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Discrete Data Load Frequency Control of Two-Area Power System with Multi-Source Power Generation

K.S.S. Ramakrishna [*1] and T.S. Bhatti [*]

Abstract – *This paper presents load frequency control (LFC) of interconnected power systems involving multi-source power generation. The investigations are carried on a typical two area power system comprising hydro, thermal, and gas power generations with speed governors in each area. A discrete time proportional-integral-derivative (PID) load frequency control is applied only to thermal and gas power generating units and hydro is allowed to operate at its scheduled generation level with only speed governor control. The transient performance of the two area power system is investigated for different combinations of generations from thermal and gas sources with different scheduled operating load conditions when subjected to step load disturbance of 1% in area-1. The PID controller gains are optimized using genetic algorithm (GA) for a sampling period of two seconds. The combination of integral squared error (ISE) and integral time an absolute error (ITAE) performance index is used for fitness evaluation.*

Keywords – Discrete load frequency control, genetic algorithm, multi-source power generation, PID control.

1. INTRODUCTION

The objective of load frequency control of interconnected power systems is to minimize the transient deviation in both scheduled frequency and inadvertent exchange of tie-line power by using proper controllers [1]. In discrete time LFC the area control error (ACE) signals are sampled for every 1 to 2s and the controller sends signals to various generating units in the control area to raise or lower the generation accordingly. The design and performance of the load frequency controller depends upon how various units respond to such 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 performance of the load frequency controller depends upon various energy source dynamics involved in the model. In literatures, lots of works have been devoted for discrete and continuous time load frequency control studies of interconnected power systems [2]-[19]. The power systems considered in these studies are generally two area interconnected thermal-thermal or hydro-thermal power systems. But in real situations control areas may have various type of energy sources 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. Therefore, it is very important to include dynamics of all type of generation in an area with their speed governors.

The transient performance of the system may vary as the contribution by different types of generation to the total generation of the area changes. A typical generation in an area may be running at its rated load capacity while others may not be due to different reasons *eg.,* lower power production cost, easy availability of the sources etc. In such case though the typical generation is inherently regulated by the speed governor alone but its dynamics play significant role in the selection of the load frequency controller for other generations in the area. The authors have studied the load frequency control of single area power system with hydro, thermal and gas power generations [20]. It has been shown that the dynamics of various power generation sources required to be incorporated in the system model in order to obtain the optimal controller parameters. It has also been shown that the system shows better transient performance with individual controllers for different types of power generating units participating in the area load frequency control instead of common controller to all types of generating units in the area.

The function of LFC is to minimize the transient deviations in the system. To achieve better transient response of the system various control strategies have been tried out for the load frequency control problem [6]-[17]. The controller performance depends upon the optimum selection of its parameters. The optimum selection of proportional- integral and proportional-integral-derivative gains by using different performance indices has been studied in [17], [18]. 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 first peak of the transient response. The ITAE criterion is more suitable in reducing long duration transients as it penalizes the error by time. In order to provide a better transient performance with less first peak deviation and more stable response a conventional PID load frequency controller is used in this paper [14], [18]. The optimum values of the PID gains are obtained by a combination of ISE and ITAE criterion [20]. Genetic algorithm is used to optimize the controller parameters under different operating load conditions for 1% step load perturbation and a sampling period of 2s.

2. POWER SYSTEM MODEL

Figure 1 represents the generalized transfer function block diagram of a power system with multi-source electric power generation in an area. The total generation is from hydro, thermal and gas power generating units which are

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equipped with speed governor control mechanisms. All types of generating units are represented by a single plant dynamics [1], [21]-[24]. Under normal operating conditions there is no mismatch between generation and load. The total generation is given by:

$$P_{Gi} = P_{Gthi} + P_{Ghyi} + P_{Ggi} \quad (1)$$

Where, $P_{Gthi} = K_{thi} P_{Gi}$, $P_{Ghyi} = K_{hyi} P_{Gi}$,

$P_{Ggi} = K_{gi} P_{Gi}$ and $i = 1,2$

K_{th}, K_{hy} and K_g represent the part of the power generation by thermal, hydro and gas respectively to the total power generation. The values of K_{th}, K_{hy} and K_g are decided by the load curve and economic operation of the system. For small perturbation, Equation 1 can be written as:

$$\Delta P_{Gi} = \Delta P_{Gthi} + \Delta P_{Ghyi} + \Delta P_{Ggi} \quad (2)$$

From Equation 1, under nominal generation and loading, $P_G^0 = P_L^0 = 1.0$ pu, therefore

$$K_{thi} + K_{hyi} + K_{gi} = 1.0 \quad (3)$$

The two area power system as 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 load frequency control of the system by having manipulations of ΔP_{Cthi} and ΔP_{Cgi} (i=1, 2). The hydro generating unit in both areas is uncontrolled, i.e. $\Delta P_{Chyi}=0$ (i=1, 2), but its dynamics play important role in the system stability following a small disturbance in the load. The speed changer signals for a PID control are given by:

$$ACE_{iI}(kT) = T_S \sum_{n=0}^{k} ACE_i(nT) \quad (4)$$

$$ACE_{iD}(kT) = \frac{ACE_i(kT) - ACE_i(kT-1)}{T_S} \quad (5)$$

$$\Delta P_{Cthi}(kT) = K_{Pthi} ACE_i(kT) + K_{Ith} ACE_{iI}(kT) + K_{Dthi} ACE_{iD}(kT) \quad (6)$$

$$\Delta P_{Cgi}(kT) = K_{Pgi} ACE_i(kT) + K_{Igi} ACE_{iI}(kT) + K_{Dgi} ACE_{iD}(kT) \quad (7)$$

Where, $i = 1,2$, T_S is sampling period.

In the above equations ACE_i is area control error and is given by:

$$ACE_i = B_i \Delta F_i + \Delta P_{Tie} \quad (8)$$

$ACE_{iI}(kT)$ is the Integral of Area Control error.
$ACE_{iD}(kT)$ is the Derivative of Area control error.

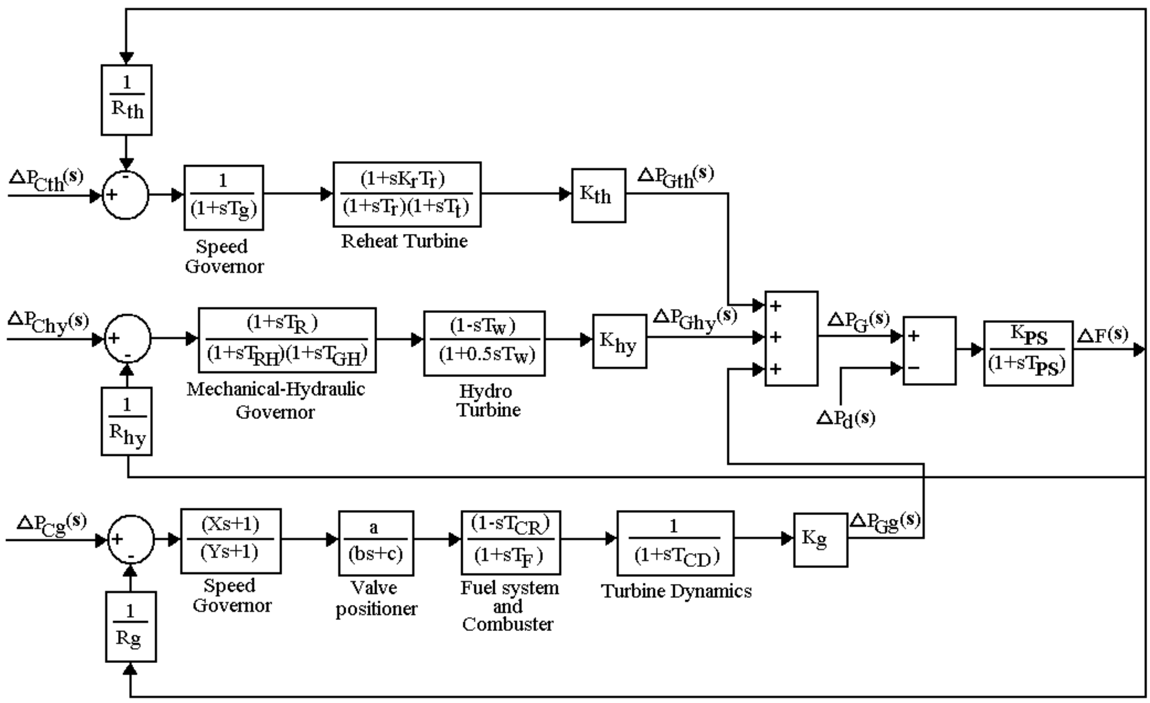


Fig. 1. Generalized transfer function block diagram of a power system having hydro, thermal and gas power generations.

3. PARAMETER OPTIMIZATION

The PID controller gains are obtained by optimizing K_P, K_I and K_D with genetic algorithm. Genetic algorithms (GA) are robust search optimizations techniques which have been successfully applied to LFC problem [16]-[18]. GA solves the optimization problems by exploitation of random search in a multi-dimensional search spaces. In this optimization process the parameters to be optimized are represented in a binary string called chromosomes. GA starts with randomly creating the initial population of these binary strings. Each chromosome representing a possible solution to the optimization problem and is evaluated according to the fitness function. GA employs different genetic operators to manipulate individuals in a population of solutions over several generations to improve their fitness gradually.

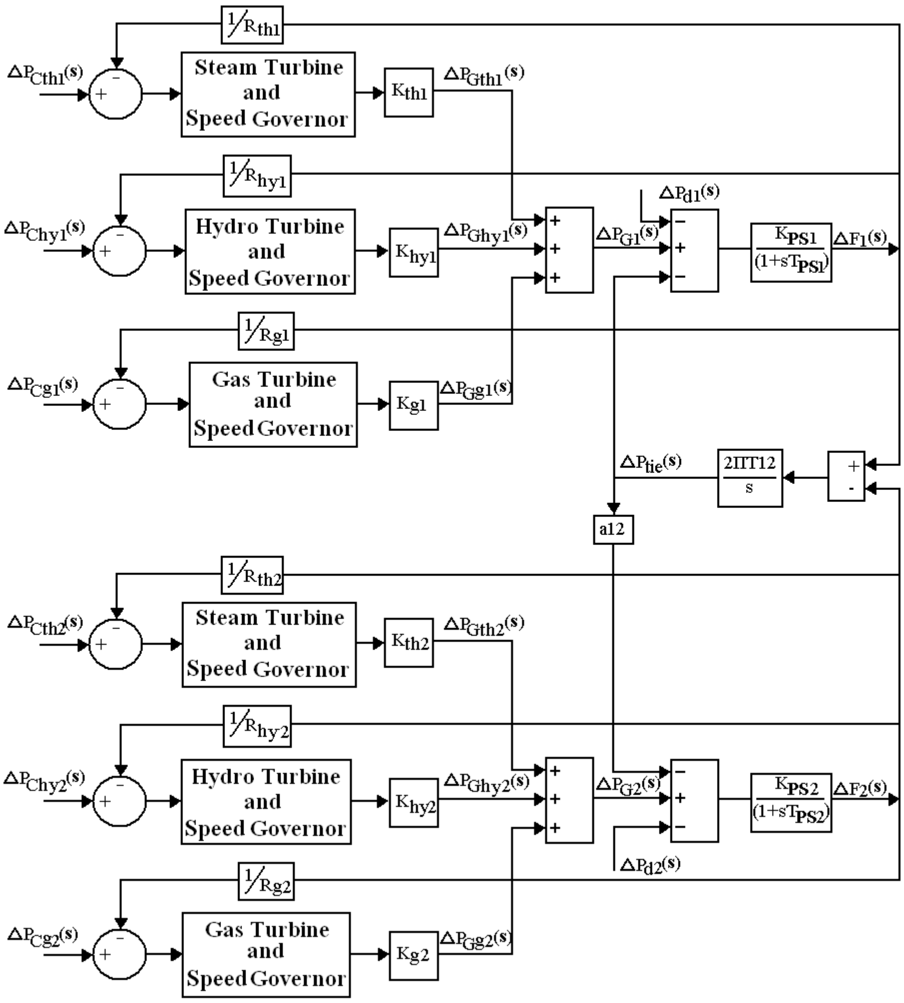


Fig. 2. Block diagram of a two area power system.

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:

$$ISE = \Delta P_{tie}^2 + \Delta f_1^2 + \Delta f_2^2 \qquad (9)$$

$$ITAE = t(|\Delta P_{tie}| + |\Delta f_1| + |\Delta f_2|) \qquad (10)$$

$$\eta_{ISE+ITAE} = \int (ISE + ITAE)dt \qquad (11)$$

GA performs three basic operations such as reproduction, cross over and mutation. Each solution of initial population is evaluated by its fitness represented by the value of objective function. Reproduction creates new generation of chromosomes by selecting some individuals with higher fitness from the initial population through various selection processes. The crossover operator 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 is random alteration of bits in a string which flips a bit from 1 to 0 or vice versa. By the end of the 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 having generation from hydro, thermal, and gas sources in both areas 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 load frequency controller gain parameters obtained from randomly selected initial population. These values were used to produce next generation of individuals and procedure is repeated. The parameters of the GA used for the simulations are given in Appendix II.

The two area power system has been simulated for different scheduled operating load conditions. The power generations from thermal and/or gas sources may vary to match the system load under normal operating conditions. The scheduled power generation from hydro source remains constant. The different operating conditions of the system considered for the simulation are given in Table A1 of Appendix I, and the values of K_{thi}, K_{hyi} and K_{gi} can be calculated using Equations 1 and 3 for the same. The optimum values of the PID controller gains are given in Tables 1 to 4 for different cases with 1% step load disturbance only in area-1.

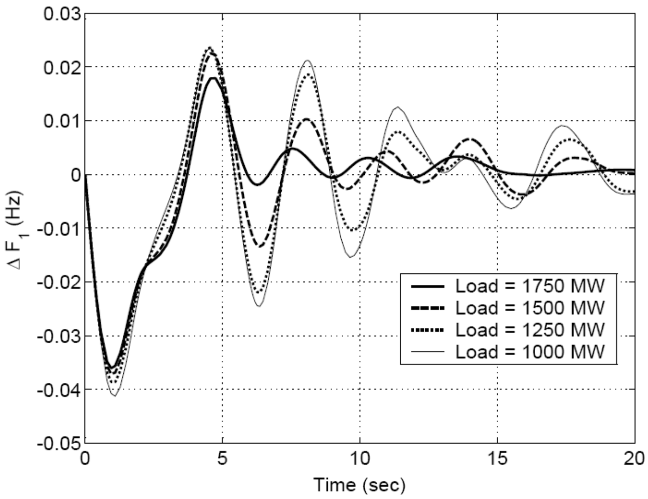
Table 1. GA Optimized PID controller gains for variation in Area-1 scheduled thermal power generation at different operating load conditions with 1% load disturbance in Area-1.

Area 1							Area 2						
Load	Thermal			Gas			Load	Thermal			Gas		
	K_{Pth1}	K_{Ith1}	K_{Dth1}	K_{Pg1}	K_{Pg1}	K_{Dg1}		K_{Pth2}	K_{Ith2}	K_{Dth2}	K_{Pg2}	K_{Pg2}	K_{Dg2}
1750	0.0056	1.002	0.0467	1.8588	0	0.0301	1750	0.2588	0.022	0.1635	0.0972	0.0216	0.0516
1500	0.0392	1.0981	0.0549	1.702	0	0.098	1750	0.8078	0.0196	0.6353	0.0863	0.0098	0.2431
1250	0.3882	1.1118	0.1647	1.3804	0	0.1098	1750	0.6941	0.0235	0.3059	0.6471	0.0035	0.9686
1000	0.4275	1.5882	0.1843	1.2314	0	0.1898	1750	0.6706	0.0157	0.4471	0.2353	0.0102	0.6549

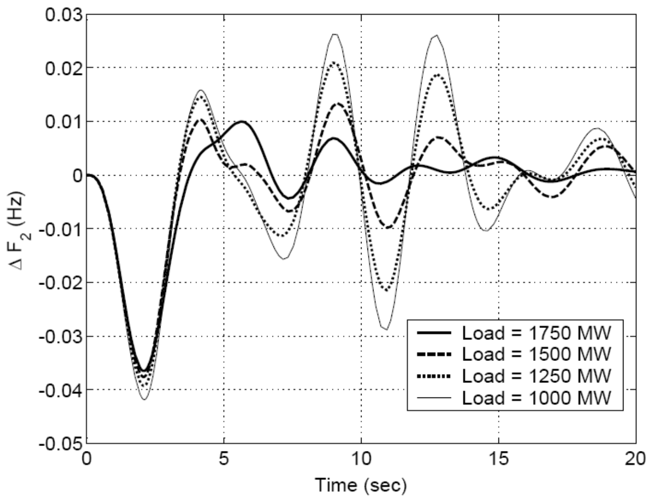
Case I: The two area power system is simulated for different operating load conditions in area-1.

a. Different scheduled thermal power generations in area-1:

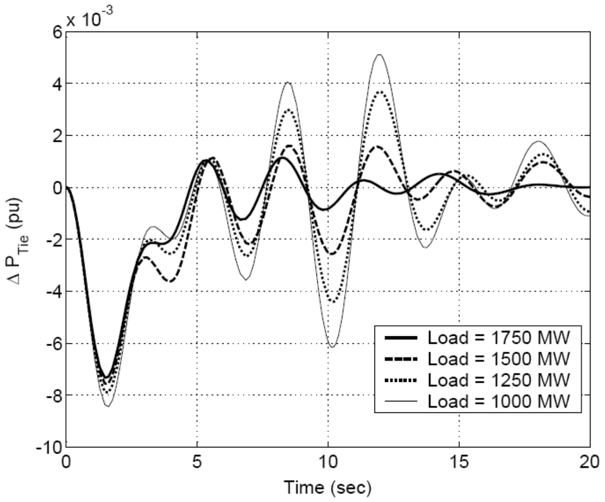
The optimum PID controller gains are given in Table 1 for different scheduled thermal power generations at different operating load conditions in area-1. The other scheduled generations are kept constant. It has been observed that the optimal values of K_{Pth1}, $K_{Ith1,}$ K_{Dth1} and K_{Dg1} increases and the optimal values of K_{Pg1} decreases as the scheduled thermal power generation is decreased to match the decrease in normal operating load. The transient responses are shown in Figure 3. It has been observed that the system transient performance of the system is becoming poor with increasing first peak deviation and more oscillatory with decrease in thermal power generation.



(a)



(b)



(c)

Fig. 3. Transient system response with variation in area-1 thermal power generation for 1% load disturbance in area-1. (a)area-1 frequency deviation (b) area-2 frequency deviation (c) tie-line power deviation.

b. Different scheduled gas power generations in area-1

The optimal PID controller gains are given in Table 2 for different cases of scheduled gas power generations in area-1. The other scheduled generations are remains same. It has been observed that the optimal values of K_{Dth1}, $K_{Pg1}$and K_{Pth2} increases and K_{Ith1} decreases as shown in Table 2. Transient system responses are as shown in Figure 4. It has been observed that there is no significant difference in the first peak deviation. The subsequent swings of area-1 frequency and tie-line power deviations are increasing and are more oscillatory with decrease in scheduled gas power generation to match decrease in load. The area-2 frequency deviation shows better transient performance during first few oscillations but deteriorates later on.

Table 2. GA Optimized PID controller gains for variation in Area-1 scheduled gas power generation at different operating load conditions with 1% load disturbance in Area-1.

Area 1							Area 2						
Load	Thermal			Gas			Load	Thermal			Gas		
	K_{Pth1}	K_{Ith1}	K_{Dth1}	K_{Pg1}	K_{Pg1}	K_{Dg1}		K_{Pth2}	K_{Ith2}	K_{Dth2}	K_{Pg2}	K_{Pg2}	K_{Dg2}
1750	0.0056	1.002	0.0467	1.8588	0	0.0301	1750	0.2588	0.022	0.1635	0.0972	0.0216	0.0516
1650	0.0015	0.8306	0.0507	2.8039	0	0.0884	1750	0.5329	0.0135	0.3471	0.0139	0.0456	0.0778
1550	0.0022	0.7176	0.0612	7.3882	0	0.034	1750	0.8155	0.0185	0.1212	0.0329	0.0125	0.0333

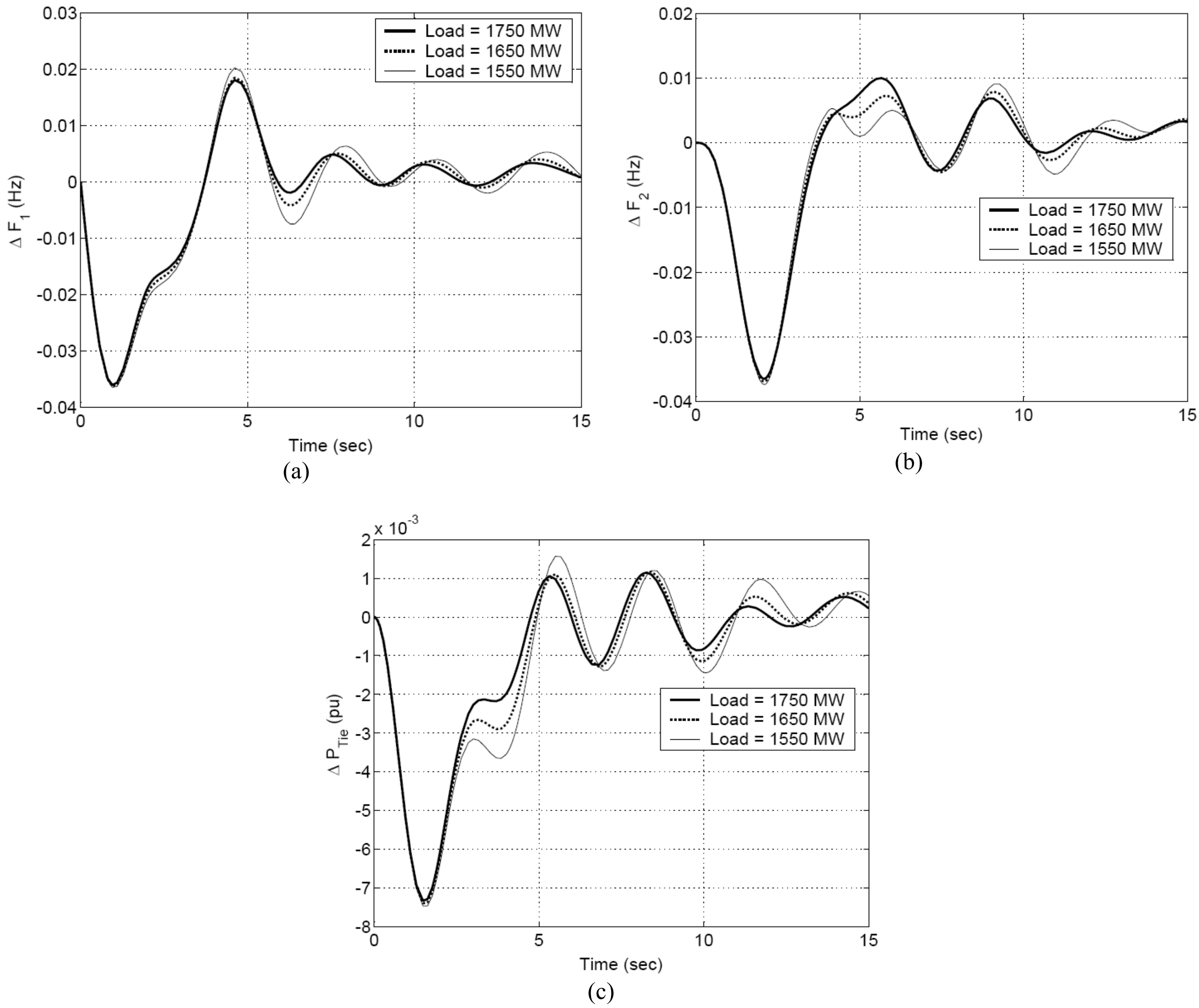


Fig. 4. Transient system response with variation in area-1 gas power generation for 1% load disturbance in area-1. (a) area-1 frequency deviation (b) area-2 frequency deviation (c) tie-line power deviation.

Case II: The two area power system is simulated for different operating load conditions in area-2.

a. Different scheduled thermal power generations in area-2:

The optimal controller gains for different cases of scheduled thermal power generation in area-2 are shown in Table 3. The other scheduled generations are kept constant. It has been observed that the optimal values of K_{Pth1}, K_{Dth1}, K_{Pg1}, K_{Dg1} and K_{Pth2} increases and the optimal values of K_{Ith1} decreases as scheduled thermal power generation decreases. The transient system responses are shown in Figure 5. It has been observed that the transient response of area-2 deteriorates with negligible effect on area-1 as thermal power generation is decreased.

Table 3. GA Optimized PID controller gains for variation in Area-2 thermal power generation at different operating load conditions with 1% load disturbance in Area-1.

Area 1							Area 2						
Load	Thermal			Gas			Load	Thermal			Gas		
	K_{Pth1}	K_{Ith1}	K_{Dth1}	K_{Pg1}	K_{Pg1}	K_{Dg1}		K_{Pth2}	K_{Ith2}	K_{Dth2}	K_{Pg2}	K_{Pg2}	K_{Dg2}
1750	0.0056	1.002	0.0467	1.8588	0	0.0301	1750	0.2588	0.022	0.1635	0.0972	0.0216	0.0516
1750	0.0346	0.9451	0.5255	2.1824	0	0.098	1500	0.3961	0	0.0431	0.0118	0.0071	0.0118
1750	0.0549	0.6929	0.2667	2.4941	0	0.1235	1250	0.5338	0	0.6784	0.6667	0.0012	0.3569
1750	0.1961	0.4776	0.4706	2.7529	0	0.2745	1000	0.7651	0.4196	0.6706	0.1412	0.0153	0.4941

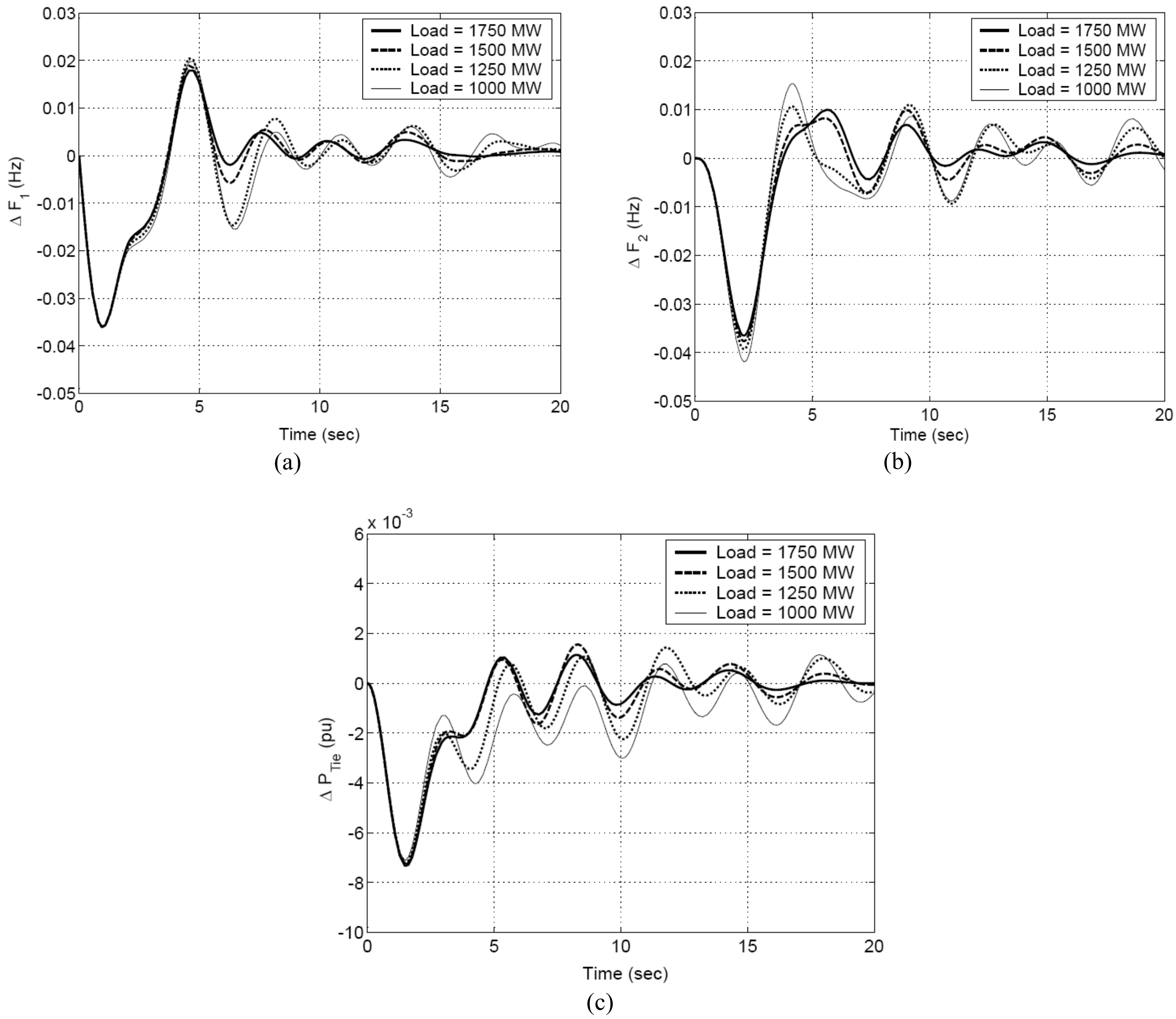


Fig. 5. Transient system response with variation in area-2 thermal power generation for 1% load disturbance in area-1. (a) area-1 frequency deviation (b) area-2 frequency deviation (c) tie-line power deviation.

b. Different scheduled gas power generations in area-2:

The optimal PID controller gains are given in Table 4 for various cases of different scheduled gas power generation in area-2 with other scheduled generations remains same. It has been observed that the optimal values of K_{Pth1}, $K_{Pg1,}$ K_{Pth2} and K_{Ith2} decreases and the optimal values of K_{Dth1} increases with decrease in scheduled gas power generation. The transient system responses are shown in Figure 6. The system performance improves with better damping of oscillations as gas power generation decreases.

Table 4. GA Optimized PID controller gains for variation in Area-2 gas power generation at different operating load conditions with 1% load disturbance in Area-1.

Area 1							Area 2						
Load	Thermal			Gas			Load	Thermal			Gas		
	K_{Pth1}	K_{Ith1}	K_{Dth1}	K_{Pg1}	K_{Pg1}	K_{Dg1}		K_{Pth2}	K_{Ith2}	K_{Dth2}	K_{Pg2}	K_{Pg2}	K_{Dg2}
1750	0.0056	1.002	0.0467	1.8588	0	0.0301	1750	0.2588	0.022	0.1635	0.0972	0.0216	0.0516
1750	0.0024	1.0412	0.0555	1.6275	0	0.0146	1650	0.1776	0.0145	0.1918	0.0901	0.0308	0.0644
1750	0.006	0.9694	0.0915	1.4667	0	0.0156	1550	0.0014	0.0109	0.1	0.0442	0.0767	0.0336

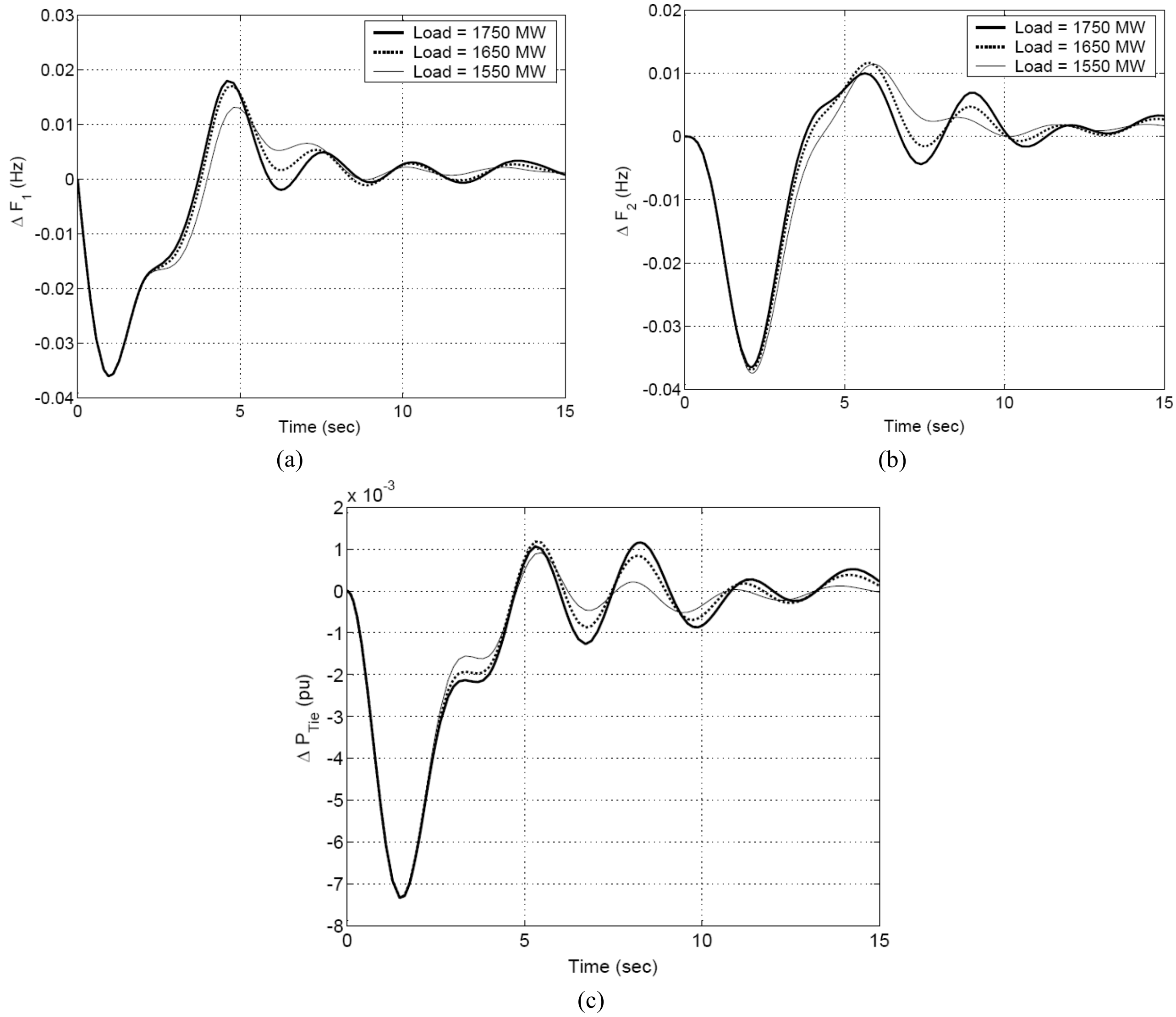


Fig. 6. Transient system response with variation in area-2 gas power generation for 1% load disturbance in area-1. (a) area-1 frequency deviation (b) area-2 frequency deviation (c) tie-line power deviation

In the above studies, the performance of the system for various operating conditions has been analyzed for transient and steady state scenarios. The system response depends upon system nominal load *i.e.* the system transient and steady state deviations are not same for different loading conditions [1]. The variation in power generation from various sources in an area affects considerably during the transient deviation. It has been observed that few of the optimal gains selected for different operating conditions using ISE+ITAE criterion with a given set of GA parameters and sampling period have followed a specific trend and which reflected in the system transient response. It can also be observed that the variation in the optimum gains also depends upon the amount of change in the nominal load/generation. The variation in the optimal gains is comparatively large for variation in thermal power generation than the variation in gas power generation. In practice, the optimal gains for different operating conditions may be selected by using gain scheduling techniques. These techniques may be developed by monitoring the operating conditions using various artificial intelligent techniques such as fuzzy logic and neural networks [19].

5. CONCLUSION

Discrete time load frequency control of a two area power system having power generation from hydro, thermal, and gas sources in each area has been studied. The typical two area system has been simulated for different scheduled generations under different operating load conditions with 1% step load disturbance only in area-1. The scheduled 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 at sampling period of 2s. It has been found that the optimal gains of the load frequency controller 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 load frequency controller gains based on one typical 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 multi-source power generation, the dynamics of all energy sources must be incorporated for load frequency controller design.

NOMENCLATURE

P_L	-	System operating load
K_{thi}	-	thermal power generation contribution
K_{gi}	-	gas power generation contribution
K_{hyi}	-	hydro power generation contribution
ΔP_{Gthi}	-	thermal power deviation, pu MW
ΔP_{Ghyi}	-	hydro power deviation, pu MW
ΔP_{Ggi}	-	gas power deviation, pu MW
ΔP_{Cthi}	-	change in thermal turbine speed-changer position, pu MW
ΔP_{Cgi}	-	change in gas turbine speed-changer position, pu MW
ΔP_{Chyi}	-	change in hydro turbine speed-changer position, pu MW
ΔP_{di}	-	change in area load, pu MW
ΔF_i	-	frequency deviation, Hz
ΔP_{Tie}	-	Tie-line power deviation, puMW
K_P	-	proportional gain
K_I	-	integral gain
K_D	-	derivative gain

REFERENCES

[1] Elgerd, O.I. 1971. *Electrical Energy Systems Theory: An Introduction*. 2nd ed. Tata McGraw Hill.

[2] Bohn, E.V., and Miniesy, S.M. 1972. Optimum load frequency sampled-data control with randomly varying system disturbances. *IEEE Transactions of Power Application Systems,* PAS-91: 1916-1923.

[3] DeMello, F.P., Mills, R.J., and B'Rells, W.F. 1973. Automatic load frequency control pt–II digital control techniques. *IEEE Transactions of Power Application Systems,* PAS-92: 716-724.

[4] Tripathy, S.C., Bhatti, T.S., Jha, C.S., Malik, O.P., and Hope, G.S. 1984. Sampled data automatic load frequency control analysis with reheat steam turbines and governor dead band effects. *IEEE Transactions of Power Application Systems,* PAS-103: 1045-1051.

[5] Kumar, A. 1989. Discrete load frequency control of interconnected power systems. *International Journal of Energy Systems*, 9(2): 73-77.

[6] Shirai, G. 1981. Load frequency sampled-data control via Lyapunov's second method. *Proceedings of the IEEE*, 69(1): 129-130.

[7] Wang, Y., Zhou, R., Chua, W.K., and Fong, F.S.M. 1993. Discrete-time robust controller for load frequency control of power systems. In *Second IEEE Conference on Control Applications.* Vancouver, BC, Canada, 13-16 September. 2(2): 891-896, 1993.

[8] Bensenouci, A., and Ghany, A.M.A. 2005. Optimal Discrete-time output feedback control for multi-area load frequency control using evolutionary programming. In *Proceedings of IEEE International Symposium on Industrial Electronics.* Dubrovnik, Croatia, 01 June. 1: 95-100.

[9] Doolla, S., and Bhatti, T.S. 2006. Frequency Control of an Isolated Small hydro Power Plant, *International Energy Journal,* 7(1): 25-41.

[10] Aliyu, U.O., Venayagamoorthy, G.K., and Musa, S.Y. 2004. Adaptive load frequency control of Nigerian hydrothermal system using unsupervised and supervised learning neural networks. In *IEEE Power Engineering Society General Meeting.* Denver, Colorado, USA, 6-10 June. 2:1553 – 1558.

[11] Hiyama, T., Zuo, D., and Funabashi, T. 2002. Multi-agent based automatic generation control of isolated stand alone power system, In *International Conference on Power System Technology*. Kunming, China, 13-17 October. 1: 139 – 143.

[12] El-Sherbiny, M.K., El-Saady, G., and Yousef, A.M. 2002. Efficient fuzzy logic load–frequency controller. *Energy Conversion and Management*, 43(14): 1853-1863.

[13] Moon, Y.H., Ryu, H.S., Lee, J.G., and Seogjoo, K. 2001. Power system load frequency control using noise-tolerable PID feedback. In *IEEE International Symposium on Industrial Electronics*. Pusan, South Korea, 12-16 June. 3: 1714 – 1718.

[14] Yesil, E., Guzelkaya, M., and Eksin, I. 2004. Self tuning fuzzy PID type load and frequency controller. *Energy Conversion and Management*, 45(3): 377-390.

[15] Yu, X., and Tomsovic, K. 2004. Application of linear matrix inequalities for load frequency control with communication delays. *IEEE Transactions on Power Systems.* 19(3):1508 – 1515.

[16] Rerkpreedapong, D., Hasanovic, A., and Feliachi, A. 2003. Robust automatic generation control using genetic algorithms and linear matrix inequalities. *IEEE Transactions on Power Systems.* 18(2): 855–861.

[17] Magid, Y.L.A., and Dawoud, M.M. 1996. Optimal AGC tuning with genetic algorithms. *Electric Power Systems Research.* 38(3): 231–235.

[18] Karnavas, Y.L. 2006. On the optimal load frequency control of an interconnected hydro electric power systems using genetic algorithms. In *Proceedings of the 6th IASTED International Conference on*

European Power and Energy Systems. Rhodes, Greece, June. Cd Ref. No 521-099.

[19] Talaq, J., and Al-Basri, F. 1999. Adaptive fuzzy gain scheduling for load frequency control. *IEEE Transactions on Power Systems*, 14(1): 145-150.

[20] Ramakrishna, K.S.S., and Bhatti, T.S. 2007. Sampled-data automatic load frequency control of a single area power system with multi-source power generation. *Electric Power Components and Systems*,35(8): 955-980.

[21] Kundur, P. 1993. *Power System Stability and Control*. New Delhi: McGraw-Hill.

[22] Hajagos, L.M., and Berube, G.R. 2001. Utility experience with gas turbine testing and modeling. In *IEEE Power Engineering Society Winter Meeting*. Columbus, Ohio, USA. 2(2): 671–677.

[23] Working group on prime mover and energy supply models for system dynamic performance studies. 1994. Dynamic models for combined cycle plants in power system studies. *IEEE Transactions on Power Systems*. 9(3): 1698-1708.

[24] Gillian, L., Ritchie, J., Flynn, D., O'Malley, and Mark, J. 2005. The impact of combined-cycle gas turbine short-term dynamics on frequency control. *IEEE Transactions on Power Systems*, 20(3): 1456-1464.

APPENDIX I

System Data:

The data of a typical two area power system having power generation from thermal, hydro and gas sources in each area 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; $a_{12} = -\frac{P_{r1}}{P_{r2}} = -1$

Inertia constant H = 5 MW-s/MVA

Rated frequency f_r = 60Hz

Tie-line P_{12max} = 100 MW $(\delta_1 - \delta_2) = 30^o$

Tie-line Coefficient = 0.272 (calculated on 2000 MW base)

Load frequency characteristic, $D_i = \frac{\partial P_{Li}}{\partial f_r} \frac{1}{P_{ri}}$ pu MW/Hz

Power system gain constant, $K_{PS\,i} = \frac{1}{D_i}$ Hz/pu MW

Power system time constant $T_{PSi} = \frac{2H}{f_r D_i}$ s

Frequency bias constant $B_i = D_i + \frac{1}{R_i}$ pu MW/HZ

Table A1. Values of power system constants for different scheduled operating loads and corresponding scheduled generations.

Load (MW)	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	1000	400	150	72.73	12.12
1550	1000	600	50	100	1000	400	50	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
Crossover function	-	Multi-point
Mutation probability	-	0.03
Number of generations	-	200