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Automatic Generation Control of a Hydro - Thermal and Thermal - Thermal Systems in a Deregulated Environment

This paper deals with the applications of automatic generation control (AGC) of a hydro – thermal and thermal– thermal systems in a power system deregulated environment and makes an attempt to provide a new practical AGC model to fulfill the needs of a modern restructured hydro-thermal and thermal - thermal power system. Several Distribution Company, distribution Participation Matrix, and area participation factor have been tried out and dynamic responses for frequency, tie line flow and power generations are obtained to examine the performance of the system in deregulated environment considering integral controllers. Investigations have been also carried out to study the effect of generation rate constraint and the importance of APF in deregulated environment. Study also reveals that the conventional integral controllers are quite robust than PI and PID controllers and the optimum integral gains once set for nominal condition need not be changed for +25% variations in system parameters and +20% variations in operating load condition from their nominal values.

Keywords: Area participation factor (APF), Deregulation, Distribution company (DISCO), generation company (GENCO), distribution participation matrix (DPM), transmission company (TRANSCO), generator rate constraint (GRC), hydro-thermal, thermal-thermal system.

1. Introduction

The electric power system has over the years been dominated by large utilities that had an overall authority and activities in generation transmission and distribution of power within its domain of operation. Such utility have often been referred to as vertically integrated utilities (VIUs). These utilities served as the only provider in the region and were obliged to provide electricity to everyone in the region. As utilities were vertically integrated, it was often difficult to segregate the costs incurred in generation, transmission and distribution. Therefore the utilities often charged their customers an average tariff rate depending on their aggregated cost during a period. The price setting was done by an external regulatory agency and often involved consideration other than economics.

The restructured or deregulation of a power system has started the emergence of independent power producers (IPPs) that can sell power to VIUs. The first step in deregulation has been to separate the generation of power from the transmission and distribution, thus putting all the generation on the same footing as IPPs.

This new development in the power system restructuring requires innovations in the energy management systems (EMS). The new restructured power system introduces the concept of competitive market system under deregulation. The introduction of market system requires a lot of changes in power system operations. Especially, the EMS should be innovated to be adapted to electricity market systems. The AGC is one of main function of EMS, and is also required to be innovated for the adaptation to the market systems with several kinds of the bidding strategies.

The principles of the deregulation of the electricity market are as follows:

(i) Unbundling: separating vertically integrated utility into three different independent entities. I.e. GENCOs, TRANSCOs and DISCOs,

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(ii) Annulling of exclusive rights: no exclusive territories for any company any more.
(iii)Third party access: all customers should get access to the transmission or supply grid.

Under the new paradigm, AGC operation is accountable to load following contracts. It will also meet the control performance criteria as long as the area control error (ACE) is a part of the control objective.

Literature survey shows that most of the earlier work in the area of automatic generation control in deregulated power system pertains to interconnected hydro-thermal system and no attention has been devoted to hydro-thermal and thermal-thermal systems involving thermal and hydro subsystems of widely different characteristics

Authors [1], have discussed the main objective of the operator in such VIUs to minimize the total system cost while satisfying all associated system constraints. Apart from operational issues, such vertically integrated utilities also had a centralized system of planning for the long term. All activities such as long term generation and transmission expansion planning, medium term planning activities such as maintenance, production and fuel scheduling were coordinated centrally. Christie et al. [2] have discussed load frequency control (LFC) issues in deregulated power system. It identifies the technical issues associated with LFC and finds solutions such as standards and algorithms, needed for the operation in the restructured power system.

Kumar et al. [3], [4] have presented an AGC simulator model for price based operation in a deregulated power system. They have suggested the modifications required in the conventional AGC to study the load following in price based market operations. Meliopoulos et al. [5] have discussed the concept that in a deregulated environment, independent generators and utility generators may or may not participate in the LFC of the system.

Donde et al. [6] have presented AGC of a two area non-reheat thermal system in deregulated power system. The concept of DISCO participation matrix (DPM) and area participation factor (APF) to represent bilateral contracts are introduced. However, they have not dealt with reheat turbine, GRC and hydro-thermal system in their work. This paper deals with the AGC of hydro-thermal and thermal-thermal system considering reheat turbine and GRC constains in deregulated environment.

2. System Investigations

The system investigated consists of two generating areas of equal size. Area 1 comprises of a reheat thermal system with two GENCOs of equal capacity and area 2 comprising a hydro system with one GENCO. Fig.1 shows the transfer function of AGC model with single stage reheat turbine in thermal area and electric governor in hydro area are considered for deregulated environment. Area 1 has two DISCOs and area 2 has one DISCO.

The other system considered consists of two generating areas of equal size with area 1 comprises a reheat thermal system with two GENCOs of equal capacity and area 2 also comprising a hydro system with two GENCOs. Appropriate GRCs have been considered for thermal and hydro area GENCOs. The investigated thermal-thermal system consists of two generating areas of equal size where area 1 consists of a reheat thermal system with two GENCOs of equal capacity and area 2 comprise of a thermal system with one GENCO.

The other thermal-thermal system considered are two generating areas of equal size. Areas 1 and 2 having a reheat thermal system with four GENCOs of equal capacity. Appropriate GRC have been considered for thermal-thermal system area GENCOs.

A bias setting of $B_i = \beta_i$ is considered for both hydro and thermal areas. The system model is considered for continuous mode operation. The optimum values of proportional and integral gains for the electric governor and optimum gain for the integral controllers have been selected using integral square error (ISE) criterion [7]. The cost function, J for ISE is given as

$$J = \int \left(\Delta P_{tie(1-2)^2} + \Delta f_1^{\,2} + \Delta f_2^{\,2} \right) dT \tag{1}$$

where, dT is the small time interval during sample,

$\Delta P_{tie(1-2)}$ is the incremental change in tie power,

Δf_i is the incremental change in frequency.

A step load perturbation of 1% of nominal loading has been considered in any one of the area. The nominal parameter of the systems for both hydro-thermal system and thermal-thermal system are given in Appendix I.

Optimization of Integral Controller Gains:

The optimum values of integral controllers and electric governor parameters are found on the basis of minimum cost function. The sets of optimum gain parameters for integral controllers and electric governor are obtained for different type of systems using ISE criterion are presented in Table 1.

Table 1: Optimum gain parameters of integral controllers and electric governor are obtained for different type of systems using ISE criterion

Types of system	electric governor		optimum controller gains		
	Kd	Kp	Ki	Ki1	Ki2
reheat hydrothermal without GRC	2.4	2.4	4.5	0..31	0.01
reheat hydrothermal with GRC	1.4	1.7	1.9	0.151	0.051

Case Study:

Two area hydro-thermal systems are considered below to illustrate the behavior of the proposed AGC scheme for deregulated environment. System considered is as follows: Each DISCO demands 0.01 p.u. MW power.

$$DPM = \begin{bmatrix} 0.5 & 0.3 & 0.4 \\ 0.3 & 0.7 & 0.4 \\ 0.2 & 0.0 & 0.2 \end{bmatrix}$$

Here in the present case the Disco Participation Matrix (DPM) is chosen on the basis of market economics. For this DPM the schedule generation of the GENCOs and the tie flow are calculated using formulas as shown:

GENCO1 $_{(schedule)}$ = (0.5+0.3+0.4)*0.01 = 0.012 p.u.
GENCO2 $_{(schedule)}$ = (0.3+0.7+0.4)*0.01 = 0.014 p.u.
GENCO3 $_{(schedule)}$ = (0.2+0.0+0.2)*0.01 = 0.004 p.u.
$P_{tie\ 1\text{-}2\ (sch.)}$ = [(0.4+0.4) – (0.2+0.0)] *0.01 = 0.006 p.u.

For the reheat hydro-thermal areas, the APF are chosen prudently so as to achieve schedule generation and tie flow. So in the present case for an interconnected reheat hydro-thermal system with GRC, the Apfs are chosen as follows: For the thermal area the Apf of

GENCOs are proportional to their respective generations and for the hydro area the ACE is divided equally among the hydro area GENCOS i.e. the Apf's of hydro area GENCOs are considered to be equal.

For the present DPM considered, the APF for the three GENCOs are:

Apf_{11} for GENCO1 = 0.012/(0.012+0.014) = 0.462 p.u

Apf_{12} for GENCO2 = 0.014/(0.012+0.014) = 0.538 p.u

As per the definition of Apf we have Apf11+Apf12=1.

Apf_{23} for GENCO3 = 1 (only one hydro GENCO present in this case) All the AGC model are simulated using MATLAB-SIMULINK of version 6.5

A two area with two Gencos thermal area and two Gencos thermal area is considered to illustrate the behavior of the proposed AGC scheme for deregulated environment. System considered is as follow. Each DISCO demands 0.01 p.u. MW power.

$$DPM = \begin{vmatrix} 0.1 & 0.5 & 0.2 & 0.3 \\ 0.2 & 0.3 & 0.5 & 0.2 \\ 0.3 & 0.1 & 0.3 & 0.3 \\ 0.4 & 0.1 & 0.0 & 0.2 \end{vmatrix}$$

Here in the present case the DPM is chosen on the basis of market economics. For this DPM the schedule generation of the GENCOs and the tie flow are:

GENCO1$_{(schedule)}$ = (0.1+0.5+0.2+0.3)*0.01 = 0.011 p.u.

GENCO2$_{(schedule)}$ = (0.2+0.3+0.5+0.2)*0.01 = 0.012 p.u.

GENCO3$_{(schedule)}$ = (0.3+0.1+0.3+0.3)*0.01 = 0.010 p.u.

GENCO4$_{(schedule)}$ = (0.4+0.1+0.0+0.2)*0.01 = 0.007 p.u.

$P_{tie\ 1\text{-}2\ (sch.)}$ = [(0.7+0.5) – (0.7+0.2)] * 0.01 = 0.003 p.u.

For the reheat thermal areas, the Apf are chosen prudently so as to achieve schedule generation and tie flow. So for an interconnected reheat thermal-thermal system with GRC, the Apfs are chosen as follows: here the Apf of GENCOs are proportional to their respective generations with the present DPM considered in two Gencos each thermal area 1 and area 2, the APF for the four GENCOs are.

Apf_{11} for GENCO1 = 0.011/(0.011+0.012) = 0.478 p.u

Apf_{12} for GENCO2 = 0.012/(0.011+0.012) = 0.522 p.u

As per the definition of APF we have Apf11+Apf12=1p.u

Apf_{23} for GENCO3 = 0.010/(0.010+0.007) = 0.588p.u

Apf_{24} for GENCO4 = 0.007/(0.010+0.007) = 0.412p.u

All the AGC model are simulated using MATLAB-SIMULINK of version 6.5 and the dynamic responses are plotted with and without GRC's , thermal with Single and double reheater are studied, hydro with electrical governor and mechanical are considered and the results were analyzed and compared in the computational resuls section.

Effect of DPM matrix

In deregulated environment, the DISCO participation matrix (DPM) is chosen on the basis of open market strategy. Due to the changing scenario of market economy the DPM matrix will not remain the same all the time. Therefore change of DPM changes the generation schedule in the restructured environment. Hence DPM matrix changes in the deregulated environment. To examine this, Different distribution participation matrices (DPM) are introduced on the basis of economics and optimum values of integral gains and electric governor parameters are obtained for each case using ISE criterion. A two area reheat hydro-thermal system with GRC, as discussed in the previous case, is considered here for the analysis. The four different DPMs considered for the present investigations are given below as A, B, C and D.

$$A = \begin{bmatrix} 0.3 & 0.4 & 0.5 \\ 0.2 & 0.3 & 0.8 \\ 0.7 & 0.3 & 0.1 \end{bmatrix} \quad B = \begin{bmatrix} 0.1 & 0.4 & 0.1 \\ 0.3 & 0.5 & 0.2 \\ 0.4 & 0.1 & 0.3 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.6 & 0.0 & 0.3 \\ 0.0 & 0.7 & 0.3 \\ 0.4 & 0.3 & 0.4 \end{bmatrix} \quad D = \begin{bmatrix} 0.5 & 0.8 & 0.5 \\ 0.5 & 0.1 & 0.3 \\ 0.0 & 0.1 & 0.2 \end{bmatrix}$$

The dynamic response comparison for sets of optimum controller is observed that although the optimum gains found for different DPM are quite different but there is hardly any difference observed in system responses when these sets of gains are used for a given DPM.

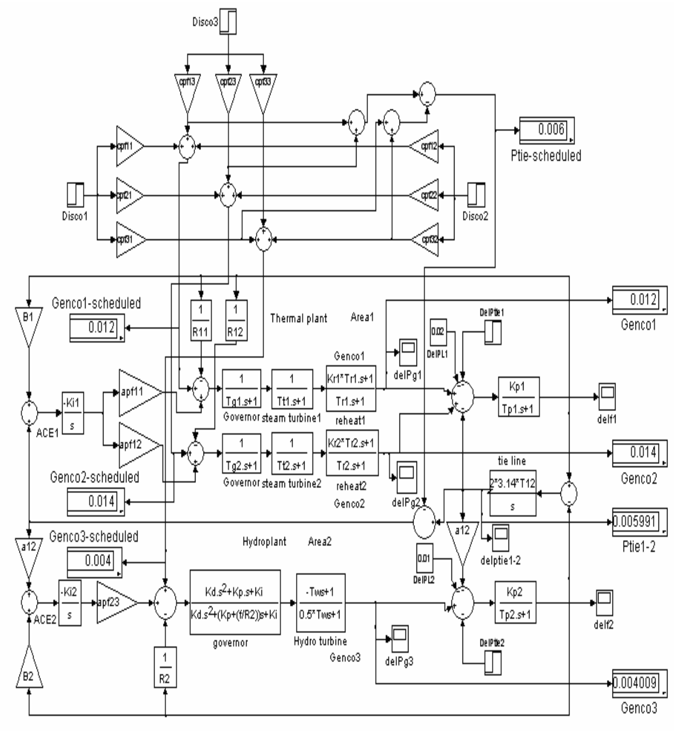

Fig. 1. Transfer function model of AGC in an interconnected two area Hydro Thermal system without GRC using Single reheat Turbine and Electric in deregulated Environment

3. Computational Results

For the optimum AGC controller gain value, the corresponding results of optimum generators participations in generations, tie line exchanges obtained by computed values using formulae and matlab/simulink based results for case study where are computed. For the first case study considered with hydro-thermal system, the different computed values are compared with the simulink values obtained in the absence and presence of GRC

Table 2: Comparison of Hydro-Thermal system in three Genco's AGC without GRC

Results	Computed values	Matlab-Simulink based values		
		single reheat turbine and electric governor	double reheat turbine	Mechanical governor
Del Pg1	0.012	0.012	0.012	0.01197
Del Pg2	0.014	0.014	0.014	0.01398
Del Pg3	0.004	0.004009	0.004009	0.004049
Del Ptie1-2	0 .0006	0 .005991	0.005991	0.005952

Table 3: Comparison of Hydro-Thermal system in three Genco's AGC with GRC

Results	Computed values	Matlab-Simulink based values		
		single reheat turbine and electric governor	double reheat turbine	Mechanical governor
Del Pg1	0.012	0.01185	0.01133	0.01205
Del Pg2	0.014	0.01415	0.01467	0.01396
Del Pg3	0.004	0.004	0.004	0.003992
Del Ptie1-2	0.0006	0.006	0.006	0.006006

Table 4: Comparison of Hydro-Thermal system in four Genco's AGC without GRC

Results	Computed values	Matlab-Simulink based values	Error
Del Pg1	0.011	0.01098	0.00002
Del Pg2	0.012	0.01198	0.00002
Del Pg3	0.010	0.01003	0.00003
Del Pg4	0.007	0.00701	0.00001
Del Ptie1-2	0.003	0.002958	0.000042

Table 5: Comparison of Hydro-Thermal system in four Genco's AGC with GRC

Results	Computed values	Matlab-Simulink based values	Error
Del Pg1	0.011	0.01173	0.00073
Del Pg2	0.012	0.01127	0.00007
Del Pg3	0.010	0.009886	0.000114
Del Pg4	0.007	0.007114	0.000114
Del Ptie1-2	0.003	0.003	0.00000

Table 6: Comparison of Thermal-Thermal system in three Genco's AGC without GRC

Results	Computed values	Matlab-simulink Based Values	
		single reheat turbine	double reheat turbine
Del Pg1	0.012	0.012	0.012
Del Pg2	0.014	0.014	0.014
Del Pg3	0.004	0.004008	0.004009
Del Ptie1-2	0.0006	0.005992	0.005991

Table 7: Comparison of Thermal-Thermal system in three Genco's AGC with GRC

Results	Computed values	Matlab-simulink Based Values	
		single reheat turbine	double reheat turbine
Del Pg1	0.012	0.01194	0.01235
Del Pg2	0.014	0.01406	0.01365
Del Pg3	0.004	0.004	0.004
Del Ptie1-2	0.0006	0.006	0.006

Table 8: Comparison of Thermal-Thermal system in four Genco's AGC without GRC

Results	Computed values	Matlab-Simulink based values	Error
Del Pg1	0.011	0.01098	0.00002
Del Pg2	0.012	0.01198	0.00002
Del Pg3	0.010	0.01003	0.00003
Del Pg4	0.007	0.007008	0.00008
Del Ptie1-2	0.003	0.002965	0.000035

Table 9: Comparison of Thermal-Thermal system in four Genco's AGC with GRC

Results	Computed values	Matlab-Simulink based values	Error
Del Pg1	0.011	0.01052	0.00048
Del Pg2	0.012	0.01248	0.00048
Del Pg3	0.010	0.01089	0.00089
Del Pg4	0.007	0.006109	0.000891
Del Ptie1-2	0.003	0.003	0.00000

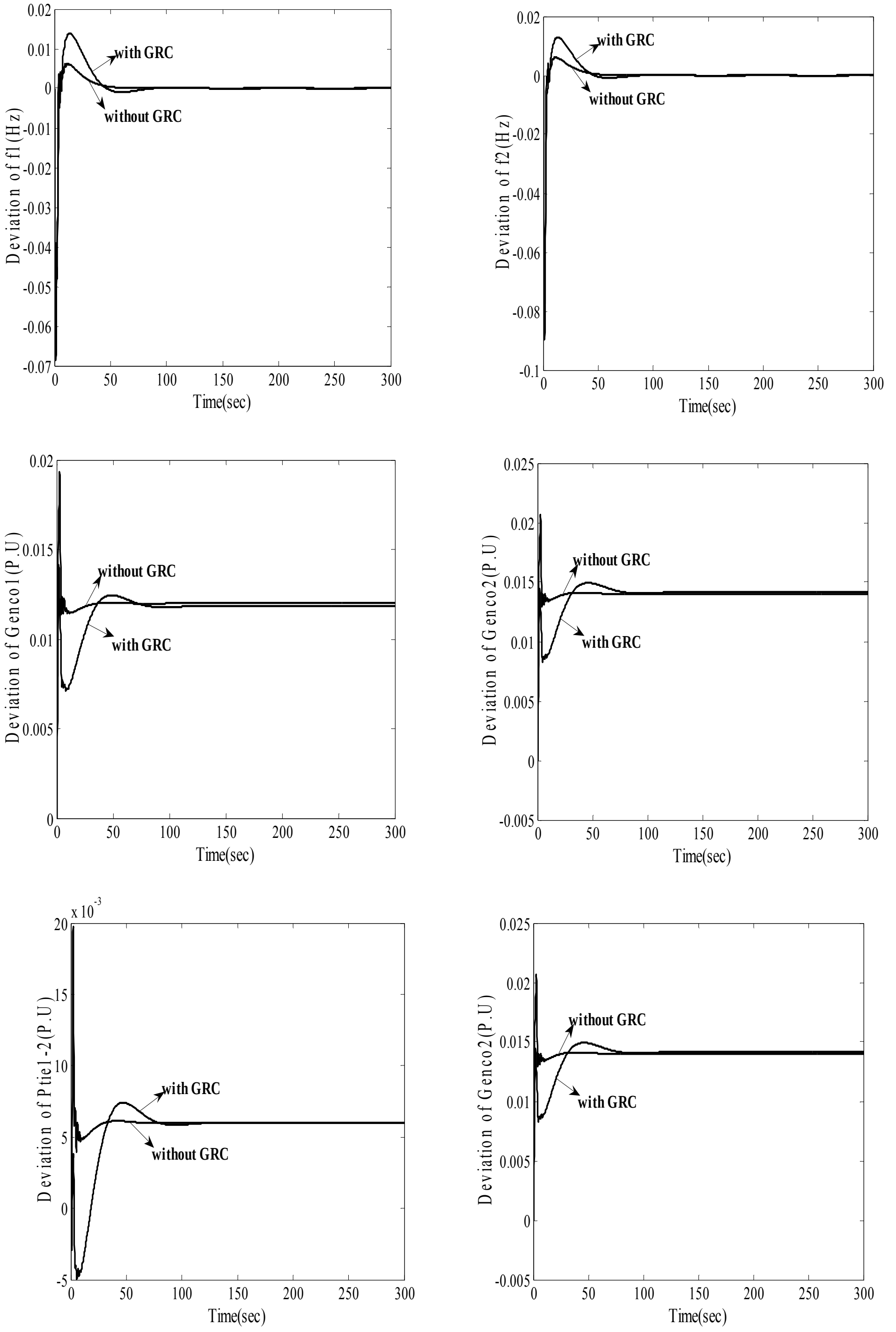

Fig. 2. Comparison of dynamic responses of AGC in an interconnected two area Hydro Thermal system with and without GRC using Single reheat Turbine and Electric in deregulated Environment

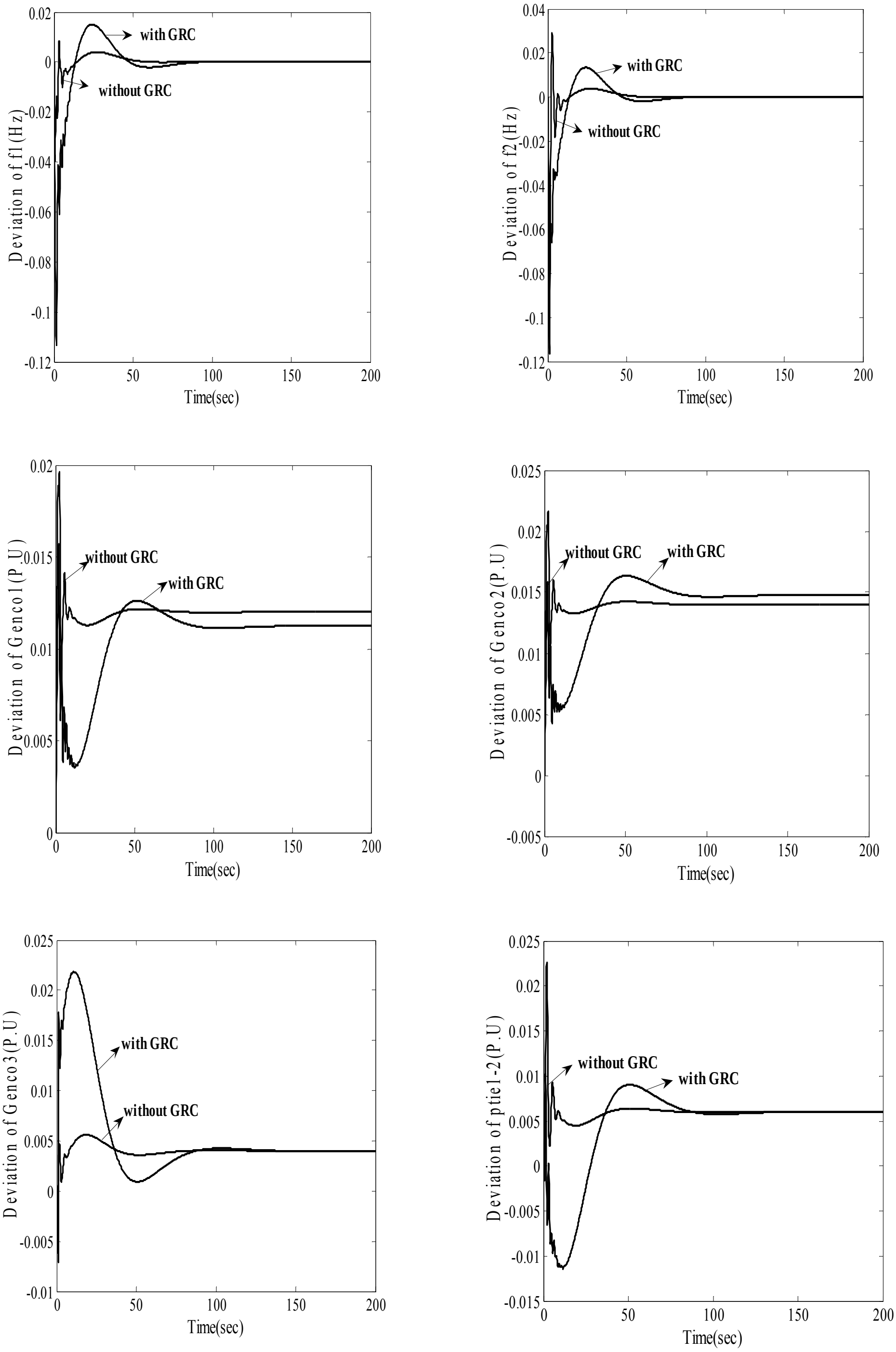

Fig. 3.Comparison of dynamic responses of AGC in an interconnected two area Hydro Thermal system with and without GRC using double reheat Turbine and Electric in deregulated Environment

Fig. 2 and 3 shows that investigations have been carried out to see the comparison of dynamic responses of AGC in an interconnected two area hydro-thermal system with and without GRC using single reheat and double reheat turbine and electrical governor in deregulated environment. The entire investigation have been carried out the impact of APF selection on system dynamics for various combinations i.e. single reheat, double reheat for thermal system, Electrical and Mechanical governor and hydro-thermal, thermal-thermal system, with and without GRC. Any arbitrary selection of APF provides the schedule generations and tie flow and APF affects only the transient behavior of the system and not the steady state behavior. However, when the system is considered with GRC in both the areas, it is observed that for the same set of APFs the generations of thermal area Gencos are found deviated from their schedule values in the steady state deviated from their schedule values in the steady state. So from all these investigations it is clear that Apf is highly sensitive and it should be chosen carefully so as to have proper functioning of AGC in deregulated environment. The optimum value of integral controller gain are obtained by using ISE technique, considering 1% step perturbation and the dynamic responses of Δf1, Δf2, Δpg1, Δpg2, Δpg3 and Δptie are obtained.

Table 2 to 3 presents the comparison of three GENCO's hydro thermal system in deregulated environment with and without GRC constrains for two areas. The tabulated results provide robust results with the various governers. Table 4 and 5 highlights the comparison of four GENCO's hydro thermal systems with and without GRC constraints for two areas.The tabulated results reveals minimum error in the system performance.

Table 6 to 7 presents the comparison of three GENCO's thermal-thermal system in deregulated environment with and without GRC constrains for two areas. The tabulated results provide robust results with the various governers. Table 8 and 9 highlights the comparison of four GENCO's thermal thermal systems with and without GRC constraints for two areas. The tabulated results reveal minimum error in the system performance.

4. Conclusions

Automatic Generation Control was implemented in interconnected hydro-thermal system and thermal-thermal system in the Deregulated Environment. Effect of GRC is clearly distinct with large oscillations and more settling time in case of reheat hydro-thermal system with GRC. For non reheat and reheat system without GRC, ACE participation factors affect only the transient behavior. In case of reheat hydro-thermal system with GRC, the ACE participation factors for thermal area GENCOs are proportional to their quantum of generation, whereas for hydro area GENCOs the ACE is distributed equally among the GENCOs present in that particular area, whereas for system without GRC any arbitrary values of APF can provide schedule generation and schedule tie flow.± 25% change in system parameters, like load, B, H, T_g, T_t etc from their nominal values considering their optimum controller gains, do not affect the system responses appreciably. Thus the optimum value of integral controller gains obtained for nominal values are quite insensitive to wide parameter variations (+25%). Hence for all practical purpose we can say that the controllers are quite robust. Sets of electric governor parameters hardly change with variation in "distribution participation matrix (DPM)". Although the integral controller gains change with change in DPM, the system responses do not change appreciably. So there is no need to change controller setting for different sets of DPM.

References

[1] M. Parida and J. Nanda, “Automatic generation control of a hydro-thermal system in deregulated environment”, Proceedings of the Eighth International Conference on Electrical Machines and Systems, 2005. ICEMS 2005. vol. 2, Sept. 2005, pp. 942– 947.

[2] R. D. Christie and A. Bose, “Load frequency control issues in power system operations after deregulation”, *IEEE Trans. Power Systems*, vol. 2, no.3, pp.1191-1196, Aug. 1996.

[3] J. Kumar, K.H. Ng, and G. Sheble, “AGC simulator for price-based operation: Part I”, *IEEE Trans. Power Systems*, vol.12, no.2, pp. 527-532, May 1997.

[4] J. Kumar, K.H. Ng, and G. Sheble, “AGC simulator for price-based operation: Part II”, *IEEE Trans. Power Systems*, vol.12, no.2, pp. 533-538, May 1997.

[5] A.P. S. Meliopoulos, G.J. Cokkinides, and A.G. Bakirtzis, “Load- frequency control service in a deregulated environment”, *Decision Support Systems*, vol. 24, pp. 243-250, 1999.

[6] V. Donde, M. A. Pai, and I. A. Hiskens, “Simulation and optimisation in an AGC System after deregulation”, *IEEE Trans. Power Systems*, vol. 16, no.3, pp. 481-488, Aug. 2001.

[7] O.I. Elgard, “Electric energy system theory, 2nd edition, McGraw – Hill, New York, USA, 1982.

Appendix

$P_{r1} = P_{r2} = 2000$ MW
$H_1 = H_2 = 5$ s
$D_1 = D_2 = 8.33*10^{-3}$ pu MW/Hz
$Kr_1 = Kr_2 = 0.5$
$R_{11} = R_{12} = R_2 = R_{21} = R_{22} = 2.4$ Hz/pu MW
$T_{r1} = T_{r2} = 10$ s
$K_{p1} = K_{p2} = 120$ Hz/pu MW
$T_{p1} = T_{p2} = 20$ s
$T_{12} = 0.086$ pu MW/rad
$B_1 = B_2 = 0.425$ Hz
$T_{g1} = T_{g2} = 0.08$ s
$T_{t1} = T_{t2} = 0.3$ s
$T_r = 5$ s
$T_t = 0.3$ s
$T_1 = 48.75$ s
$T_2 = 0.513$ s
$f = 60$ Hz
$T_w = 1.0$ s
$a_{12} = -1.0$