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Automatic Generation Control (AGC) of a multi sources power system (PS) with natural choice of power plants

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Abstract

This paper presents an application of optimal control theory in multi sources PS by considering natural choice of power plants participating in AGC scheme. However, for successful operation of large power system, the natural choices of generation suitable for AGC system are hydro and thermal power plants since gas and nuclear power plants are rarely participates in the AGC scheme. Therefore, this work presents design and implementation of proportional integral (PI) structured optimal AGC controller in the presence of hydro and thermal power plants by using state vector feedback control theory. Moreover, various case studies are identified to obtain: (i) Comparison of optimal value of cost function for various case studies, (ii) Closed loop system stability margin through patterns of eigenvalues and (iii) System dynamic performance. Further, results have shown that dynamic performance of PS with optimal AGC controller is outstanding over those obtained with genetic algorithms (GAs) tuned PI structured AGC controller. Besides, with optimal AGC controller, optimal value of cost function, increased in system closed loop stability margin and outstanding dynamic performance of PS have been found when lessening in hydro generation is replaced by generation from thermal power plants for various case studies under investigation.

Keywords: Multi Sources; AGC; Optimal Controller; Eigenvalues; Dynamic Performance.

1. INTRODUCTION

The PS control areas are grouped to operate in interconnected fashion for providing reliable electric supply to the consumers at specified voltage and frequency. These parameters are maintained at desired level of the specified value, which are necessary for minimum stresses in the PS also for good health of the consumer equipments by implementing AGC scheme in power system. However, AGC adjust the output power of the multiple power plants for removing of small changes or deviations (up to 5%) in the load.

Many AGC studies [1-47] have been accomplished by power researcher for designing and performance analysis of AGC controller for single/multi area power systems. After the novel work of Elgerd and Fosha [1-2], a wide range of AGC publications have been appeared for addressing the problem of AGC as reviewed in [4-7]. Many meta-heuristic optimization algorithms such as; Artificial Neural Network [8-10], Fuzzy Logic [11-15], Genetic Algorithm [15-23], Particle Swarm Optimization [24-26], Bat Optimization [27-28], Bacterial Foraging Optimization [29-31], Artificial Bee Colony [32], Gravitational Search Algorithms [33-34] and imperialist competitive algorithms [47], were also developed to demonstrate the effectiveness of AGC controllers in power system.

But the above meta-heuristic algorithms [8-34] consume larger simulation time and sometime give unsatisfactory solution to the AGC design problem in power system. In power system, tuning of AGC controller is a multi-input and multi-output design problem which cannot be solved by applying classical control theory in an effective manner as well as these controllers are generally introduced relatively larger oscillations and enormous settling time for transient period. Therefore, first attempt to apply modern/optimal control theory for designing of AGC controller has been proposed in [1-2] for 2-area PS by considering non reheat types of thermal turbines. Since then many research articles [35-46] on AGC have been appeared by using optimal control theory. The enhanced system transient performance and higher system stability margins in PS have been witnessed in [35-46] with optimal AGC controllers rather than using conventional AGC controllers. Moreover, these optimal AGC controllers are also found to be very robust, cheaper and simple in design [35-46]. In majority of the works, the AGC studies were demonstrated by considering either hydro or thermal power units in each connected areas. Depending upon the availability of energy resources a control area practically may have many power plants such as hydro, thermal, gas, nuclear etc. By considering this practical situation many AGC studies [15, 18, 22-26, 36-37, 46] were carried out by assuming diverse sources based power units in each connected areas.

Nuclear units are used to provide partial the base load power due to higher efficiency and gas units are typically ideal for supplying peak demands only. Therefore, gas and nuclear power plants seldom play any role by participating in AGC schemes in interconnected PS. Therefore, the natural choices of power generation for AGC are hydro and thermal power plants to operate the PS successfully. But no work has been witnessed in the literatures so far by considering the above natural choice of power plants (hydro and thermal) for participating in AGC scheme by adapting optimal control theory. Therefore, in this research work, the following AGC studies are proposed by incorporating above power units in each connected areas:-

• To develop transfer function model of 2-area interconnected PS by considering hydro and thermal power generation in each area interconnected by AC tie line.

• To find the design of optimal gain matrix [⍰*] for the above PS model using optimal control theory for various case studies based upon share of power generation.

• To investigate PS stability margin by using patterns of closed-loop eigenvalues for PS under consideration.

• To compare dynamic performance of the PS with optimal AGC controller and GAs based PI structured classical controller.

• To obtain dynamic performance of the PS with optimal AGC controller for 1% step load disturbance in the connected areas for various case studies under consideration.

2. Model of PS

The transfer function model of hydro and thermal power plants has been reported in many literatures [1-46]. However, in this work, a 2-area interconnected PS having hydro and thermal power units in each connected areas with equal generation capacities is developed as shown in Fig. 1. These areas are interconnected by AC tie line for exchanging power between control areas to get the operation benefits.

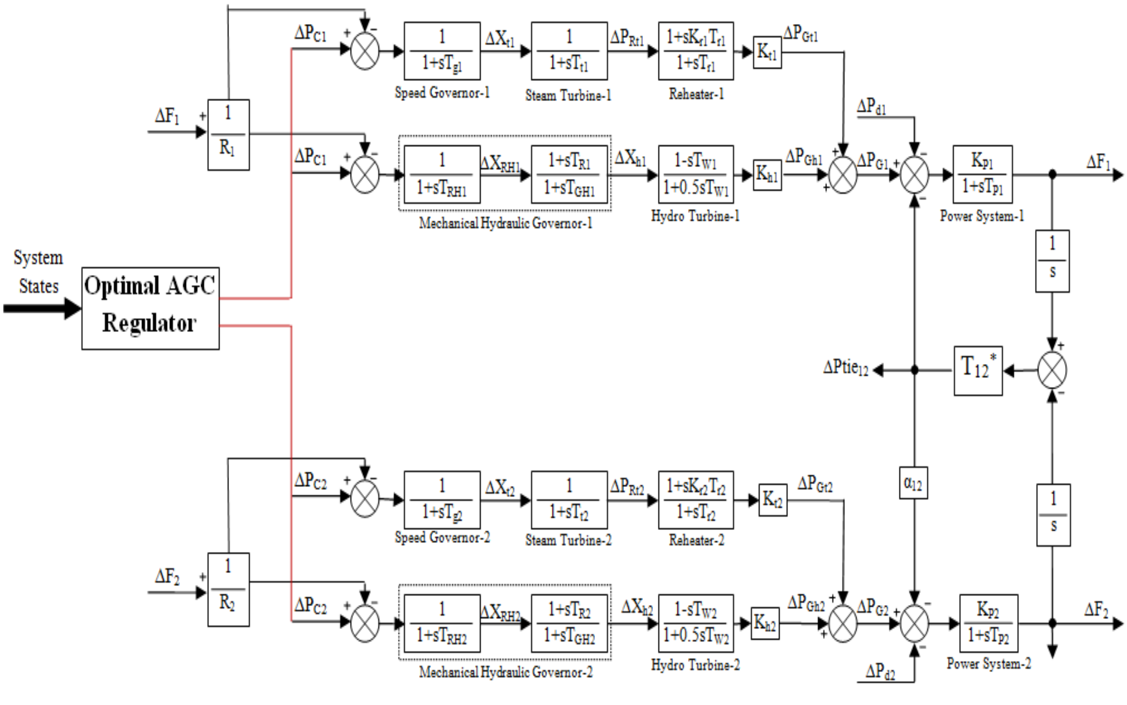


Fig. 1: Transfer function model of PS with natural choice of power plants.

The symbol has their usual meaning as given in [1-2, 43]. In this model, not only all the thermal power plants are lumped together and shown by a single thermal power plant dynamics but hydro power plants are also lumped together represented by respective single hydro power plant dynamics [20-23, 31, 33, 35, 43]. There is no mismatch between generation and load for PS model operating under normal steady state conditions. Therefore, the hydro and thermal power generations in area-1 is given by;

$$P_{Gh1} = K_{h1}P_{G1} \tag{1}$$

$$P_{Gt1} = K_{t1}P_{G1} \tag{2}$$

Under nominal generation loading, the total power generated (P_{G1}) in area-1 is given by:

$$P_{G1} = P_{Gh1} + P_{Gt1} \tag{3}$$

Putting the value of $P_{Gh1}$and P_{Gt1} from equations (1)-(2), then, value of P_{G1} is given by

$$P_{G1} = K_{h1}P_{G1} + K_{t1}P_{G1} \tag{4}$$

$$K_{h1} + K_{t1} = 1 \tag{5}$$

The above equation is relation between generation sharing factor also known as participation factor of hydro and thermal units in area-1, however, similar relation for area-2 is given by;

$$K_{h2} + K_{t2} = 1 \tag{6}$$

The deviation in power generation; P_{G1} can be formulated using (3) to obtain transient responses for small load perturbation in area-1;

$$\Delta P_{G1} = \Delta P_{Gh1} + \Delta P_{Gt1} \tag{7}$$

Similarly for control area-2, P_{G2} is given by:

$$\Delta P_{G2} = \Delta P_{Gh2} + \Delta P_{Gt2} \tag{8}$$

3. STATE VARIABLE MODEL OF PS

The PS model shown in Fig. 1 may be formulated in state variable form with the following differential equations;

$$\frac{d}{dt}\underline{X} = A\underline{X} + B\underline{U} + \Gamma\underline{P_d} \tag{9}$$

$$\underline{Y} = C\underline{X} + D\underline{U} \tag{10}$$

Where, $\underline{X}$, $\underline{U}$, $\underline{P}_d$ and $\underline{Y}$ are the state, control, disturbance and output vectors respectively. However, A, B, C and Γ are system input, system control, and system output and disturbance matrices of appropriate dimensions respectively. Each state shown in Fig. 1 is represented by a set of differential equation. The transfer function model of reheat thermal turbine and the speed governing mechanism of hydro turbine have been modified or rewritten to account for the term in the numerator. The modified the transfer function model of reheater-1, may be represented by following equation;

$$\frac{1 + sK_{r1}T_{r1}}{1 + sT_{r1}} = K_{r1} + \frac{1 - K_{r1}}{1 + sT_{r1}} \tag{11}$$

The transfer function of hydro turbine-1 may be represented by following equation;

$$\frac{1-sT_{w1}}{1+0.5sT_{w1}}=-2+\frac{6}{2+sT_{w1}} \tag{12}$$

The transfer function of governor of hydro turbine-1 may be represented by following equation;

$$\frac{1}{1+sT_{RH1}}+\frac{1+sT_{R1}}{1+sT_{GH1}}=\frac{1}{1+sT_{RH1}}+(\frac{T_{R1}}{T_{GH1}}+\frac{1-\frac{T_{R1}}{T_{GH1}}}{1+sT_{GH1}}) \tag{13}$$

Similarly transfer function of reheater-2 and hydro turbine-2 may be represented by following equations:-

$$\frac{1+sK_{r2}T_{r2}}{1+sT_{r2}}=K_{r2}+\frac{1-K_{r2}}{1+sT_{r2}} \tag{14}$$

$$\frac{1-sT_{w2}}{1+0.5sT_{w2}}=-2+\frac{6}{2+sT_{w2}} \tag{15}$$

$$\frac{1}{1+sT_{RH2}}+\frac{1+sT_{R2}}{1+sT_{GH2}}=\frac{1}{1+sT_{RH2}}+\frac{T_{R2}}{T_{GH2}}+\frac{1-\frac{T_{R2}}{T_{GH2}}}{1+sT_{GH2}} \tag{16}$$

The model of PS taking into examination is developed in Fig. 2 with consideration of intermediate states (P_{Gti1}, X_{hi1}, P_{Ghi1}, P_{Gti2}, X_{hi2} and P_{Ghi2},) and using equations (11)-(16).

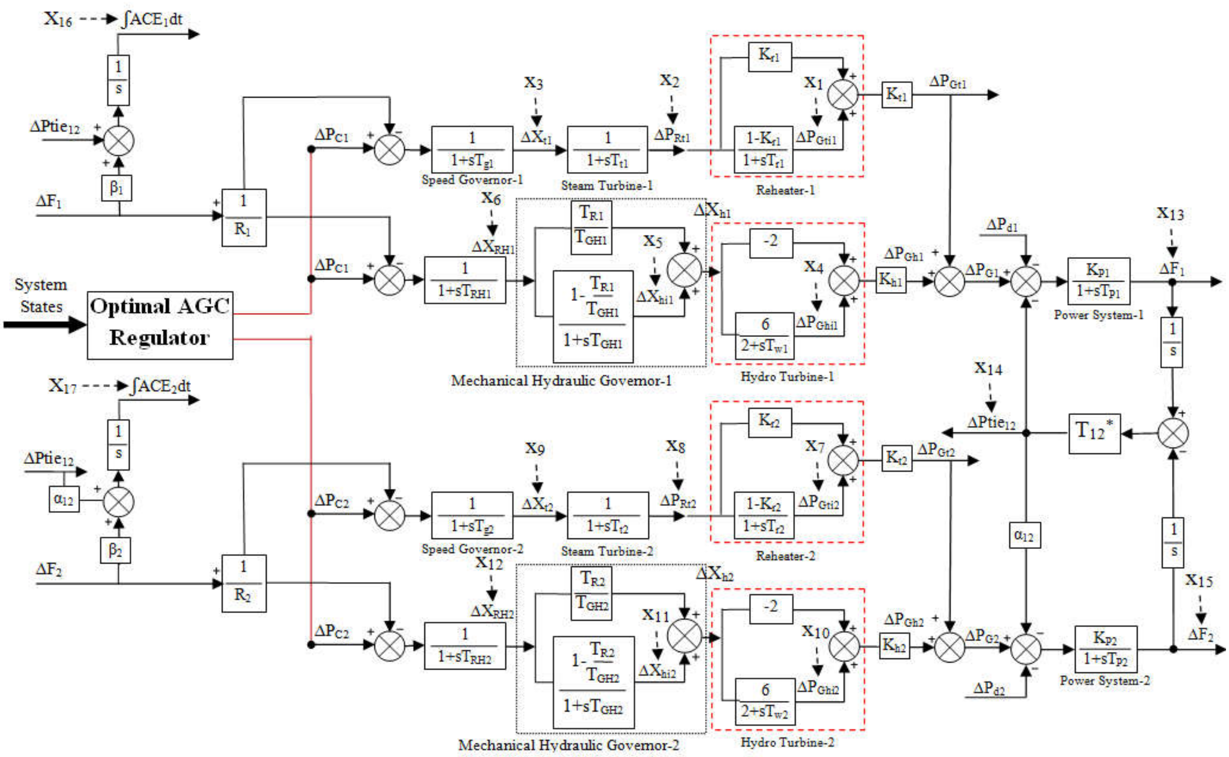


Fig. 2: Reformulated model of PS with natural choice of power plants.

Besides, $\underline{X}$, $\underline{U}$ and $\underline{P}_d$ vectors considered for the above PS model are as follows;

$$\underline{X}=[x_1\ x_2\ x_3\ x_4\ x_5\ x_6\ x_7\ x_8\ x_9\ x_{10}\ x_{11}\ x_{12}\ x_{13}\ x_{14}\ x_{15}\ x_{16}\ x_{17}]^T \quad (17)$$

$$\underline{U}=[\ P_{C1}\quad P_{C2}]^T \quad (18)$$

$$\underline{P}_d=[\ P_{d1}\quad P_{d2}]^T \quad (19)$$

However, following differential equations are derived to obtain the A, B, C and Γ matrices to represent PS model into state variable form;

$$\frac{d}{dt}(x_1) = -\frac{1}{T_{r1}}x_1 + \frac{1-K_{r1}}{T_{r1}}x_2 \quad (20)$$

$$\frac{d}{dt}(x_2) = -\frac{1}{T_{t1}}x_2 + \frac{1}{T_{t1}}x_3 \quad (21)$$

$$\frac{d}{dt}(x_3) = -\frac{1}{T_{g1}}x_3 - \frac{1}{R_1T_{g1}}x_{13} + \frac{1}{T_{g1}}\Delta P_{C1} \quad (22)$$

$$\frac{d}{dt}(x_4) = -\frac{2}{T_{w1}}x_4 + \frac{6}{T_{w1}}x_5 + \frac{6T_{R1}}{T_{W1}T_{RH1}}x_6 \quad (23)$$

$$\frac{d}{dt}(x_5) = -\frac{1}{T_{GH1}}x_5 + \left(\frac{1}{T_{GH1}} - \frac{T_{R1}}{T^2_{GH1}}\right)x_6 \quad (24)$$

$$\frac{d}{dt}(x_6) = -\frac{1}{T_{RH1}}x_6 - \frac{1}{R_1T_{RH1}}x_{13} + \frac{1}{T_{RH1}}\Delta P_{C1} \quad (25)$$

$$\frac{d}{dt}(x_7) = -\frac{1}{T_{r2}}x_7 + \frac{1-K_{r2}}{T_{r2}}x_8 \quad (26)$$

$$\frac{d}{dt}(x_8) = -\frac{1}{T_{t2}}x_8 + \frac{1}{T_{t2}}x_9 \quad (27)$$

$$\frac{d}{dt}(x_9) = -\frac{1}{T_{g2}}x_9 - \frac{1}{R_2T_{g2}}x_{15} + \frac{1}{T_{g2}}\Delta P_{C2} \quad (28)$$

$$\frac{d}{dt}(x_{10}) = -\frac{2}{T_{w2}}x_{10} + \frac{6}{T_{w2}}x_{11} + \frac{6T_{R2}}{T_{W2}T_{RH2}}x_{12} \quad (29)$$

$$\frac{d}{dt}(x_{11}) = -\frac{1}{T_{GH2}}x_{11} + \left(\frac{1}{T_{GH2}} - \frac{T_{R2}}{T^2_{GH2}}\right)x_{12} \quad (30)$$

$$\frac{d}{dt}(x_{12}) = -\frac{1}{T_{RH2}}x_{12} - \frac{1}{R_2T_{RH2}}x_{15} + \frac{1}{T_{RH2}}\Delta P_{C2} \quad (31)$$

$$\frac{d}{dt}(x_{13}) = \frac{K_{P1}K_{t1}}{T_{P1}}x_1 + \frac{K_{P1}K_{t1}K_{r1}}{T_{P1}}x_2 + \frac{K_{P1}K_{h1}}{T_{P1}}x_4 - \frac{2K_{P1}K_{h1}}{T_{P1}}x_5 - \frac{1}{T_{P1}}x_{13} - \frac{K_{P1}}{T_{P1}}x_{14} - \frac{K_{P1}}{T_{P1}}\Delta P_{d1} \quad (32)$$

$$\frac{d}{dt}(x_{14}) = T^*_{12}x_{13} - T^*_{12}x_{15} \quad (33)$$

$$\frac{d}{dt}(x_{15}) = \frac{K_{P2}K_{t2}}{T_{P2}}x_7 + \frac{K_{P2}K_{t2}K_{r2}}{T_{P2}}x_8 + \frac{K_{P2}K_{h2}}{T_{P2}}x_{10} - \frac{2K_{P2}K_{h2}}{T_{P2}}x_{11} - \frac{\alpha_{12}K_{P2}}{T_{P2}}x_{14} - \frac{1}{T_{P2}}x_{15} - \frac{K_{P2}}{T_{P2}}\Delta P_{d2} \quad (34)$$

$$\frac{d}{dt}(x_{16}) = \beta_1 x_{13} + x_{14} \qquad (35)$$

$$\frac{d}{dt}(x_{17}) = \alpha_{12} x_{14} + \beta_2 x_{15} \qquad (36)$$

Now matrices A, B, C and Γ are obtained by arranging the above state space equations (20)-(36). These matrices are given in Appendix-A. These matrices are utilized to obtain $[\Psi^*]$ for PS model shown as in Fig. 2.

4. DESIGNING OF OPTIMAL AGC CONTROLLER

The design of optimal control signal $\underline{U}^*$ for state variable equations (9)-(10) is such that to minimize cost function (J), also known as performance index, which is given by the following equations;

$$J = \int_0^\infty \frac{1}{2}[\underline{X}^T Q \underline{X} + \underline{U}^T R \underline{U}]dt \qquad (37)$$

$$\underline{U}^* = -\Psi^* \underline{X} \qquad (38)$$

The optimal control signal ($\underline{U}^*$) for above equation is acquired by adapting state vector feedback control theory [35-45], which is given by;

$$\underline{U}^* = -R^{-1} B^T P \underline{X} \qquad (39)$$

Where; P represents positive definite symmetric matrix of compatible dimensions. By comparing (38)-(39), $[\Psi^*]$ is now given by [35-45];

$$\Psi^* = -R^{-1} B^T P \qquad (40)$$

The derivation of above $[\Psi^*]$ has been given in references [1-2, 15, 35-45].

5. SYSTEM DATA AND CASE STUDIES

In this work, various case studies are proposed to examine transient performance of PS model with optimal AGC controller based upon sharing factors of hydro and thermal units. These case studies are identified in Table 1.

Table 1. Various case studies

Case study no.	Sharing factor in area-1		Sharing factor in area-2	
	K_{t1}	K_{h1}	K_{t2}	K_{h2}
1	0.2	0.8	0.2	0.8
2	0.5	0.5	0.5	0.5
3	0.8	0.2	0.8	0.2

The system parameters for i^{th} area connected to j^{th} area (i = 1 and j = 2) for PS model under examination are identified in Table 2.

Table 2. System parameters

PS Parameters and its values		Hydro and thermal turbine parameter and its values	
P_{ri}	2000 MW	T_{gi}	0.08 s
H_i	5.0 MW-s/MVA	T_{ti}	0.30 s
F_r	60.0 Hz	T_{ri}	10.0 s
T_{ij}	0.0433	K_{ri}	0.3
R_i	2.4 Hz/pu MW	T_{RHi}	31.25 s
β_i	0.4249 puMW/Hz	T_{Ri}	5.000 s
D_i	8.33×10^{-3} pu MW/Hz	T_{GHi}	0.513 s
α_{ij}	-1.0	T_{wi}	1.500 s

The above system parameters given in Table 2 are utilized to design optimal AGC controller in the next section.

6. SIMULATION OF RESULTS

The PS model in the form of state space representation as shown in Fig. 2, by using A, B, C and D matrices is simulated at the platform of standard MATLAB software. The [Ψ^*] with associated J^* and system closed-loop eigenvalues are determined by using above software, which are given in Tables 3-4. The optimal gains of GAs tuned PI structured AGC controller [16-17] is given in Table 5. The dynamic performances of PS with natural regulation, classical GAs controller and optimal controller for +1% step load disturbance in area-1 are shown in Fig. 3. The dynamic performances with optimal PI controller for various case studies are compared in Figs. 4 & 5 for +1% step load disturbance in area-1 & 2, respectively.

Table 3. [Ψ^*] and J^* for various case studies

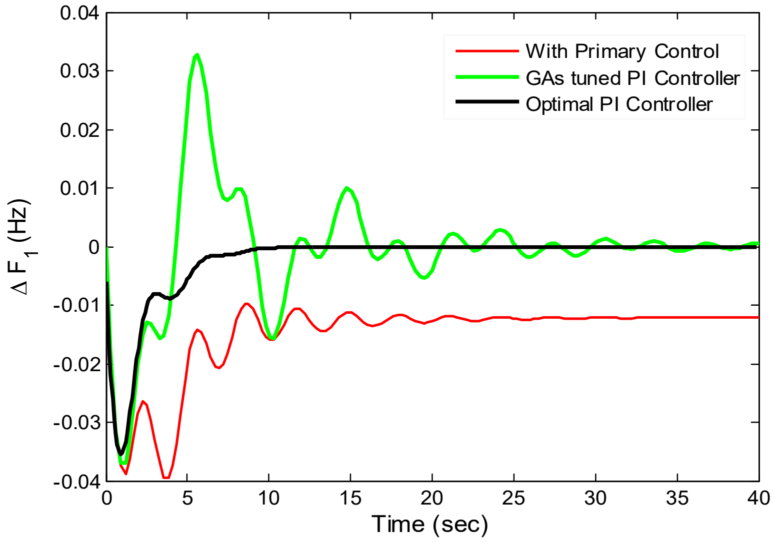
Case Studies	Elements of [Ψ^*]	J^*
1	3.4364 0.3601 0.4555 3.9246 3.8172 39.1812 0.8036 0.0307 0.0044 1.3334 -0.6349 -6.8952 0.1748 -6.6306 1.0791 0.9661 -0.2582 1.1689 0.0383 -0.0028 1.6166 1.4699 12.4574 2.1764 0.8254 0.1073 3.6640 -1.1424 -11.7444 0.3728 1.2029 1.6049 0.2582 0.9661	6731.3
2	4.6778 0.5420 0.5129 1.8467 0.3555 4.2634 0.5920 0.0215 0.0030 0.2971 0.0815 -0.0169 0.6400 -3.4126 0.3301 0.9769 -0.2135 1.4290 0.0564 0.0067 0.6391 0.7904 5.8599 2.9965 0.8911 0.1131 1.7678 -1.2965 -14.0100 0.0975 0.2594 1.5989 0.2135 0.9769	2972.8
3	5.2785 0.6711 0.5370 0.6577 -0.1009 -0.3603 0.4423 0.0133 0.0017 0.0561 0.0463 -0.1423 0.7790 -2.2567 0.1364 0.9905 -0.1377 1.1387 0.0630 0.0123 0.1645 0.1504 0.4567 3.3098 0.9287 0.1143 0.5271 -0.5020 -5.7577 0.0599 0.0599 1.3833 0.1377 0.9905	2728.5

Table 4. Patterns of PS closed-loop eigenvalues

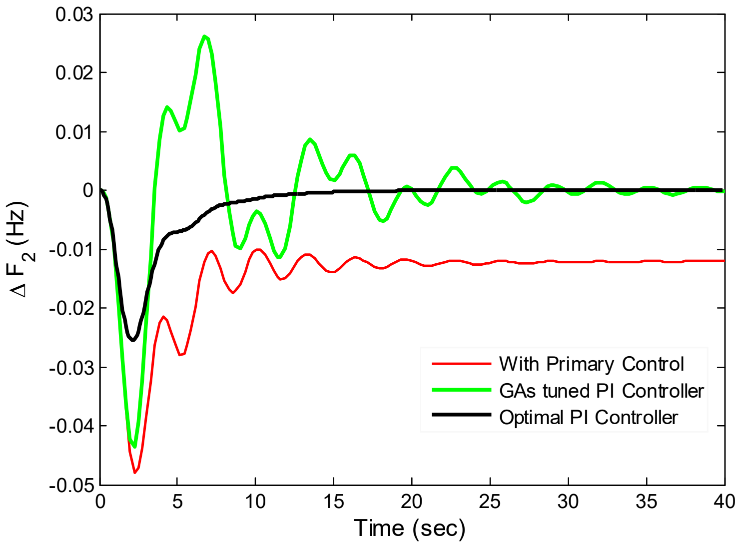
Sr. No.	Case study-1	Case study-2	Case study-3
1	-17.5656	-17.5808	-17.5964
2	-13.2824	-13.5788	-13.7844
3	-0.2398 + 1.8289i	-0.3503 + 1.8287i	-0.5790 + 1.7912i
4	-0.2398 - 1.8289i	-0.3503 - 1.8287i	-0.5790 - 1.7912i
5	-1.1173	-1.1375	-1.0746 + 0.5523i
6	-0.5420 + 0.5373i	-0.7524 + 0.6215i	-1.0746 - 0.5523i
7	-0.5420 - 0.5373i	-0.7524 - 0.6215i	-1.2370
8	-0.4051	-0.4312	-0.4427
9	-0.2435	-0.2883	-0.3094
10	-0.1388 + 0.0653i	-0.1838 + 0.0946i	-0.2121 + 0.1117i
11	-0.1388 - 0.0653i	-0.1838 - 0.0946i	-0.2121 - 0.1117i
12	-0.0312	-0.0466	-0.0361
13	-12.1308	-11.7654	-11.4603
14	-4.1283	-3.9711	-3.7490
15	-2.7997	-2.6304	-2.4144
16	-2.2132	-2.2063	-2.0984
17	-0.0659	-0.0313	-0.0313

Table 5. Gains of GAs controller

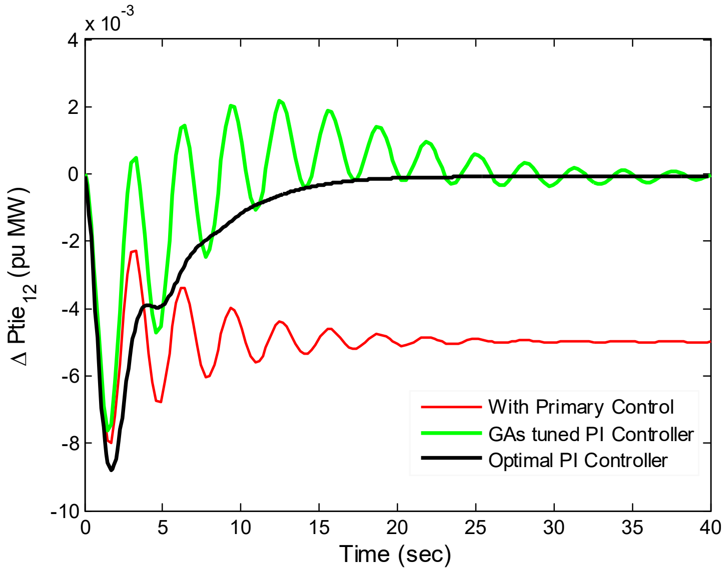
Gains of Controller in Area-1		Gains of Controller in Area-2	
k_{p1}	k_{i1}	k_{p2}	k_{i2}
0.0001	0.5022	0.0001	0.5023



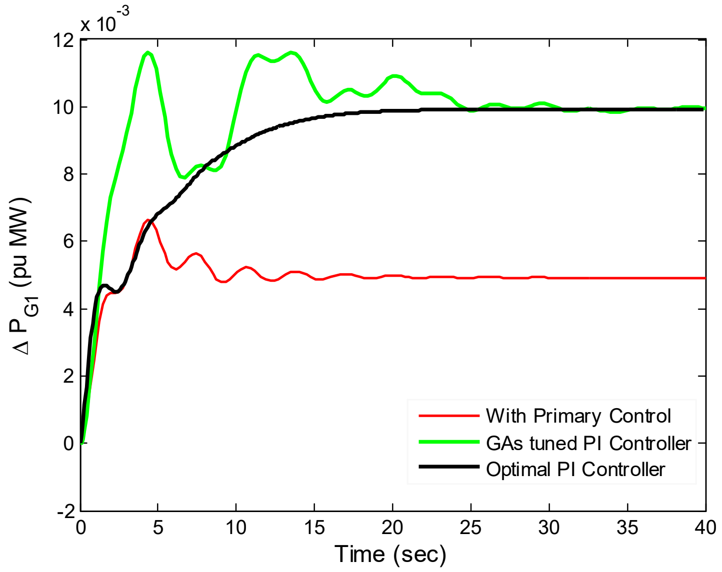
(a)


0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
Δ F2 (Hz)
0 5 10 15 20 25 30 35 40
Time (sec)
With Primary Control
GAs tuned PI Controller
Optimal PI Controller

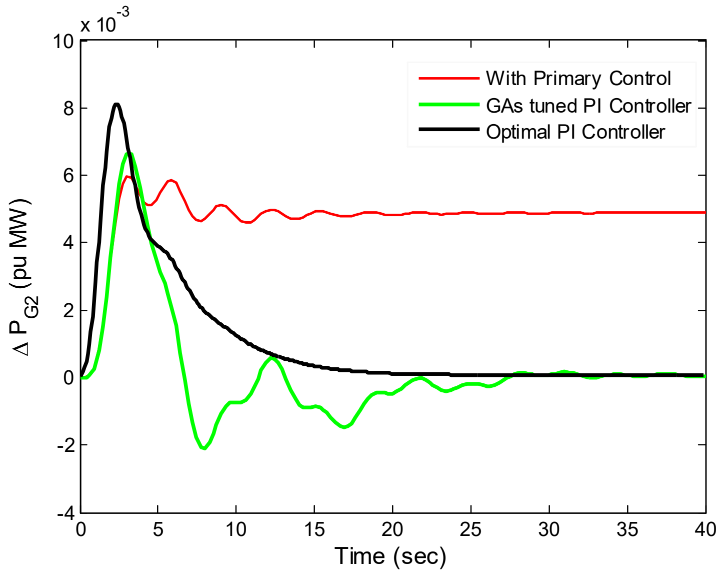
(b)


x 10-3
4
2
0
-2
-4
-6
-8
-10
Δ Ptie12 (pu MW)
0 5 10 15 20 25 30 35 40
Time (sec)
With Primary Control
GAs tuned PI Controller
Optimal PI Controller

(c)

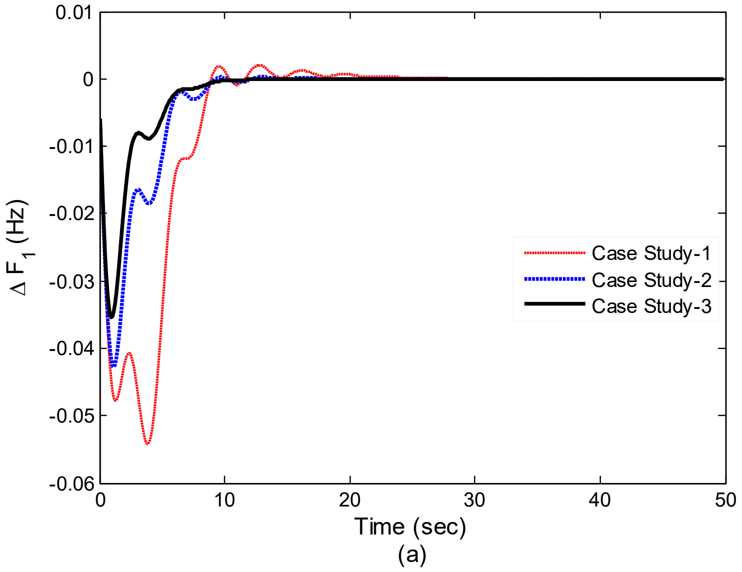


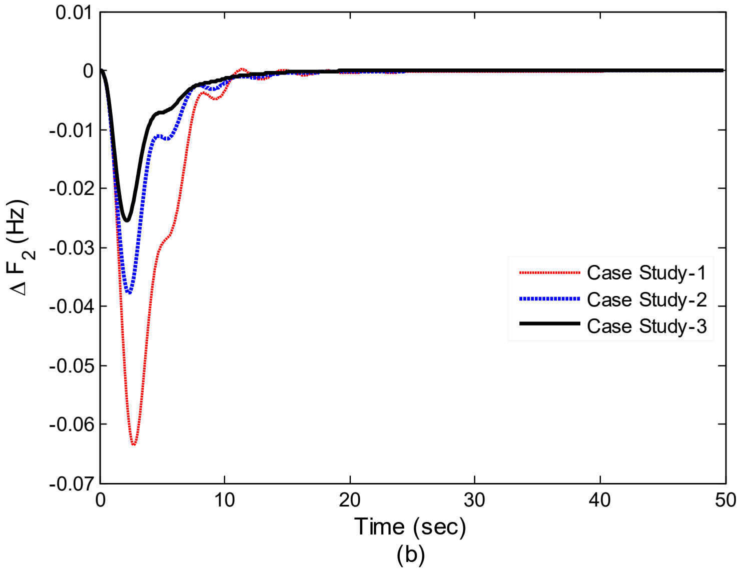
(d)

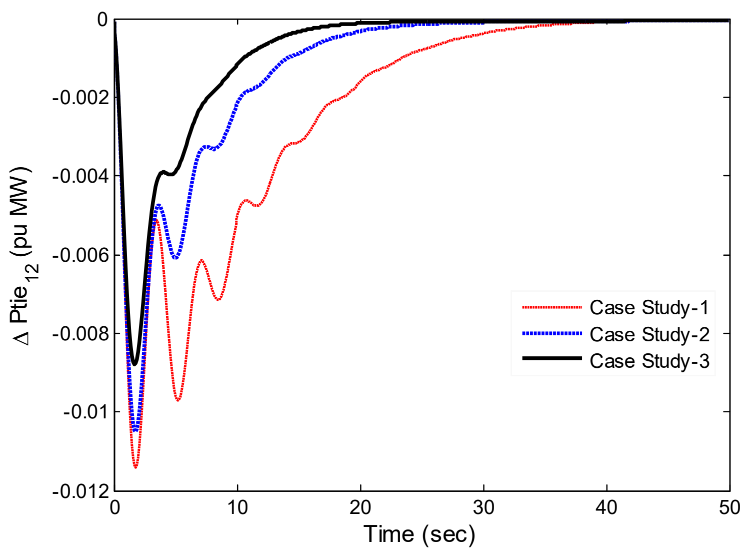


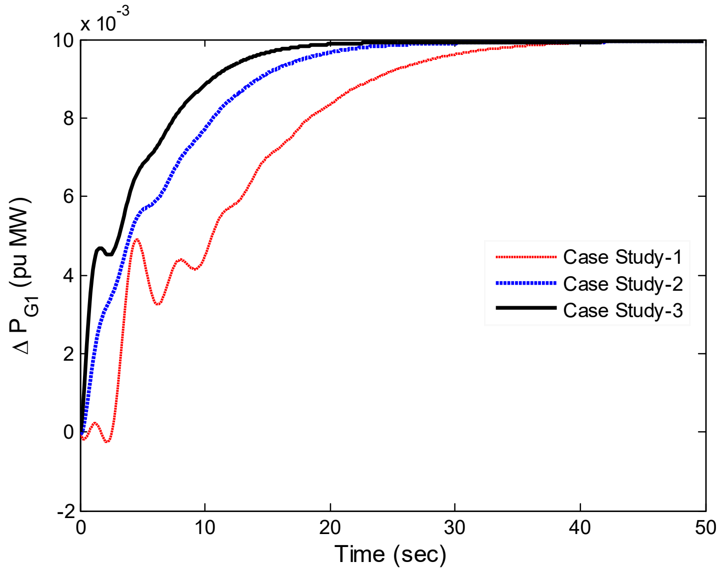
(e)

Fig. 3: Dynamic responses of PS for +1% step load disturbance in area-1; (a) F_1 Vs. Time, (b) F_2 Vs. Time, (c) $Ptie_{12}$ Vs. Time, (d) P_{G1} Vs. Time and (e) P_{G2} Vs. Time


0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
Δ F1 (Hz)
0
10
20
30
40
50
Time (sec)
Case Study-1
Case Study-2
Case Study-3
(a)


0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
Δ F2 (Hz)
0
10
20
30
40
50
Time (sec)
Case Study-1
Case Study-2
Case Study-3
(b)


0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
Δ Ptie 12 (pu MW)
0
10
20
30
40
50
Time (sec)
Case Study-1
Case Study-2
Case Study-3
(c)


x 10-3
10
8
6
4
2
0
-2
Δ PG1 (pu MW)
0
10
20
30
40
50
Time (sec)
Case Study-1
Case Study-2
Case Study-3
(d)

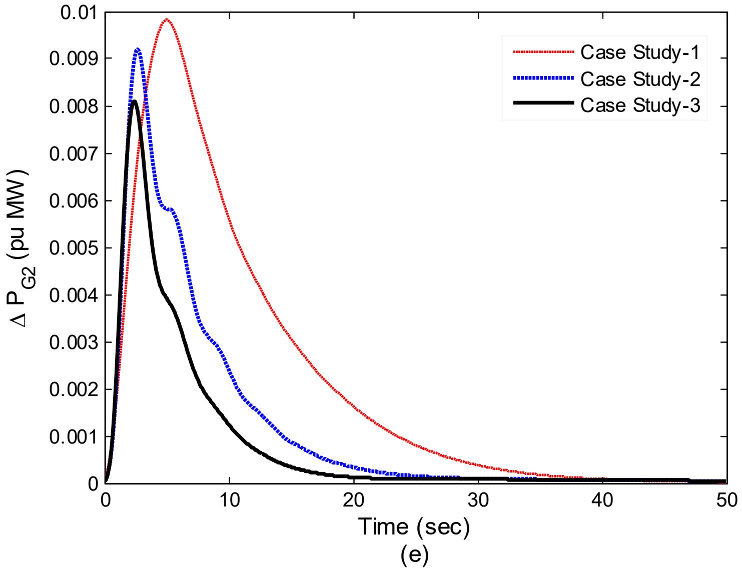
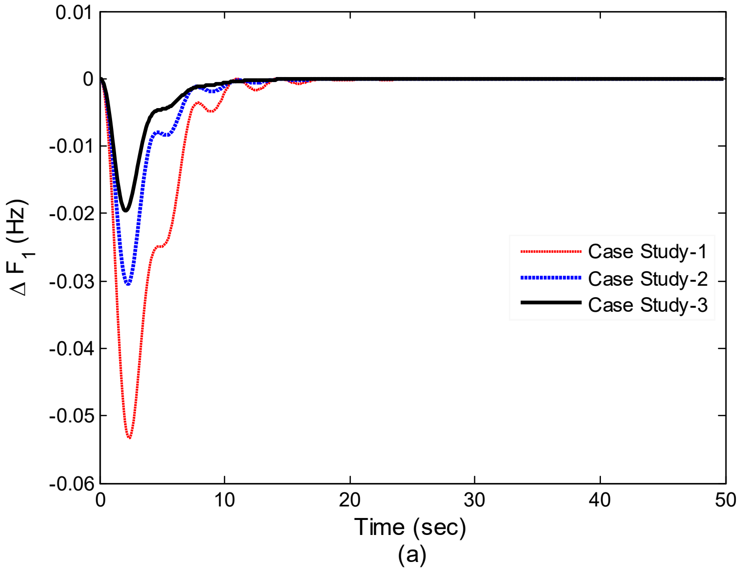
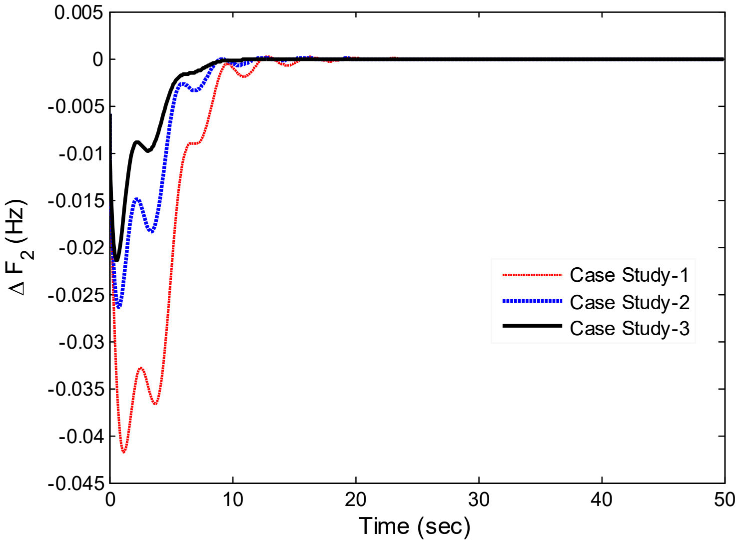
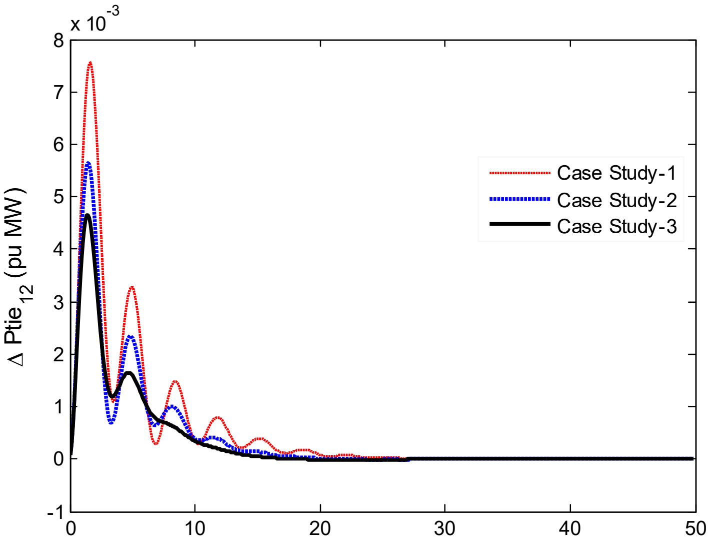


Fig. 4: Dynamic responses of PS with 1% load disturbance in area-1 for case studies 1-3 (a) F_1 Vs. Time, (b) F_2 Vs. Time, (c) $Ptie_{12}$ Vs. Time, (d) P_{G1} Vs. Time and (e) P_{G2} Vs. Time

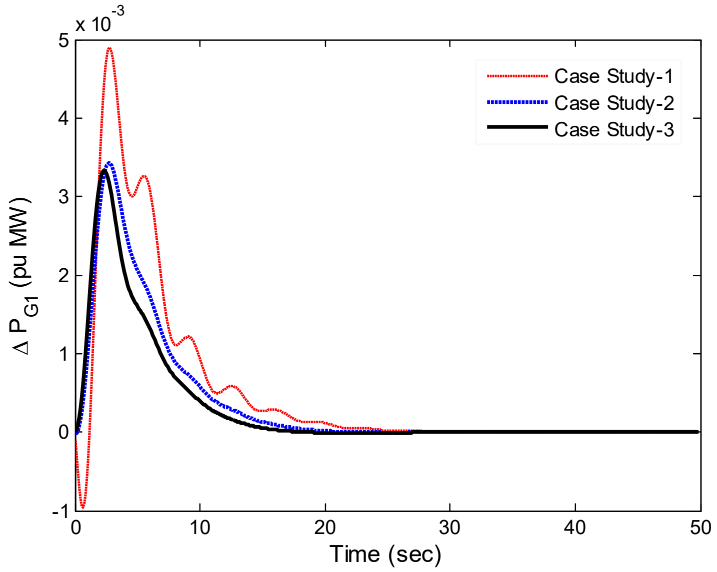



0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
-0.035
-0.04
-0.045
Δ F 2 (Hz)
0
10
20
30
40
50
Time (sec)
Case Study-1
Case Study-2
Case Study-3

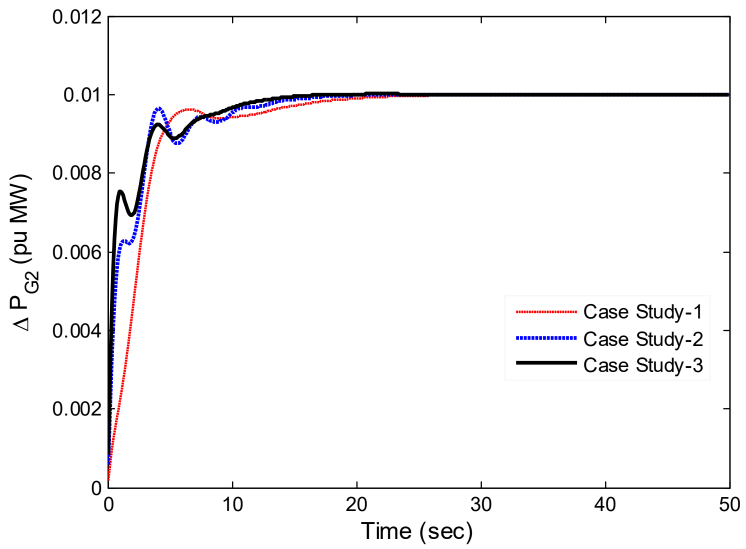
(b)


x 10-3
8
7
6
5
4
3
2
1
0
-1
Δ Ptie 12 (pu MW)
0
10
20
30
40
50
Time (sec)
Case Study-1
Case Study-2
Case Study-3

(c)



(d)



(e)

Fig. 5: Dynamic responses of PS with +1% step load disturbance in area-2 for case studies 1-3; (a) F_1 Vs. Time, (b) F_2 Vs. Time, (c) $Ptie_{12}$ Vs. Time, (d) P_{G1} Vs. Time and (e) P_{G2} Vs. Time.

7. DISCUSSION OF RESULTS

Analysis of J* from Table 3 revealed that the optimal value of cost function is showing decreasing trend when moving from case study 1 to 3. This infers that the transient responses with optimal AGC controller would be better for case study 3 in comparison to other case studies, when most of the hydro generation is substituted by thermal generation. However, worst dynamic performance would be obtained for case study 1, when most of the thermal generation is substituted by hydro power generation.

However, the investigation of Table 4 predicts that closed-loop PS is found to be stable for all case studies since real parts of all eigenvalues lie in the negative half of the complex s-plane. Besides, magnitudes corresponding to closed-loop eigenvalues given at serial number 1-12 and 13-17 are towards considerably increasing and decreasing trends respectably. But closed-loop system stability is improved more due to more significantly increment in the negative part of the eigenvalues of state variables corresponding to serial number (1-12) rather than eigenvalues of the other state variables as given in Table 4.

It has been observed from Figs. 3 (a)-(e) that in the condition of 'With Primary Controller', the system is unable to control the steam/hydro speed governors in the desired manner to mitigate the step load disturbance. This infers that there is need of supplementary control to mitigate instantaneous load disturbance in a desired manner. When supplementary control using GAs tuned PI controller is implemented in the power system; the system is able to control the steam/hydro speed governors in the desired manner for mitigating the load disturbances. But larger oscillations and enormous settling time are associated in the dynamic performance responses for PS with implementation of above GAs controller.

It has been inferred from Fig. 3 that the transient performance of optimal AGC controller is outstanding over GAs tuned PI structured controller. It has also been demonstrated that the optimal AGC controller is capable to mitigate load disturbance by adjusting setting of the speed governors to the hydro and thermal turbines located in respective control areas. The implementation of above optimal AGC controller demonstrates a fruitful improvement in settling time, reduction in number of oscillatory modes in comparison to GAs tuned AGC controller for power system. Therefore, optimal AGC controller is found to be far superior over GAs tuned PI structured AGC controller.

It has been observed from Fig 4 that the transient responses of ΔF_1, ΔF_2 and $\Delta Ptie_{12}$ gets improved with optimal AGC controller for case study 2 in comparison to case study 1 due to increased part of generation share by the thermal plant in case study 2. However, further improvements of system dynamic of above states have been seen for case study 3 in comparison to other case studies. This inferred that system dynamic responses of these states have been performed outstanding when a huge reduction in the share of hydro generation and it is replaced by generation from thermal power plants.

It has been found from the responses shown in Fig. 5 that the final deviation in power generations i.e., $\Delta P_{G1}$and ΔP_{G2} are setting to the value of 0.01 pu MW and 0.00 pu MW, respectively, which is equal in magnitude to the +1% step load disturbance. This trend also presents that the disturbed area is capable to execute its responsibility for mitigate the load disturbance in its own area by generating power equal to load disturbance due to the presence of optimal AGC controller in the PS.

It has been observed with optimal AGC controller, the lower value of cost function, increased in closed loop system stability margin and outstanding dynamic performance of PS have been observed when subject to the reduction in share of hydro generation is replaced by thermal power plants for tracing of case study 1 to 3 via 2. Moreover, opposite trend of results have been observed for moving towards case study 3 to 1 via 2 but an appreciable improvements in reduction of air pollution is also obtained when thermal generation is replaced by hydro generation. Similar performance of the PS have been obtained with optimal AGC controller for +1% instantaneous load demand in area-2 as shown in Figs. 5 (a)-(e).

8. CONCLUSION

This paper presents an application of optimal control theory to a 2-area PS by considering natural choices of power plants participating in AGC scheme. The 2-area multi source PS connected by AC tie line with hydro and thermal generation has been taken for state space modeling. However, with optimal AGC controller, lower value of cost function, increased in closed-loop system stability margin and an outstanding system dynamic responses have been observed when the share of hydro power generation is reduced and it has been replaced by thermal power generation by conducting various case studies. It has been observed that, when optimal PI structured AGC scheme is implemented in PS, the performance of PS is found to be better than those obtained with GAs controller. It has also been observed that when optimal AGC scheme is implemented in PS, the disturbed area is responsible to meet load disturbance by generating power, which is equal to the load disturbance.

REFERENCES

[1] O.I. Elgerd and C.E. Fosha, **Optimum megawatt-frequency control of multi-area electric energy systems**, *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-89, no. 4, pp. 556-563, 1970.

[2] C.E. Fosha and O. I. Elgerd, **The megawatt frequency control problem: A new approach via optimal control theory**, *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-89, no. 4, pp. 563-577, 1970.

[3] P. Kundur, ***Power System Stability and Control***, McGraw-Hill: New York, USA, 1994.

[4] Ibraheem, P. Kumar and D.P. Kothari, **Recent philosophies of automatic generation control strategies in power systems**, *IEEE Transactions on Power Systems*, vol. 20, no. 1, pp. 346-357, 2005.

[5] P. Kumar and Ibraheem, **AGC strategies: a comprehensive review**, *Int. Journal of Power and Energy Systems*, vol. 16, no. 1, pp. 371-376, 1996.

[6] Ibraheem, P. Kumar and S. Khatoon, **Overview of power system operational and control philosophies**, *International Journal of Power and Energy Systems*, vol. 26, no. 1, pp. 1-11, 2006.

[7] S.K. Pandey, S.R. Mohanty and N. Kishor, **A literature survey on load frequency control for conventional and distribution generation power systems**, *Renewable and Sustainable Energy Reviwes*, no. 25, pp. 318–334, 2013.

[8] A.M. Kassem, **Neural predictive controller of a two-area load frequency control for interconnected power system**, *Ain Shams Engineering Journal*, vol. 1, no. 1, pp. 49–58, 2010.
[9] F. Beaufays, Y. Abdel-Magid and B. Widrow, **Application of neural networks to load-frequency control in power systems**, *Journal of Neural Network*, vol. 7, no. 1, pp. 183-194, 1994.
[10] A. Demiroren, N.S. Sengor and H.L. Zeynelgil, **Automatic generation control by using ANN technique**, *Electric Power Components and Systems*, vol. 29, no. 10, pp. 883-896, 2001.
[11] Y. Oysal, A.S. Yilmaz and E. Koklukaya, **Dynamic fuzzy networks based load frequency controller design in electrical power systems**, *Gazi University Journal of Science*, vol. 17, no. 3, pp. 101-114, 2004.
[12] E. Cam, **Application of fuzzy logic for load frequency control of hydro electrical power plants**, *Energy Conversion and Management*, vol. 48, no. 4, pp. 1281-1288, 2007.
[13] Y. Oguz, **Fuzzy PI Control with Parallel Fuzzy PD Control for Automatic Generation Control of a Two-Area Power Systems**, *Gazi University Journal of Science*, vol. 24, no. 4, pp. 805-816, 2011.
[14] Y. Arya, N. Kumar and S. K. Sinha, **Fuzzy logic based load frequency control of multi-area electrical power system considering non-linearities and boiler dynamics**, *Int. Energy Journal*, vol. 13, no. 2, pp. 97-111, 2012.
[15] Y. Arya and N. Kumar, **Fuzzy gain scheduling controllers for AGC of two-area interconnected electrical power systems**, *Electric Power Components and Systems*, vol. 44, no. 7, pp. 737–751, 2016.
[16] Y.L. Abdel-Magid and M.M. Dawoud, **Optimal AGC tuning with genetic algorithms**, *Electric Power Systems Research*, vol. 38, no. 3, pp. 231-238, 1996.
[17] Z.M. Al-Hamouz and H.N. Al-Duwaish, **A new load frequency variable structure controller using genetic algorithms**, *Electric Power Systems Research*, vol. 55, no. 1, pp. 1-6, 2000.
[18] A. Abdennour, **Adaptive optimal gain scheduling for the load frequency control problem**, *Electric Power Components and Systems*, vol. 30, no. 1, pp. 45-56, 2002.
[19] D. Rerkpreedapong, A. Hasanovic, and A. Feliachi, **Robust load frequency control using genetic algorithms and linear matrix inequalities**, *IEEE Transactions on Power Systems*, vol. 18, no. 2, pp. 855-861, 2003.
[20] K.S.S. Ramakrishna and T.S. Bhatti, **Sampled-data automatic load frequency control of a single area power system with multi-source power generation**, *Electric Power Components and Systems*, vol. 35, no. 8, pp. 955-980, 2007.
[21] K.S.S. Ramakrishna and T.S. Bhatti, **Discrete data load frequency control of two-area power system with multi-source power**, *Int. Energy Journal*, vol. 9, no. 2, pp. 145-154, 2008.

[22] K.S.S. Ramakrishna, P. Sharma and T.S. Bhatti, **Automatic generation control of interconnected power system with diverse sources of power generation**, *Int. Journal of Engineering, Science and Technology*, vol. 2, no. 5, pp. 51-65, 2010.
[23] K.S.S. Ramakrishna and T.S. Bhatti, **Automatic generation control of single area power system with multi-source power generation**, *Proc. of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, vol. 222, pp. 1-11, 2008.
[24] A.M. Jadhav and K. Vadirajacharya, **Performance verification of PID controller in an interconnected power system using particle swarm optimization**, *Energy Procedia*, vol. 14, pp. 2075-2080, 2012.
[25] H. Gozde and M.C. Taplamacioglu, **Automatic generation control application with craziness based particle swarm optimization in a thermal power system**, *Int. Journal of Electrical Power & Energy Systems*, vol. 33, no. 1, pp. 8-16, 2011.
[26] N. Pathak, A. Verma, T.S. Bhatti and I. Nasiruddin, **Modeling of HVDC tie-links and their utilization in AGC/LFC operations of multi-area power systems**, *IEEE Transactions on Industrial Electronics*, (Early Access), 2018.
[27] S.M. Abd-Elazim and E.S. Ali, **Load frequency controller design via BAT algorithm for nonlinear interconnected power system**, *International Journal of Electrical Power & Energy Systems*, vol. 77, pp. 166-177, 2016.
[28] N. Hasan, Ibraheem and S. Farooq, **Parameter optimization of automatic generation controller for interconnected power systems using BAT algorithm**, *Proc. National Conference on Emerging Trends in Electrical and Electronics Engineering*, Jamia Millia Islamia, New Delhi, India.
[29] E.S. Ali and S.M. Abd-Elazim, **Bacteria foraging optimization algorithm based load frequency controller for interconnected power system**, *International Journal of Electrical Power & Energy Systems*, vol. 33, no. 3, pp. 633-638, 2011.
[30] E.S. Ali and S.M. Abd-Elazim, **BFOA based design of PID controller for two area load frequency control with nonlinearities**, *International Journal of Electrical Power & Energy Systems*, vol. 51, pp. 224-231, 2013.
[31] I. Nasiruddin, T.S. Bhatti and N. Hakimuddin, **Automatic generation control in an interconnected power system incorporating diverse source power plants using bacteria foraging optimization technique**, *Electric Power Components and Systems*, vol. 43, no. 2, pp. 189-199, 2015.
[32] H. Gozde, M.C. Taplamacıoğlu, I. Kocaarslan, **Comparative performance analysis of artificial bee colony algorithm in automatic generation control for interconnected reheat thermal power system**, *International Journal of Electrical Power & Energy Systems*, vol. 42, no. 1, pp. 167-178, 2012.

[33] S.J. Safi, S.S. Tezcan, I. Eke and Z. Farhad, **Gravitational search algorithm (GSA) based pid controller design for two area multi-source power system load frequency control (LFC)**, *Gazi University Journal of Science*, vol. 31, no. 1, pp. 139-153, 2018.
[34] R.K. Sahu, S. Panda and S. Padhan, **Optimal gravitational search algorithm for automatic generation control of interconnected power systems**, *Ain Shams Engineering Journal*, vol. 5, no. 3, pp. 721-733, 2014.
[35] P. Dahiya, P. Mukhija, A. R. Saxena, and Y. Arya, **Comparative performance investigation of optimal controller for AGC of electric power generating systems**, *Automatika-Journal for Control, Measurement, Electronics, Computing and Communications*, vol. 57, no. 4, pp. 902–921, 2016.
[36] Y. Arya and N. Kumar, **Optimal AGC with redox flow batteries in multi-area restructured power systems**, *Engineering Science and Technology, an International Journal*, vol. 19, no. 3, pp. 1145–1159, 2016.
[37] Y. Arya, N. Kumar and Ibraheem, **AGC of a two-area multi-source power system interconnected via AC/DC parallel links under restructured power environment**, *Optimal Control Applications & Methods*, vol. 37, no. 4, pp. 590–**607, 2016.**
[38] P. Kumar and Ibraheem, **Dynamic performance evaluation of 2-area interconnected power systems: A comparative study**, *Journal of Institution of Engineers (India)*, vol. 78, pp. 199-208, 1998.
[39] Ibraheem and P. Kumar, **A novel approach to the matrix Riccati equation solution: An application to optimal control of interconnected power systems**, *Electric Power Components and Systems*, vol. 32, no. 1, pp. 33–52, Jan. 2004.
[40] Ibraheem and P. Kumar, **Current status of the Indian power system and dynamic performance enhancement of hydro-power systems with asynchronous tie-lines**, *Electric Power Components and Systems*, vol. 31, no. 7, pp. 605-626, 2003.
[41] Ibraheem, P. Kumar and S. Ahmad, **Dynamic performance enhancement of hydro-power systems with asynchronous tie-lines**, *Journal of Institution of Engineers (India)*, vol. 85, no. EL-1, pp. 23-34, 2004.
[42] Ibraheem and P. Kumar, **Study of dynamic performance of power systems with asynchronous tie-lines considering parameter uncertainties**, *Journal of Institution of Engineers (India)*, vol. 85, no. EL-1, pp. 35-42, 2004.
[43] Ibraheem, Nizamuddin and T.S. Bhatti, **AGC of two area power system interconnected by AC/DC links with diverse sources in each area**, *International Journal of Electrical Power and Energy Systems*, vol. 55, pp. 297-304, 2014.
[44] Y. Arya and N. Kumar, **Optimal control strategy-based AGC of electrical power systems: A comparative performance analysis**, *Optimal Control Applications & Methods*, vol. 38, no. 6, pp. 982-992, 2017.

[45] Y. Arya, N. Kumar and S.K. Gupta, **Optimal automatic generation control of two-area power systems with energy storage units under deregulated environment**, *Journal of Renewable and Sustainable Energy*, vol. 9, no. 6, pp. 1-20, 2017.
[46] I. Nasiruddin and S.B. Altamini, **Effect of wind energy participation in AGC of interconnected multisource power systems**, *Journal of Electrical & Electronics Systems*, vol. 5, no. 2, pp. 1-6, 2016.
[47] M.R. Djalal, M.Y. Yunus, A. Imran and H. Setiadi, **Capacity energy storage (CES) optimization for load frequency control in micro hydro power plant using imperialist competitive algorithm (ICA)**, *EMITTER International Journal of Engineering Technology,* vol. 5, no. 2, pp. 279-297, 2017.

Appendix-A

$$A=\begin{bmatrix}
-\frac{1}{T_{r1}} & \frac{1-K_{r1}}{T_{r1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & -\frac{1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & -\frac{1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{R_1T_{g1}} & 0 & 0 & 0 & 0\\
0 & 0 & 0 & -\frac{2}{T_{w1}} & \frac{6}{T_{w1}} & \frac{6T_{R1}}{T_{W1}T_{RH1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & -\frac{1}{T_{GH1}} & \frac{1}{T_{GH1}}-\frac{T_{R1}}{T_{GH1}^2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{RH1}} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{R_1T_{RH1}} & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{r2}} & \frac{1-K_{r2}}{T_{r2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{t2}} & \frac{1}{T_{t2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{g2}} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{R_2T_{g2}} & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{2}{T_{w2}} & \frac{6}{T_{w2}} & \frac{6T_{R2}}{T_{W2}T_{RH2}} & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{GH2}} & \frac{1}{T_{GH2}}-\frac{T_{R2}}{T_{GH2}^2} & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{RH2}} & 0 & 0 & -\frac{1}{R_2T_{RH2}} & 0 & 0\\
\frac{K_{P1}K_{t1}}{T_{P1}} & \frac{K_{P1}K_{t1}K_{r1}}{T_{P1}} & 0 & \frac{K_{P1}K_{h1}}{T_{P1}} & -\frac{2K_{P1}K_{h1}}{T_{P1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{P1}} & -\frac{K_{P1}}{T_{P1}} & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{12}^* & 0 & -T_{12}^* & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & \frac{K_{P2}K_{t2}}{T_{P2}} & \frac{K_{P2}K_{t2}K_{r2}}{T_{P2}} & 0 & \frac{K_{P2}K_{h2}}{T_{P2}} & -\frac{2K_{P2}K_{h2}}{T_{P2}} & 0 & 0 & -\frac{\alpha_{12}K_{P2}}{T_{P2}} & -\frac{1}{T_{P2}} & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \beta_1 & 1 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \alpha_{12} & \beta_2 & 0 & 0
\end{bmatrix} \quad (37)$$

$$B = \begin{bmatrix} 0 & 0 & \frac{1}{T_{g1}} & 0 & 0 & \frac{1}{T_{RH1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{g2}} & 0 & 0 & \frac{1}{T_{RH2}} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \tag{38}$$

$$\Gamma = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{K_{P2}}{T_{P2}} & 0 \end{bmatrix}^T \tag{39}$$

The matrices C, Q and R are considered to be an identity matrix of appropriate dimensions.