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Automatic generation control of interconnected power system with diverse sources of power generation

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Abstract

In this paper, automatic generation control (AGC) of two area interconnected power system having diverse sources of power generation is studied. A two area power system comprises power generations from hydro, thermal and gas sources in area-1 and power generations from hydro and thermal sources in area-2. All the power generation units from different sources are equipped with speed governors. A continuous time transfer function model of the system for studying dynamic response for small load disturbances is presented. A proportional-integral-derivative (PID) automatic generation control scheme is applied only to power generations from thermal and gas sources and power generation from hydro source is allowed to operate at its scheduled level with only speed governor control. The two area power system is simulated for different nominal loading conditions. Genetic algorithm (GA) is used to obtain the optimal PID gains for various cases using integral squared error plus integral time absolute error (ISE+ITAE) performance index for fitness evaluation. Some of the transient responses are shown for different nominal loading conditions due to step load disturbances in the system.

Keywords: Two area power system, Diverse sources of power generation, Automatic generation Control , Genetic algorithm, PID controller

1. Introduction

Power systems consist of control areas representing a coherent group of generators i.e. generators which swing in unison characterized by equal frequency deviations. In addition to their own generations and to eliminate mismatch between generation and demand these control areas are interconnected through tie-lines for providing contractual exchange of power under normal operating conditions. One of the control problems in power system operation is to maintain the frequency and power interchange between the areas at their rated values. Automatic generation control is to provide control signals to regulate the real power output of various electric generators within a prescribed area in response to changes in system frequency and tie-line loading so as to maintain the scheduled system frequency and established interchange with other areas (Elgerd, 1971). The performance of the automatic generation control depends upon how various power generating units respond to these signals. The speed of their response is limited by natural time lags of the various turbine dynamics and the power system itself. In other words the design of automatic generation controller depends upon various energy source dynamics involved in the AGC of the area. A large number of research papers have been published in the last three decades in which the power system considered for these studies were two area thermal-thermal or hydro-thermal systems (Abdel-Magid et al. 1995; Elgerd et al. 1970; Karnavas 2006; Wang, 1993). But in real situations each control area may have large number of various sources of power generation such as hydro, thermal, gas, nuclear etc. The various generations are connected by a stiff network that is why the frequency deviations are assumed to be equal in an area.

The load over a day varies which is evident from a daily load curve. Therefore the contributions of generations from various sources in an area are adjusted to meet the load variations. The performance of the Automatic Generation Control may also vary in respect to the changes in the share of different type of power generations to the total generation of the area. In order to obtain the optimum realistic AGC performance, the automatic generation controller parameters have to be optimized for various nominal loading conditions. In practice, it is not necessary that all type of power generating units having speed governors may take part in the area AGC activity. Due to the lower power production cost a typical generation in an area may be contributing to its maximum by running at its rated load capacity while others may not be. In such case the typical generation is regulated by the speed governor alone but its dynamics will also play a role in the selection of the automatic generation controller parameters for other generations in the area. The authors have studied the automatic generation control of single area power system with diverse sources of power generation (Ramakrishna et al., 2007). It has been shown that the dynamics of all the energy sources in the area are required to be incorporated for obtaining the optimum controller parameters. It has also been shown that the dynamic performance of the system is better if each individual source have an optimum automatic generation controller than a common controller for all sources in an area.

In order to obtain better transient performance of the system various control strategies have been applied to the automatic generation control problem (Abdel-Magid et al. 1995, El-Saady et al. 2002, Karnavas 2006, Olmos et al. 2004). The optimum response can only be achieved with proper tuning of various controller parameters subjected to minimization of different performances indices. Tuning of conventional proportional and integral gains by using different performance indices have been studied in (Abdel-Magid 1995, Karnavas 2006). It has been observed that ISE criterion weighs heavily on the large fluctuation as compared to the small one. Therefore, it is more effective in reducing the initial swings of the transient response. The ITAE criterion is more suitable in reducing long duration transients as it penalizes the error by time. In this paper selection of PID controller gains using a combination of ISE and ITAE (Ramakrishna et al., 2007) criterion is presented for automatic generation control of two area interconnected power system with diverse sources of power generation. Genetic algorithm (GA) is used to optimize the controller parameters for different nominal loading conditions. The genetic algorithms are a stochastic global search method that mimics the process of natural evolution. Due to its high potential for global optimization, GA has received great attention in control systems such as the search of optimal PID controller parameters.

2. Power System Model

Figure 1 represents the detailed transfer function block diagram of an area with diverse sources of electric power generation namely, thermal, hydro and gas. The uncontrolled two area power system as shown in Figure 2 has power generations from hydro, thermal and gas sources in area-1 and from hydro and thermal sources in area-2.

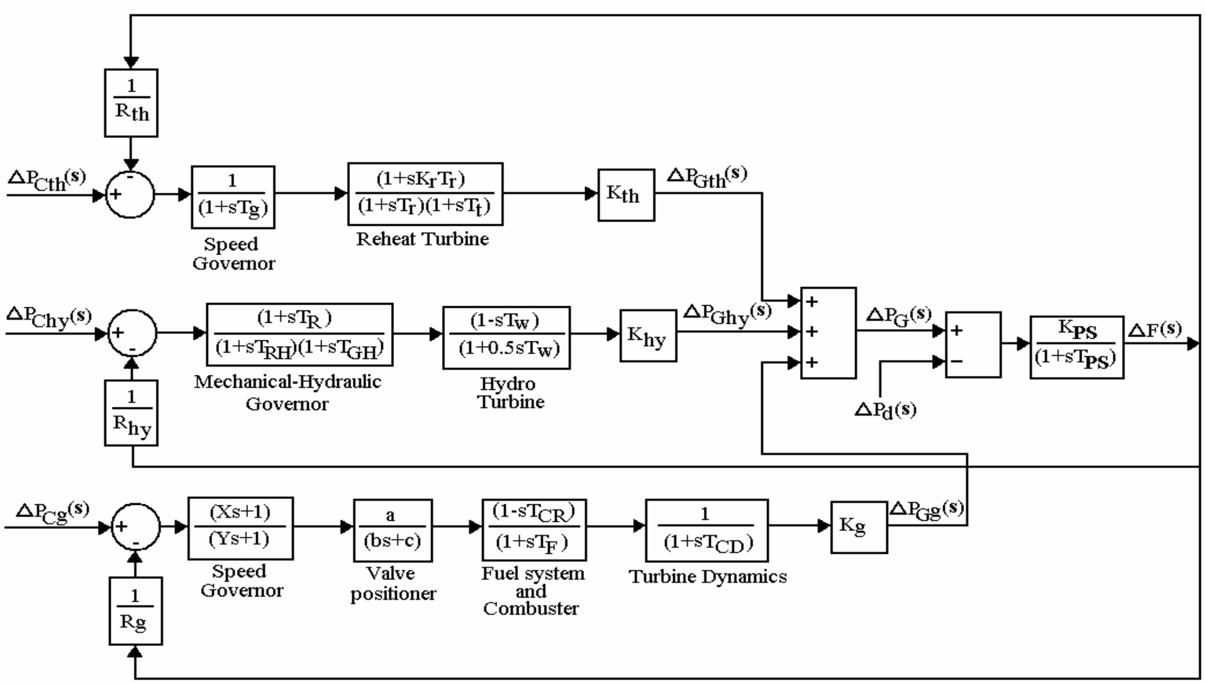


Figure 1. Transfer function block diagram of an area having power generations from hydro, thermal and gas sources

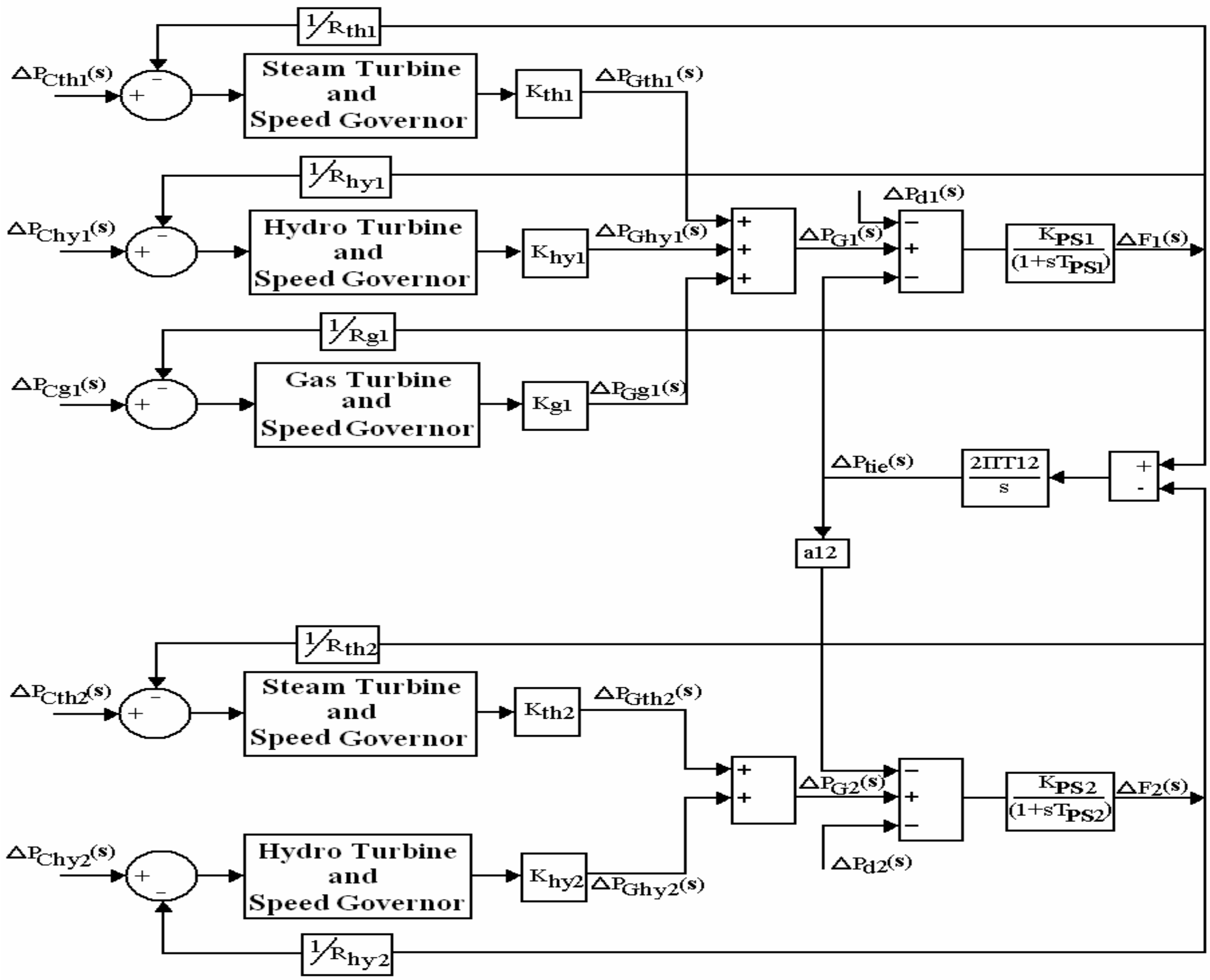


Figure 2. Block diagram of a two area power system

The thermal, hydro and gas based power generating units are represented by respective single plant dynamics (Elgerd, 1971, Hajagos et al. 2001, Lalor et al. 2005, Kundur 1970). Under normal operating conditions there is no mismatch between generation and load. The total generations in area-1 and area -2 are given by

$$P_{G1} = P_{Gth1} + P_{Ghy1} + P_{Gg1} \tag{1}$$

$$P_{G2} = P_{Gth2} + P_{Ghy2} \tag{2}$$

where

$$P_{Gthi} = K_{thi} P_{Gi},\ P_{Ghyi} = K_{hyi} P_{Gi},\quad i = 1,2 \text{ and } P_{Gg1} = K_{g1} P_{G1}$$

K_{th}, K_{hy} and K_g represent the share of the power generation by thermal, hydro and gas sources respectively to the total power generation. The values of K_{th}, K_{hy} and K_g depend upon the total load and also involve economic load dispatch. For small perturbation Eqns. (1) and (2) can be written as

$$\Delta P_{G1} = \Delta P_{Gth1} + \Delta P_{Ghy1} + \Delta P_{Gg1} \tag{3}$$

$$\Delta P_{G2} = \Delta P_{Gth2} + \Delta P_{Ghy2} \tag{4}$$

From Eqns. (1) and (2), under nominal generation and loading, $P_G^0 = P_L^0 = 1.0$ pu, we have

$$K_{th1} + K_{hy1} + K_{g1} = 1.0 \tag{5}$$

$$K_{th2} + K_{hy2} = 1.0 \tag{6}$$

The uncontrolled two area power system shown in Figure 2 becomes controlled system by having manipulations of the speed changer signals. It is assumed that only thermal and gas power generating units act in the automatic generation control of the system by having manipulations of ΔP_{Cth1}, ΔP_{Cth2} and ΔP_{Cg1}. The hydro generating unit in both areas is uncontrolled, i.e. $\Delta P_{Chyi}=0$ (i=1, 2). The speed changer signals are given by,

$$\Delta P_{Cthi} = K_{Pthi} ACE_i + K_{Ithi} \int ACE_i dt + K_{Dthi} \frac{d}{dt}(ACE_i) \qquad i = 1, 2 \tag{7}$$

$$\Delta P_{Cg1} = K_{Pg1} ACE_1 + K_{Ig1} \int ACE_1 dt + K_{Dg1} \frac{d}{dt}(ACE_1) \tag{8}$$

$$ACE_i = B\Delta f_i + \Delta P_{Tie} \tag{9}$$

The dynamic performance of the system depends upon these proportional, integral and derivative gains.

3. Parameter Optimization

The controller gains given in Eqns. (7) and (8) are optimized using genetic algorithm (Rerkpreedapong et al., 2003; Abdel-Magid 1995; Karnavas, 2006; Ramakrishna et al., 2007). GA solves optimization problems by exploitation of random search. When searching a large space GA may offer significant benefits over the traditional optimization techniques such as; (i) they work on encoding of control variables, rather than variables themselves, (ii) they search from one population of solution to another, rather than from individual to individual, (iii) they use only objective functions, not derivatives, hence they are derivative free optimization techniques and they do not rely on the detailed model of the system to be optimized.

In this problem GA is used to optimize the gains of conventional PID controller with (ISE+ITAE) performance index as fitness functions. The performance indices are given by,

$$ISE = \Delta P_{tie}^2 + \Delta f_1^2 + \Delta f_2^2 \tag{10}$$

$$ITAE = t(|\Delta P_{tie}| + |\Delta f_1| + |\Delta f_2|) \tag{11}$$

$$\eta_{ISE+ITAE} = \int (ISE + ITAE) dt \tag{12}$$

GA starts with randomly creating the initial population of binary strings called chromosomes. Each chromosome representing a possible solution to the optimization problem and is evaluated according to the fitness function. GA performs three basic operations such as reproduction, cross over and mutation.

Reproduction: creates new generation of chromosomes, fitness proportionate reproduction is achieved through roulette wheel selection.

Crossover: allows information to be exchanged between individuals in the population. Two parent strings are selected randomly and a new child string is created by combining random sub-string from two parent strings.

Mutation: random alteration of bits in a string which flips a bit from 1 to 0 or vice versa.

By the end of mutation new generation is complete and process is repeated for evaluation of new fitness.

4. Simulation Studies

A typical example of two area power system is considered for the simulation and the values of the different parameters of the system are given in Appendix-I. The initial values of the performance indices were obtained by carrying simulation of the system over a period of 100 sec with automatic generation controller gain parameters obtained from randomly selected initial population. These values were used to produce next generation of individuals and procedure is repeated until the population has converged to some minimum value of the performance index. The parameters for GA process are given in Appendix-II.

The two area system with diverse sources of power generation is simulated for different cases with 1% step load perturbation in either of the areas. The scheduled generations from each of the sources for different nominal loading conditions for both areas are given in Table T1 in Appendix-I. The transient responses of the system are given below for optimum values of PID gains which are evaluated using ISE+ITAE criterion.

Case I: 1% step load disturbance in area-1:

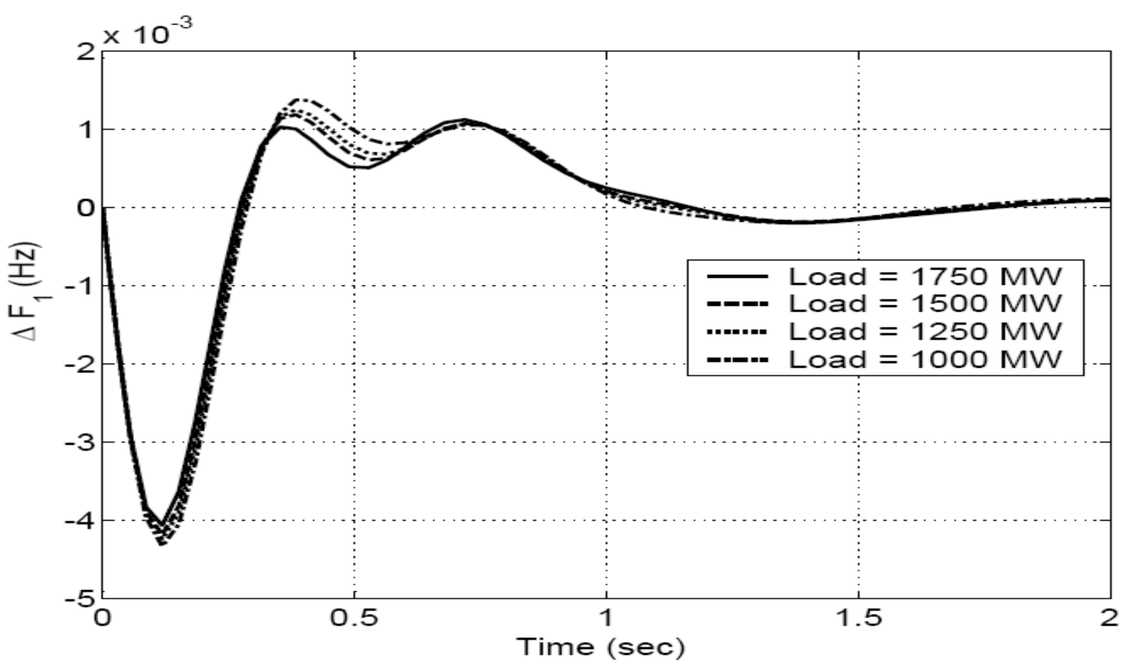
The two area system is simulated for various operating conditions for 1% step load disturbance only in area-1.

(i)Different scheduled thermal power generations in area-1:

The optimal values of the PID controller gains are given in Table 1 for different thermal power generations in area-1 to match the system nominal loading conditions. The other scheduled generations are kept constant. It has been observed that the optimal values of K_{Pth1}, K_{Ith1}, K_{Dth1}, K_{Ig1} and K_{Ith2} are increasing and K_{Dth2} is decreasing with decrease in thermal power generation. The transient system responses are shown in Figure 3. It has been observed that as the scheduled thermal generation is reduced to match the reduced nominal loading, system shows poor transient response with increase in first peak deviation.

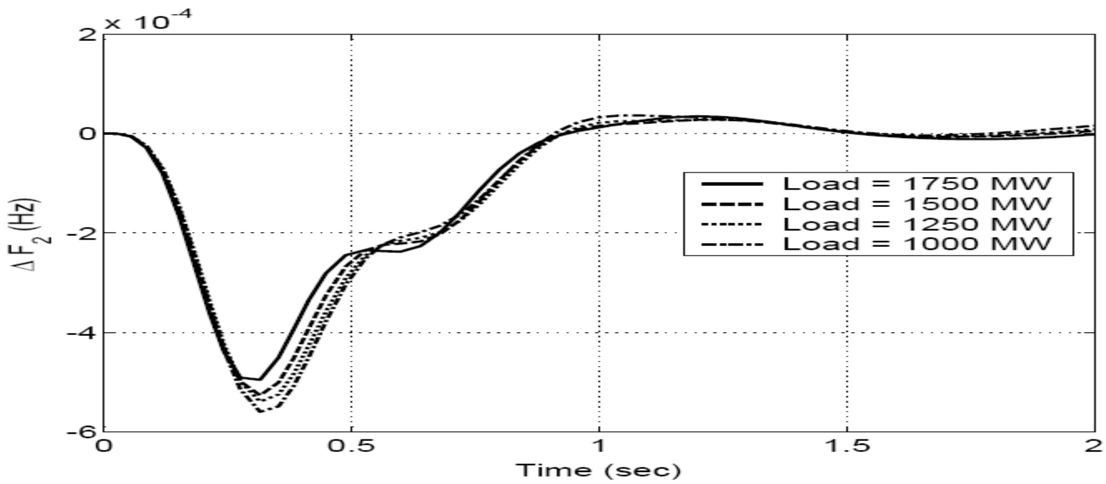
Table 1. Optimal PID controller gain values for different thermal power generation in area-1 to match nominal loading conditions with 1% step load disturbance in area-1.

Area 1							Area 2			
Load	Thermal			Gas			Load	Thermal		
	K_{Pth1}	K_{Ith1}	K_{Dth1}	K_{Pg1}	K_{Ig1}	K_{Dg1}		K_{Pth2}	K_{Ith2}	K_{Dth2}
1750	59.4706	305.8798	16.0235	0.0121	0.6631	0.0001	1750	3.651	0.5583	21.0392
1500	68.5882	338.0647	17.559	0.0138	0.896	0.0001	1750	3.5176	3.3941	18.0118
1250	85.7059	415.5332	21.7647	0.0171	1.2912	0.0001	1750	3.7314	4.4164	16.5059
1000	137.4118	671.2426	34.1922	0.0269	4.0732	0.0001	1750	4.6706	8.5287	16.302



(a)

Figure 3. System transient responses for different thermal power generations of area-1 with 1% step load disturbance in area-1, (a) area-1 frequency deviation



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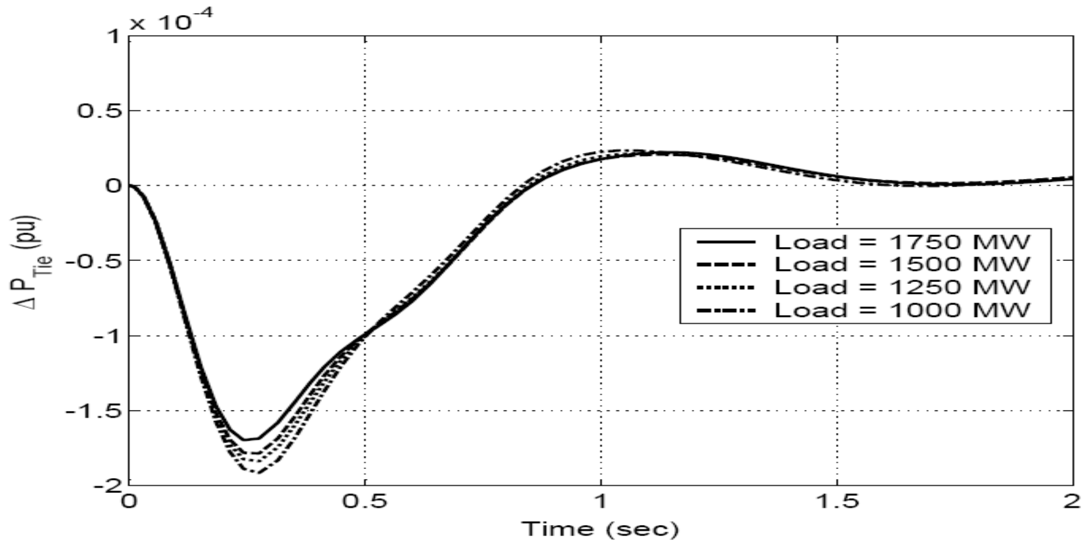


(c)

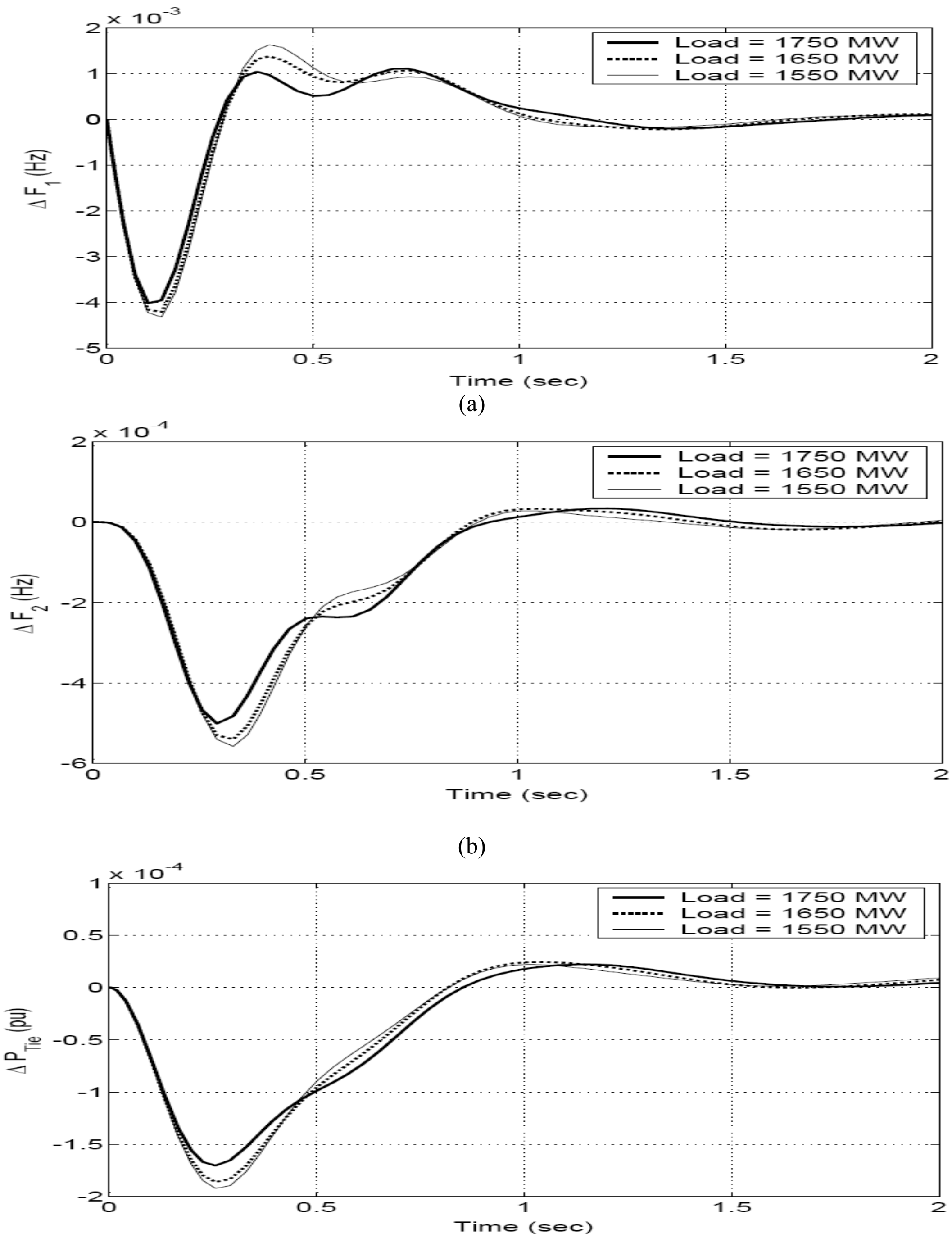
Figure 3 (cont'd). System transient responses for different thermal power generations of area-1 with 1% step load disturbance in area-1, (b) area-2 frequency deviation (c) tie-line power deviation.

(ii) Different scheduled gas power generations in area-1:

The optimal values of PID controller gains are given in Table 2 for different gas power generations in area-1 to match the system nominal loading conditions and keeping other scheduled power generations constant. It has been observed that the optimal values of K_{Pth1}, K_{Ith1}, K_{Dth1}, K_{Pth2} and K_{Dth2} are decreasing and K_{Pg1} and K_{Ig1} are increasing with decrease in scheduled load. As the scheduled gas power generation is reduced to match the reduced nominal loading, the system transient response deteriorates by increasing the first peak as shown in Figure 4.

Table 2. Optimal PID controller gain values for different gas power generation in area-1 to match the nominal loading conditions with 1% step load disturbance in area-1.

Area 1							Area 2			
Load	Thermal			Gas			Load	Thermal		
	K_{Pth1}	K_{Ith1}	K_{Dth1}	K_{Pg1}	K_{Ig1}	K_{Dg1}		K_{Pth2}	K_{Ith2}	K_{Dth2}
1750	59.4706	305.8798	16.0235	0.0121	0.6631	0.0001	1750	3.651	0.5583	21.0392
1650	54.4706	285.1784	13.8078	0.0199	2.9789	0.0001	1750	2.0235	0.8146	17.8235
1550	53.0706	262.5354	12.4745	0.0531	28.196	0.0001	1750	1.5294	0.3673	17.0759



(a)

(b)

(c)

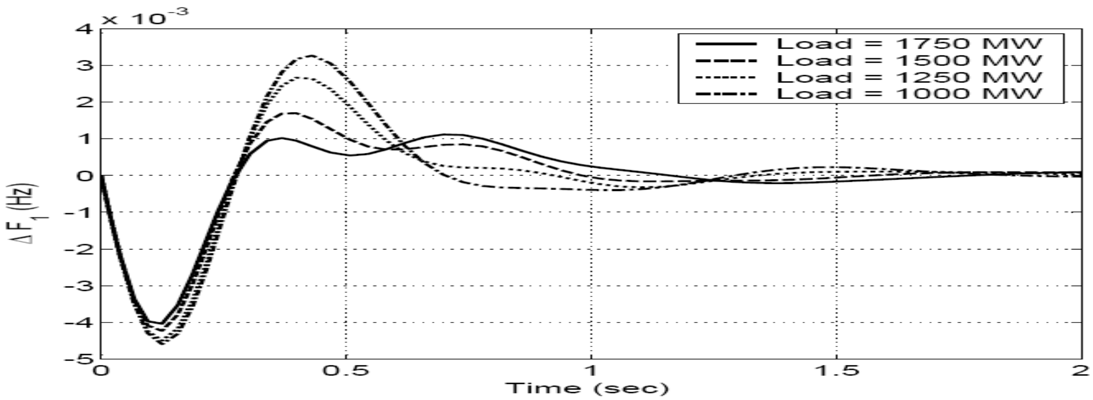
Figure 4. System transient responses for different gas power generations of area-1 with 1% step load disturbance in area-1, (a) area-1 frequency deviation (b) area-2 frequency deviation (c) tie-line power deviation.

(i) Different scheduled thermal power generation in area-2:

The optimal values of PID controller gains are given in Table 3 for different thermal power generations in area-2 to match the system nominal loading conditions. The other scheduled power generations are kept constant. The optimal values of K_{Ith1}, $K_{Pg1,}$ K_{Ig1} and K_{Dth2} are increasing and $K_{Dth1,}$ K_{Pth2} and K_{Ith2} are decreasing with decrease in scheduled thermal power generation. The transient system responses are shown in Figure5. Again it has been observed that the system shows poor transient response with increase in first peak deviation as thermal power generation is reduced.

Table 3. Optimal PID controller gain values for different thermal power generation in area-2 to match different nominal loading conditions with 1% load disturbance in area-1.

Area 1							Area 2			
Load	Thermal			Gas			Load	Thermal		
	K_{Pth1}	K_{Ith1}	K_{Dth1}	K_{Pg1}	K_{Ig1}	K_{Dg1}		K_{Pth2}	K_{Ith2}	K_{Dth2}
1750	59.4706	305.8798	16.0235	0.0121	0.6631	0.0001	1750	3.651	0.5583	21.0392
1750	64.2353	327.8815	14.5804	0.0213	3.7439	0.0001	1500	3.0078	0.4162	27.051
1750	65.5255	347.3483	12.8627	0.0679	28.604	0.0001	1250	2.7641	0.2101	32.3059
1750	64.3137	365.1788	12.2902	0.0975	88.794	0.0001	1000	2.4588	0.1817	40.2



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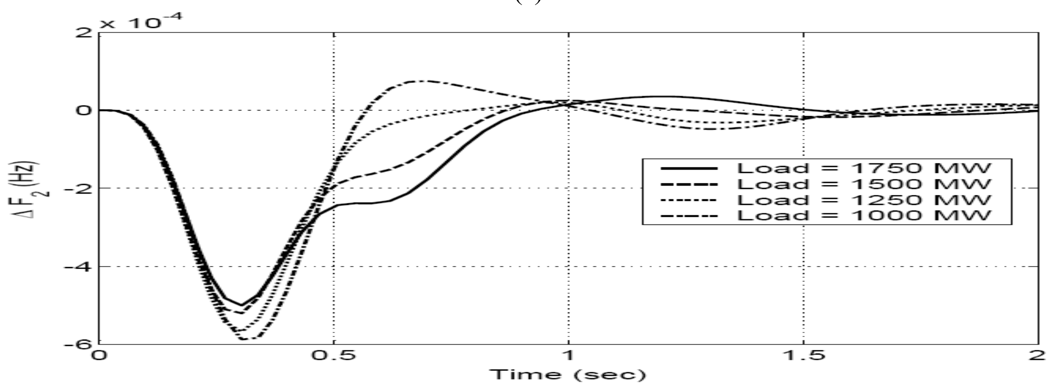

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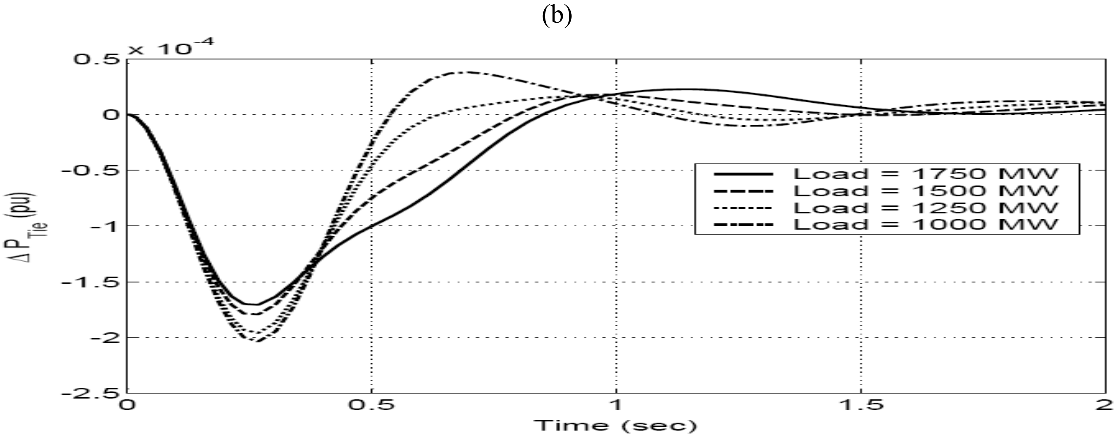


(c)

Figure 5 System transient responses for different thermal power generations of area-2 with 1% step load disturbance in area-1, (a) area-1 frequency deviation (b) area-2 frequency deviation (c) tie-line power deviation

Case II. 1% load disturbance in area-2:

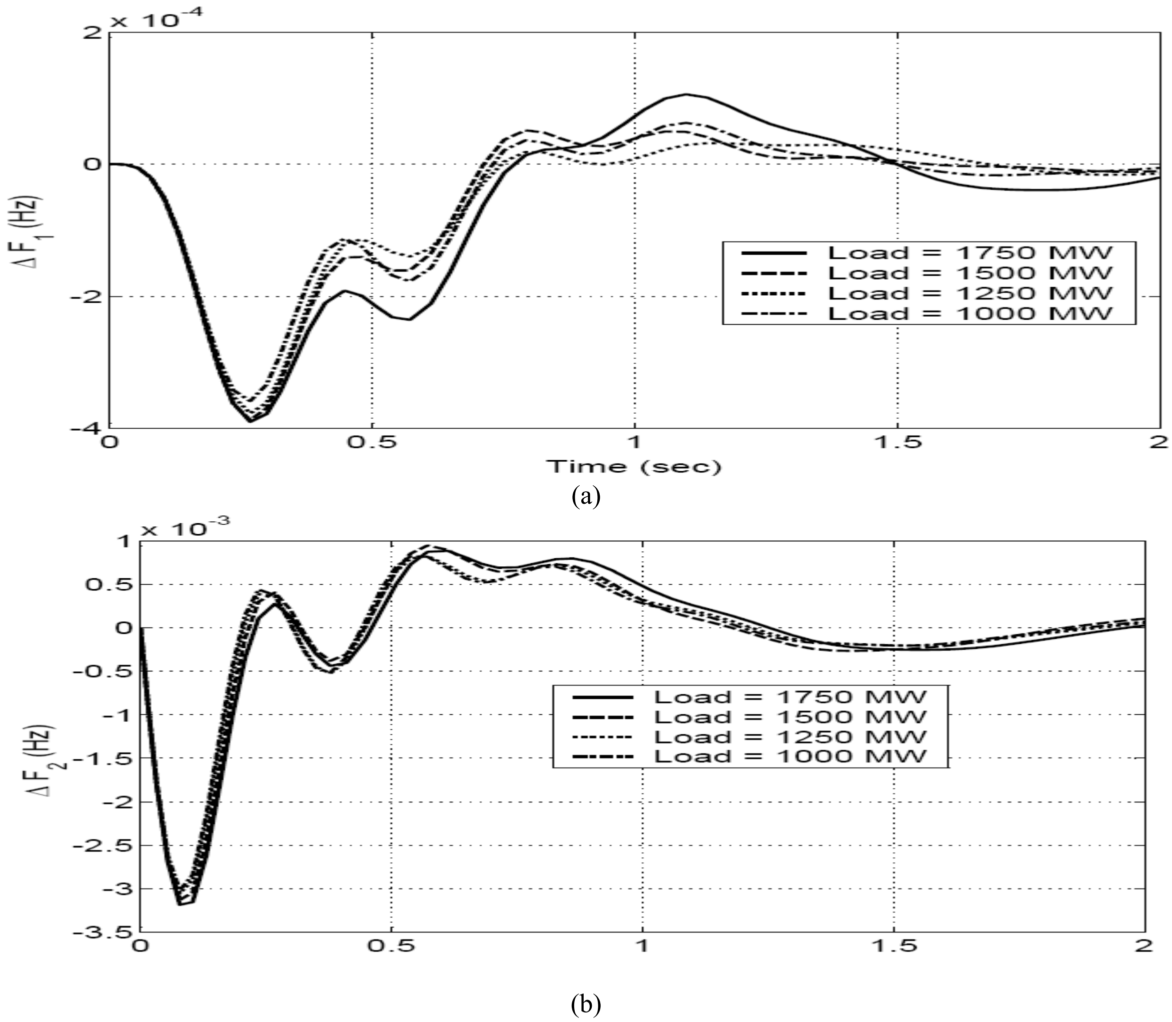
The two area power system is simulated for various operating conditions for 1% step load disturbance in area-2.

(i) Different scheduled thermal power generation in area-1:

The optimal values of the PID controller gains are given in Table 4 for different thermal power generations in area-1 to match the system nominal loading conditions. The other scheduled generations are kept constant. It has been observed that with decrease in scheduled thermal power generation the optimal values of K_{Pth1}, K_{Ith1}, K_{Dth1}, K_{Pth2}, K_{Ith2} and K_{Dth2} are increasing as nominal load decreases. The transient system responses are shown in Figure 6. It has been observed that the system transient response improves with decrease in first peak deviation as scheduled thermal power generation is reduced to match the normal operating load.

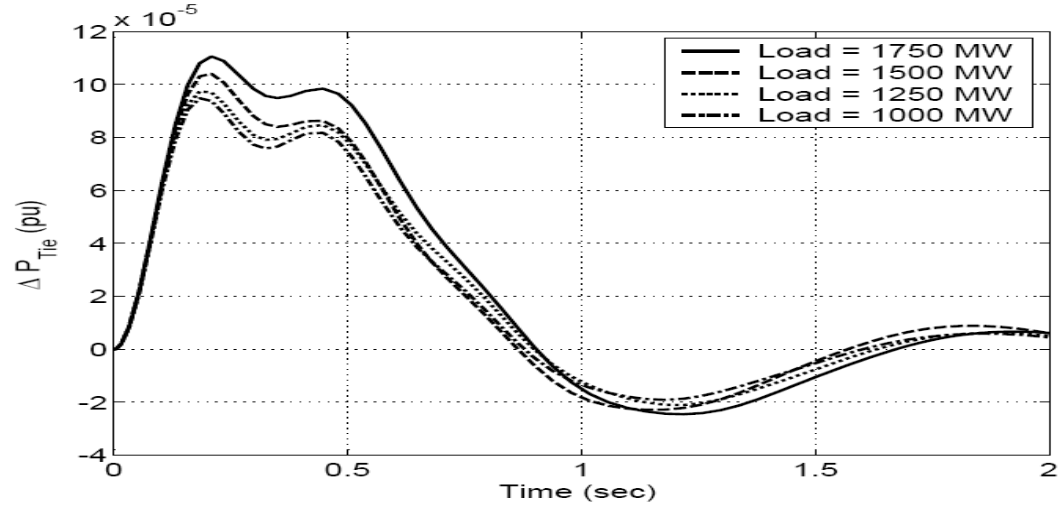
Table 4. Optimal PID controller gain values for different thermal power generation in area-1 at different nominal loading conditions with 1% load disturbance in area-2.

Area 1							Area 2			
Load	Thermal			Gas			Load	Thermal		
	K_{Pth1}	K_{Ith1}	K_{Dth1}	K_{Pg1}	K_{Ig1}	K_{Dg1}		K_{Pth2}	K_{Ith2}	K_{Dth2}
1750	75.2941	779.6395	21.8431	0.0968	347.82	0.0001	1750	54.882	374.3781	22.2745
1500	84	1047.519	26.0275	0.0555	33.916	0.0001	1750	56.863	402.1714	23.1627
1250	121.5686	1391.467	30.2941	0.0841	83.732	0.0001	1750	63.431	419.4703	24.5068
1000	240.1961	1475.106	49.8431	0.0901	117.16	0.0001	1750	63.922	439.4933	24.9651



(b)

Figure 6 System transient responses for different thermal power generations of area-1 with 1% step load disturbance in area-2, (a) area-1 frequency deviation (b) area-2 frequency deviation



(c)

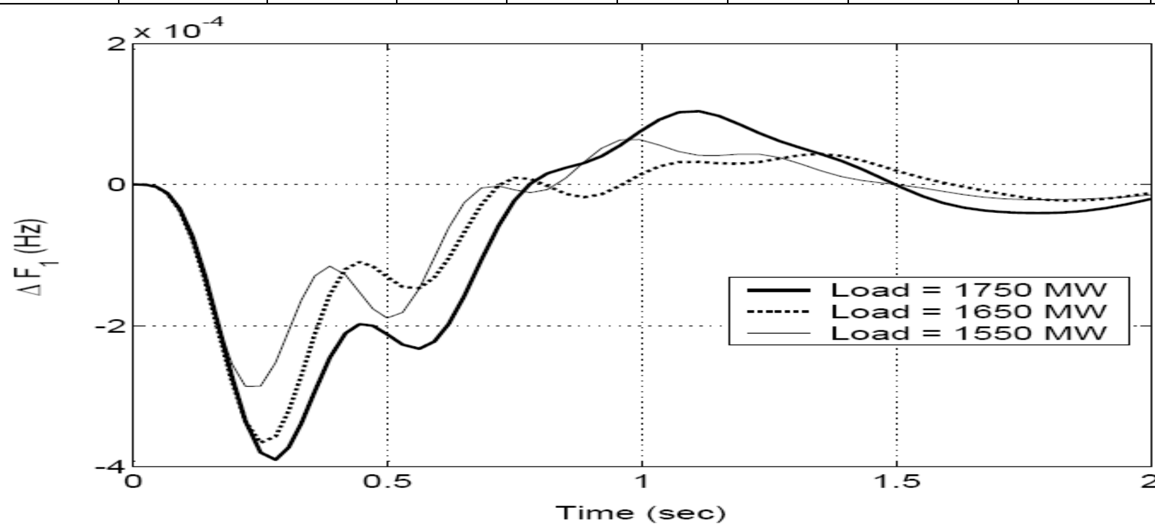
Figure 6 (cont'd) System transient responses for different thermal power generations of area-1 with 1% step load disturbance in area-2, (c) tie-line power deviation

(ii) Different scheduled gas power generation in area-1:

The optimal values of PID controller gains are given in Table 5 for different gas power generations in area-1 to match the system nominal loading conditions and keeping other scheduled power generations constant. It has been observed that the optimal gains K_{Pth1}, K_{Dth1}, K_{Ith2} and K_{Dth2} are increasing with decrease in nominal loading. The transient system responses are shown in Figure 7. It has been found that the decrease in gas power generation the system shows better transient response.

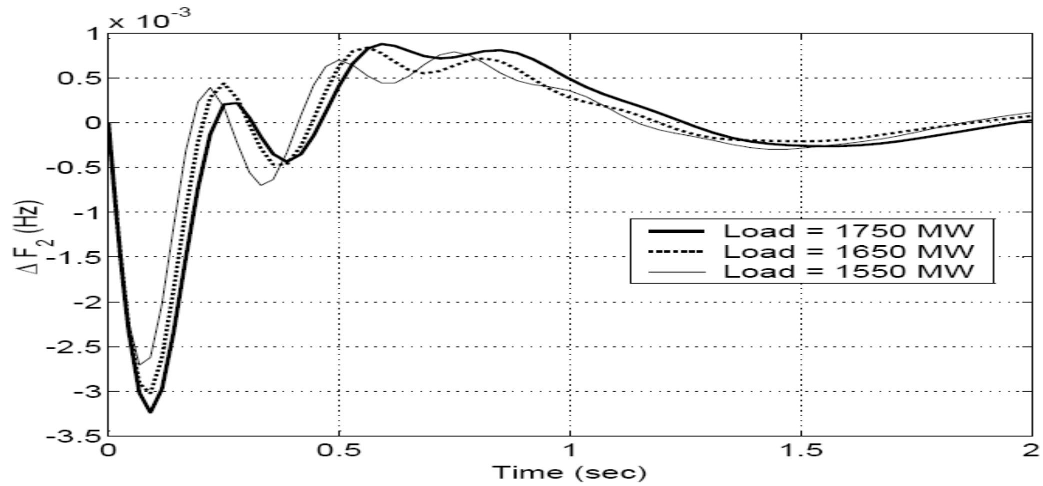
Table 5. Optimal PID controller gain values for different gas power generation of area-1 at different nominal loading conditions with 1% load disturbance in area-2.

Area 1							Area 2			
Load	Thermal			Gas			Load	Thermal		
	K_{Pth1}	K_{Ith1}	K_{Dth1}	K_{Pg1}	K_{Ig1}	K_{Dg1}		K_{Pth2}	K_{Ith2}	K_{Dth2}
1750	75.2941	410.0837	21.8431	0.0968	347.82	0.0001	1750	54.8824	374.3781	22.2745
1650	77.1569	1254.739	23.2235	0.0471	12.01	0.0001	1750	64.9804	451.1844	24.7059
1550	81.5373	993.7297	24.651	0.01	0.5862	0.0001	1750	61.0588	540.9572	30.098



(a)

Figure 7 System transient responses for different gas power generations of area-1 with 1% step load disturbance in area-2. (a) area-1 frequency deviation



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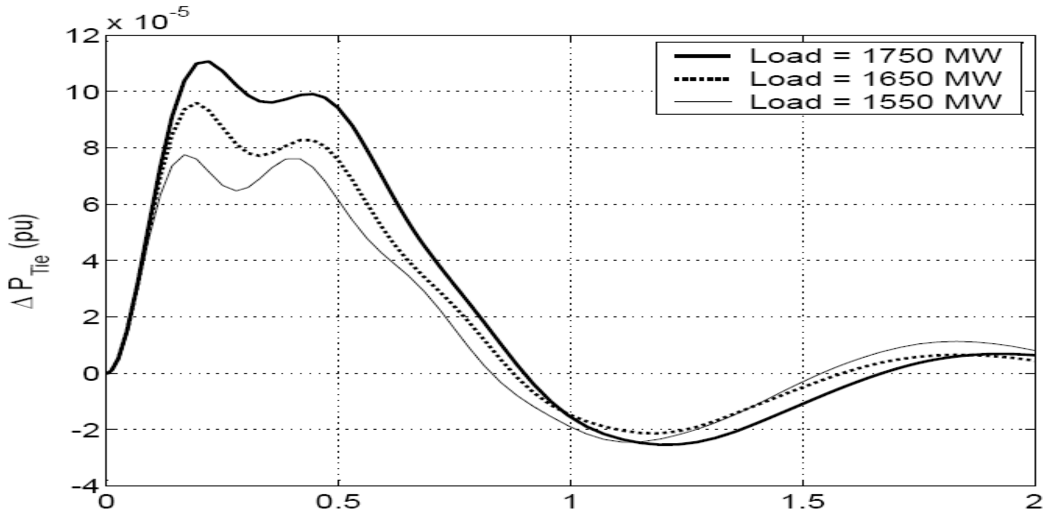


(c)

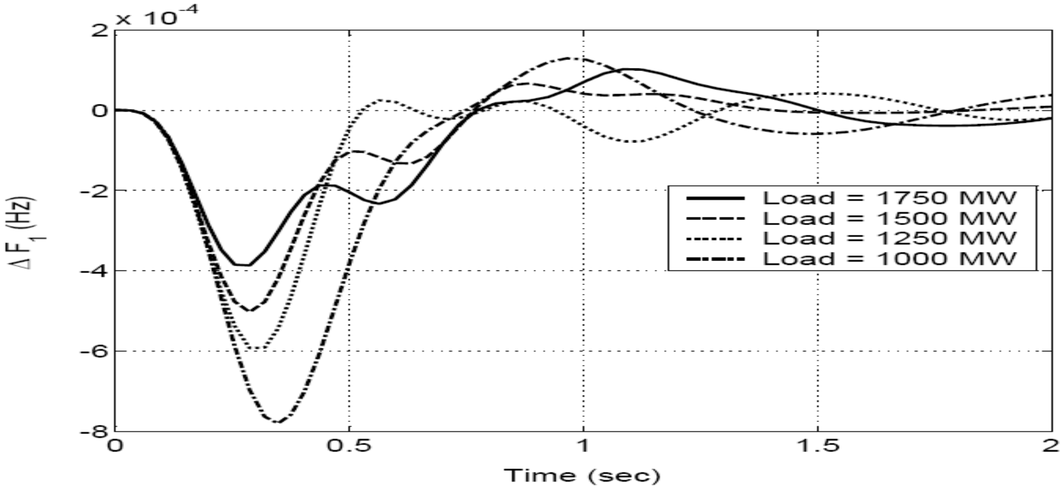
Figure 7 (cont'd) System transient responses for different gas power generations of area-1 with 1% step load disturbance in area-2. (b) area-2 frequency deviation (c) tie-line power deviation

(iii) Different scheduled thermal power generation in area-2:

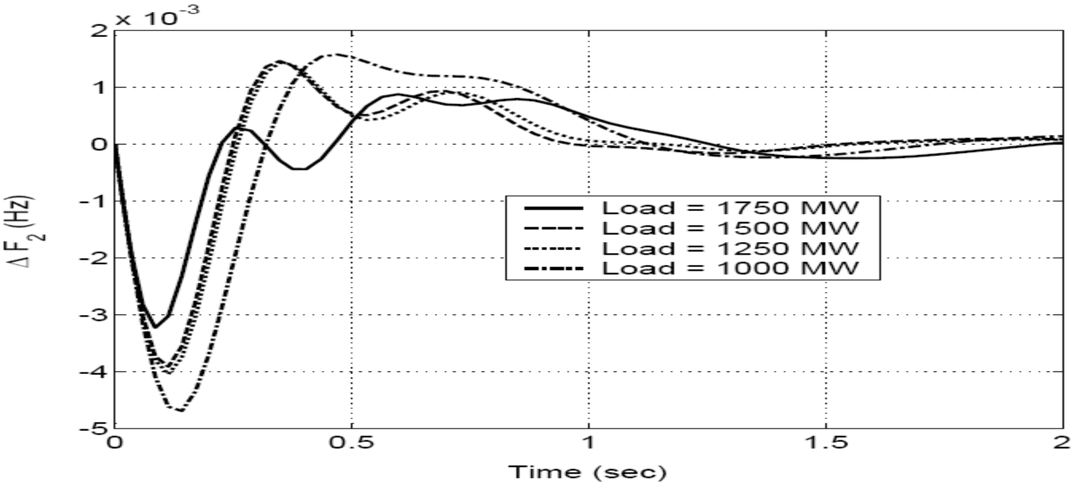
The optimal values of the PID controller gains are given Table 6 for different scheduled thermal power generation in area-2. It has been observed that the optimal gains K_{Pth1} and K_{Dth1} are decreasing but K_{Pth2} and K_{Ith2} are increasing as thermal power generation is reduced to match the nominal loading. The transient responses of the system are shown in Figure 8. It has been observed that the system transient responses deteriorate with decrease in the thermal power generation.

Table 6. Optimal PID controller gain values for different thermal power generation in area-2 to match nominal loading conditions with 1% load disturbance in area-2.

Area 1							Area 2			
Load	Thermal			Gas			Load	Thermal		
	K_{Pth1}	K_{Ith1}	K_{Dth1}	K_{Pg1}	K_{Ig1}	K_{Dg1}		K_{Pth2}	K_{Ith2}	K_{Dth2}
1750	75.2941	410.0837	21.8431	0.0968	347.82	0.0001	1750	54.882	374.3781	22.2745
1750	67.1529	112.8548	22.5882	0.0566	15.62	0.0001	1500	72.529	394.7567	17.1373
1750	65.9843	102.7351	21.6745	0.0884	27.41	0.0001	1250	88.871	419.3691	19.9608
1750	63.9882	496.7189	18.3098	0.0608	35.841	0.0001	1000	98	453.2444	24.3725



(a)



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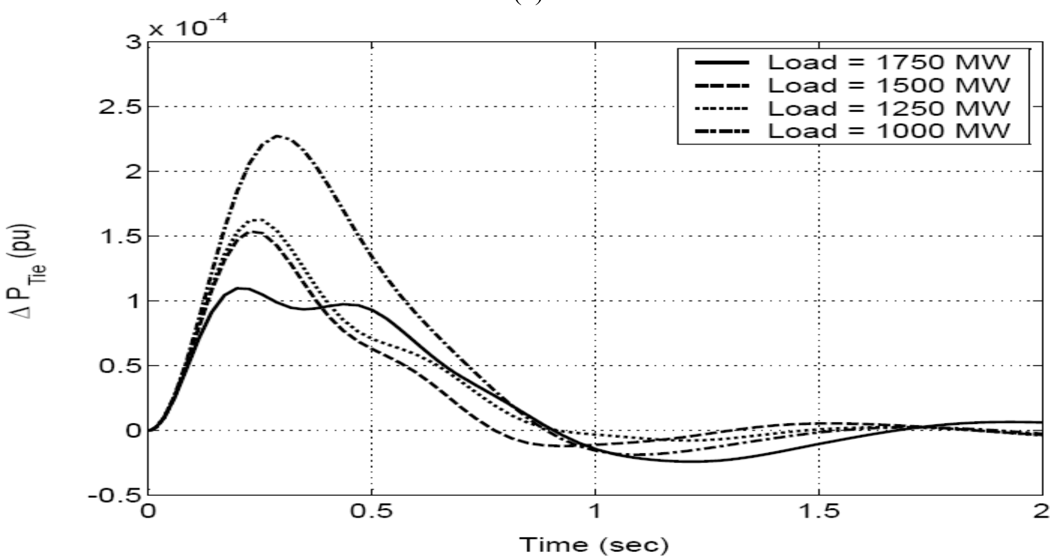

(c)

Figure 8 System transient responses for different thermal power generations of area-2 with 1% step load disturbance in area-2, (a) area-1 frequency deviation (b) area-2 frequency deviation (c) tie-line power deviation.

5. Conclusion

AGC of a two area power system having power generation from hydro, thermal and gas sources in area-1 and from hydro and thermal in area-2 has been studied. The typical two area system has been simulated for different scheduled generations under different normal loading conditions with 1% step load disturbance in either area. The scheduled power generations from thermal or gas are adjusted to match the system normal operating load. The PID controller gains have been optimized using genetic algorithm for various cases. It has been found that the optimal gains of the AGC are different for different loading conditions. Also to achieve better dynamic performance, the gains have been found to be different for each source in an area. Therefore the selection of AGC gains based on one typical nominal loading of the system and also by considering one source of power generation in area is not a realistic study. Hence in realistic power system having diverse sources of power generation, the dynamics of all energy sources must be incorporated for automatic generation controller design.

Appendix–I

System Data:
The data of a typical two area power system having diverse sources of power generation are given below.

Steam Turbine:
Speed governor time constant T_g = 0.08 sec
Turbine time constant T_t = 0.3 sec
Re-heater time constant T_r = 10 sec
Coefficient of re-heat steam turbine K_r = 0.3
Speed governor regulation parameter R_{th} = 2.4 Hz/pu MW

Hydro turbine:
Speed governor rest time T_R = 5.0 sec
Transient droop time constant T_{RH} = 28.75 sec
Main servo time constant T_{GH} = 0.2 sec
Water time constant T_W =1.0 sec
Speed governor regulation parameter R_{hy}=2.4 Hz/pu MW

Gas Turbine:
Speed governor lead and lag time constants X = 0.6 sec and Y=1.0 sec
Valve positioner constants a = 1, b = 0.05 and c = 1
Fuel time constant T_F = 0.23 sec
Combustion reaction time delay T_{CR} = 0.3 sec
Compressor discharge volume time constant T_{CD} = 0.2 sec
Speed governor regulation parameter R_g = 2.4 Hz/pu MW

Power System:
Rated area capacity $P_{r1} = P_{r2}$ = 2000MW
Inertia constant H = 5 MW-s/MVA
Rated frequency f_r = 60Hz

Load Frequency characteristic, $D = \dfrac{\partial P_L}{\partial f}\dfrac{1}{P_r}$ pu MW/Hz

Power System Gain Constant $K_{PS} = \dfrac{1}{D}$ Hz/pu MW

Power System Time Constant $T_{PS} = \dfrac{2H}{f_r D}$ sec

Frequency bias constant B_1=B_2 = 0.425 puMW/Hz
Tie-Line: P_{12max}=100 MW $(\delta_1 - \delta_2) = 30^o$

Table T1. The values of the power system constants for different nominal loads and corresponding scheduled power generations

Load (MW) in each area	Area-1 Generation			$P_{tie,\,12}$ (MW)	Area-2 Generation			Power System Constants	
	Thermal (MW)	Hydro (MW)	Gas (MW)		Thermal (MW)	Hydro (MW)	Gas (MW)	K_{PS} (Hz/puMW)	T_{PS} (sec)
Thermal Power Variation									
1750	1000	600	250	100	1000	400	250	68.57	11.43
1500	750	600	250	100	750	400	250	80	13.34
1250	500	600	250	100	500	400	250	96	16
1000	250	600	250	100	250	400	250	120	20
Gas Power Variation									
1650	1000	600	150	100				72.73	12.12
1550	1000	600	50	100				77.42	12.9

Appendix-II

List of GA parameters:

Initial Population Size - 20
Fitness Function - 1/1+ (ISE+ITAE)
Elitism - 2
Selection - Roulette wheel
Crossover Probability - 0.8
Cross Over Function - Diverse-point
Mutation Probability - 0.03
No. of Generations - 200

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