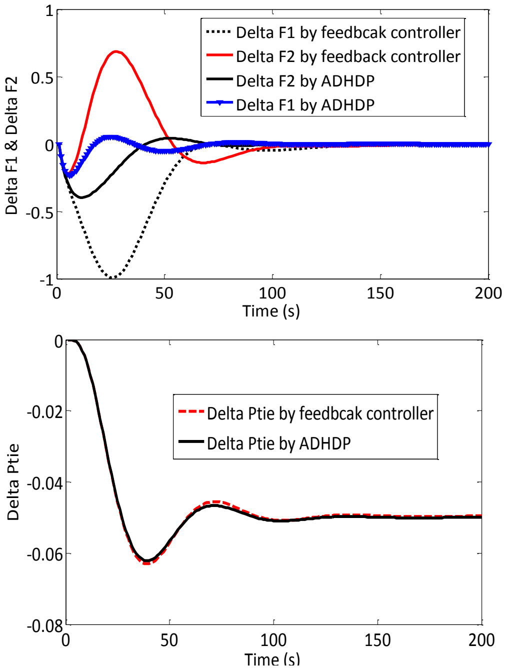


Figure 4. (a) Deviations in Frequency, (b) Deviations in Tie-line Power

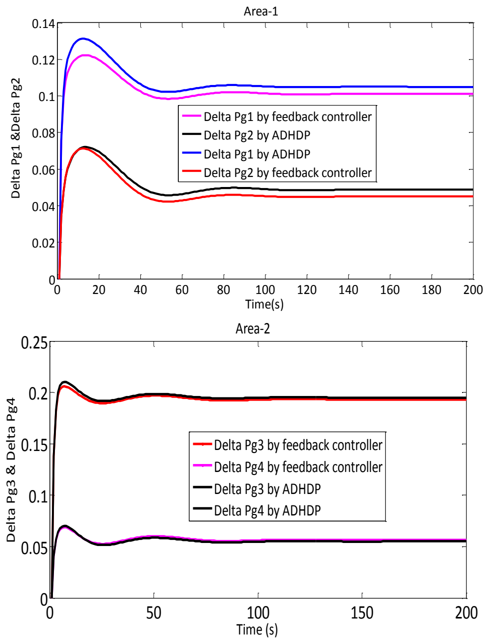


Figure 4. (c) Generated Power

It is evident that deviations in tie-line power and frequency settle down and stabilized, with the required generation change within the desired time, in both *area-1* and *area-2* [21],[22]. Results show that the performance of ADHDP controller is better than state feedback controller in terms of oscillation and settling time. Furthermore the higher flexibility and simple structure of ADHDP based controller provide solution for a wide range of load disturbances.

5. Conclusion

A deregulated two area AGC scheme with Action Dependent Heuristic Dynamic Programming (ADHDP) based controller has been studied in this paper. Several load perturbations have been considered to check the performance of the designed controller. Results of ADHDP based controller have also been compared with the results of state feedback controller. Comparative results prove the better and effective performance of ADHDP controller over state feedback controller. The results also indicate that ADHDP control satisfy the AGC requirements. Further, the ADHDP approach can be extended to multi-area system, considering the various non linearities.

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