Optimal control of restructured electric power systems interconnected via AC-DC links

Pankaj Chawla[1], S.K. Gupta[2], Yogendra Arya[3]

[1,2] *Department of Electrical Engineering, Deenbandhu Chhotu Ram University of Science and Technology, Murthal, Sonepat, Haryana, India*

[3] *Department of Electrical & Electronics Engineering, Maharaja Surajmal Institute of Technology, Janakpuri, Delhi, India*

Abstract: A comparative analysis of automatic generation control of two-area restructured electric power systems interconnected by AC and AC-DC links has been considered in this study. Each area has thermal-hydro (TH) power sources. The state space model of the power systems have been developed and optimal proportional integral structured controller is designed to simulate all market contracts probable in a deregulated power environment. The eigenvalue analysis is carried out to assess the comparative stability analysis of the power systems with or without AC/DC links. Further, the dynamic responses are obtained in the presence of AC link and AC-DC links. It can be observed that the inclusion of AC-DC links improves the dynamic performance of all the systems remarkably, moreover, optimal controller is found competent to demonstrate the matching of generation with power demand under different market transactions.

Keywords: automatic generation control; deregulation; optimal control, optimal control application; hydro power system; AC/DC parallel links; vertically integrated utility.

I. INTRODUCTION

Automatic generation control (AGC) has mainly two objectives (a) maintain the frequency of each area within the specified limits and (b) controlling the inter area tie-line power exchanges within the scheduled values [1-3]. In conventional power systems, the power generation, transmission and distribution are governed by a single entity called vertically integrated utility (VIU). The world power industry is presently undergoing restructuring and adopting the deregulated industry structure for optimum utilization of all resources and to provide the quality services. ISO arranges various ancillary services including AGC and keeps the entire power system stable in highly competitive and distributed control environment. Due to lack of proper controller design in deregulated environment, the instability may spread to other control areas leading to severe system black out. In order to cope with these situations, a lot of work is being done on various control strategies in deregulated power systems; notable among these are gradient Newton algorithm [2], optimal control [1,4-8], sub-optimal control [8], H2/H∞/LMI control [9] etc. In addition, various soft computing techniques such as genetic algorithm [3, 5, 7, 10] particle swarm optimization [4], neural networks [11], fuzzy logic [4, 7, 12], firefly algorithm [12], hybrid neuro fuzzy [13-14], artificial cooperative search algorithm [14] have been reported.

Recently FACTS devices [10] are employed in series with AC tie-line to stabilize the system frequency and tie-power oscillations. Due to the growth of AC/DC and DC/AC converters with higher ratings the application of HVDC transmission systems is increasing at fast rate. One of the major applications of HVDC transmission is as a DC link in parallel with AC link interconnecting two control areas. The literature survey indicates that largely works reported so far as for AGC have been carried out considering the area interconnection as an AC transmission line only [1-3]. A very few studies have been observed in the literature with AC-DC links [4, 6].

Hence, in this paper, a comparative performance investigation of AGC of two-area restructured power systems interconnected by AC link and AC-DC links is performed deliberately. In the present study, a maiden attempt is made to compare the dynamic performances of restructured thermal-hydro systems in the presence of AC link and AC-DC links under all power transactions possible in a deregulated environment. For all the studied systems, it is observed that the AC-DC links improve the dynamic performance appreciably in comparison the AC link. However, responses of hydro-hydro power system are lethargic and corrupted having more undershoots, overshoots and settling time in comparison to of thermal-hydro and thermal-thermal power systems.

II. MODELLING OF THE POWER SYSTEM

In restructured electric power system, the generation companies (GENCOs) sell power to the distribution companies (DISCOs) through bilateral contracts under the supervision of ISO [1-2]. A pool market is a centralized place that clears the market for sellers and buyers of electrical power for pool contracts. The role of TRANSO is to transport the contracted power. In poolco based transactions where GENCOs of an area have contracts only with the DISCOs of their own area [1-2, 5-7]. AGC, thus, should be designed to house all types of possible contracts like poolco as well as bilateral transactions. To bilateral contracts between DISCOs and GENCOs are represented by DISCO participation matrix (DPM) [2]. The rows in DPM correspond to the GENCOs and the columns correspond to DISCOs. The entry in DPM represents contract participation factor (cpf) as stated in Eq. (1). Sum of the entries of a column of DPM is equal to one, which indicates that the total per unit demand of a DISCO is under contract among the available GENCOs on the basis of cpfs in a column.

$$DPM=\begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix} \qquad (1)$$

In two-area power system models under study, each control area has two DISCOs and two GENCOs. Let GENCO-1, GENCO-2, DISCO-1 and DISCO-2 be in control area-1, while GENCO-3, GENCO-4, DISCO-3 and DISCO-4 be in control area-2. Thermal-hydro (TH) two-area system incorporates one single reheat type thermal and one mechanical governor based hydro GENCOs in each area as shown in Fig. 1. The actual steady state tie-line power flows (ΔPtieactual (s)) via AC link is given by Eq. (2) [5-6].

$$\Delta Ptie_{actual}\,(s) = \frac{2\pi T_{12}}{s}\,[\Delta F_1\,(s) - \Delta F_2\,(s)] \qquad (2)$$

Here, ΔF1 and ΔF2 are the deviations the area-1 and 2 frequencies, respectively and T12 is the synchronization coefficient. The DC link is supposed to be operated in constant current control mode. The incremental power flow through DC link (ΔPtiedc (s)) is modelled with incremental change in frequency at rectifier end. The transfer function of DC link is taken from [4, 6]. For small perturbation, the DC tie-line flow can be given by Eq. (3) [4-6].

$$\Delta Ptie_{dc}\,(s) = \frac{K_{dc}}{1+sT_{dc}}\,[\Delta F_1\,(s) - \Delta F_2\,(s)]$$
(3)

Here, Kdc is the gain and Tdc is time constant of DC link. For small change in load, the actual tie-line power flow, as given by Eq. (2) for the system interconnected via AC link, is adapted in the presence of a DC link as [6]:

$$\Delta Ptie_{mactual}\,(s) = \Delta Ptie_{actual}\,(s) + \Delta Ptie_{dc}\,(s) \qquad (4)$$

The scheduled steady state power flow on the tie-line is given by Eq. (5).

$$\Delta Ptie_{scheduled}\,(s)\,\sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\,\Delta P_{Lj} - \sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\,\Delta P_{Lj}. \quad (5)$$

The tie-line power flow error is stated Eq. (6).

$$\Delta Ptie_{error}\,(s) = \Delta Ptie_{mactual}\,(s) - \Delta Ptie_{scheduled}\,(s) \qquad (6)$$

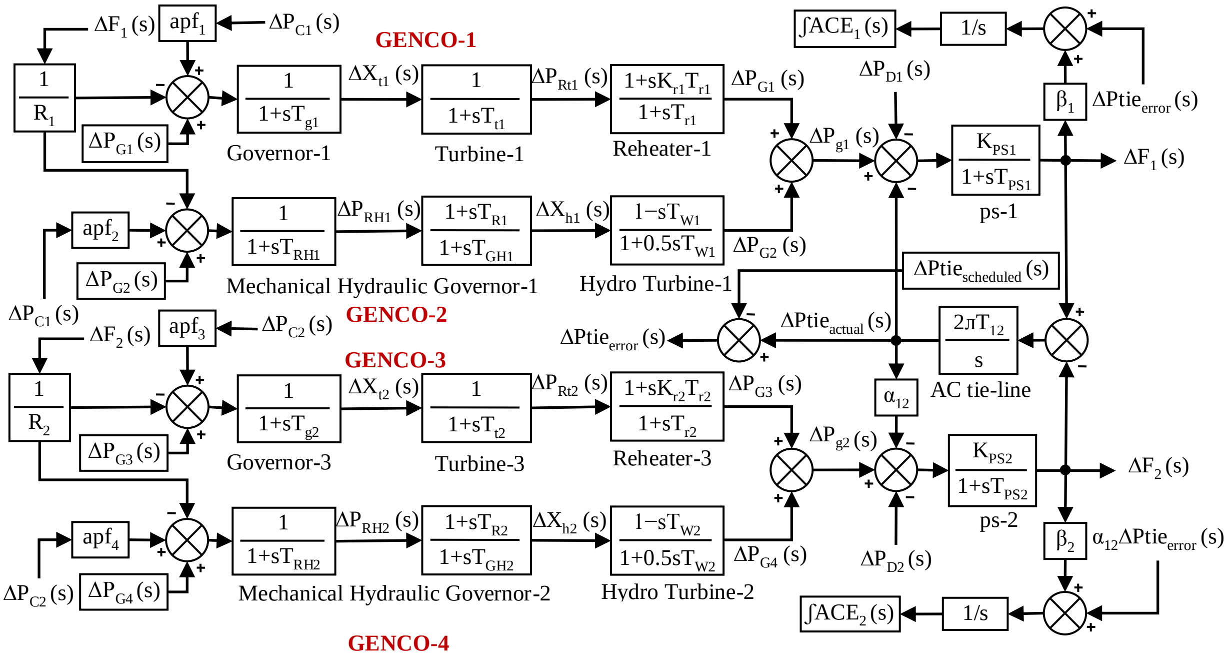


Fig. 1 Transfer function model of two-area thermal-hydro power system with AC link.

In the steady state ΔPtieerror (s) disappears when ΔPtiemactual (s) achieves ΔPtiescheduled (s) values. In the presence of AC/DC parallel links ACE is tailored as given by Eqs. (7-8).

$$ACE_{m1}\,(s) = \beta_1 \Delta F_1\,(s) + \Delta Ptie_{error}\,(s) \qquad (7)$$

$$ACE_{m2}\,(s) = \beta_2 \Delta F_2\,(s) + \alpha_{12} \Delta Ptie_{error}\,(s) \qquad (8)$$

Here, α12 is area size ratio, ΔF1, ΔF2, β1, β2 are deviation in frequency and frequency bias by ACE constants of areas 1 and 2, respectively. The ACEm (s) is shared by all the GENCOs by all the GENCOS of that area as decided participation factors (apfs). The expressions for generated power output signals of thermal/hydro GENCOs is given in Eq. (9):

$$\Delta P_{Gi}\,(s) = cpf_{i1}\Delta P_{L1} + cpf_{i2}\Delta P_{L2} + cpf_{i3}\Delta P_{L3} + cpf_{i4}\Delta P_{L4} \qquad (9)$$

Where i = 1 to 4 and ΔPLi denotes the power demanded by DISCO-i. In Figs. 1, the signals ΔPCi indicates the output of the controller belonging to control area-i. The other states stated in figure are deviations in area frequency (ΔFi), power outputs of thermal GENCOs (ΔPGti), power outputs of hydro GENCOs (ΔPGhi), thermal turbine outputs (ΔPRti), thermal governor outputs (ΔXti), intermediate outputs of hydro governor (ΔPRHi), outputs of hydro governor (ΔXhi) and the speed regulation due to governor action (Ri), reheat coefficient of thermal power plant (Kri), reheat time constant of steam power plant (Tri), turbine time constant of thermal power plant (Tti), governor time constant of thermal power plant (Tgi), nominal starting time of water in penstock (TWi), time constants of hydro plant (TGHi, TRi, TRHi), power system gain (KPSi) and power system time constant (TPSi) and synchronizing coefficient of the line between area-1 and 2 (T12).

III. STATE SPACE MODEL

The state space model of the system under consideration for Figs. 2 is as follows:

$$\frac{d}{dt}X = AX + BU + \Gamma P_D, \qquad X(0) = 0 \qquad (10)$$

where, X is system state vector (18×1), U is control input vector (2×1) and ΔPD is disturbance vector having sizes of (18×1), (2×1) and (6×1) with AC-DC links, respectively. A, B and Γ are system, control and disturbance matrices of dimensions (18×18), (18×2) and (18×6), respectively with AC-DC links. Where:

State vector

$$X = [\Delta F_1\ \Delta F_2\ \Delta Ptie_{actual}\ \Delta P_{Gt1}\ \Delta P_{Gh1}\ \Delta P_{Gt2}\ \Delta P_{Gh2}\ \Delta P_{Rt1}\ \Delta X_{h1}\ \Delta P_{Rt2}\ \Delta X_{h2}\ \Delta X_{t1}\ \Delta P_{RH1}\ \Delta X_{t2}\ \Delta P_{RH2}\ \int ACE_{m1}dt\ \int ACE_{m2}dt\ \Delta Ptie_{dc}]^T$$

(11)

Control vector

$$U = [\Delta P_{C1}\ \Delta P_{C2}]^T \qquad (12)$$

Disturbance vector (All systems)

$$P_D = [\Delta P_{L1}\ \Delta P_{L2}\ \Delta P_{L3}\ \Delta P_{L4}\ \Delta P_{UC1}\ \Delta P_{UC2}]^T \qquad (13)$$

The ΔPLi is the deviation in DISCO power demand, ΔPUCi indicates the deviation in un contracted power demand in an area and ΔPDi is the deviation in total power demand in an area.

IV. CONTROLLER DESIGN

A PI structured optimal controller is designed to perform the simulation of the system models under study. The design of optimal controller has been taken fron [1, 4-8]. The object is to minimize the performance index J given Eq. (14).

$$J=\int_0^{\infty}\frac{1}{2}\,[X^TQX+U^T RU]dt \qquad (14)$$

Where Q is weighting matrix and R is positive definite symmetric control cost weighting matrix. The dimensions of Q and R with AC-DC parallel links are (18×18) and (2×2), respectively for the system under consideration. The optimal control law is given by Eqn. (15).

$$U^* = -K^*X \qquad (15)$$

where, $K^* = R^{-1}B^TP$ and P is the solution of algebraic matrix Riccati equation.

$$PA + A^TP - PBR^{-1}B^TP + Q = 0 \qquad (16)$$

V. RESULTS AND DISCUSSION

The state space model of the system (data are given in Appendix) is simulated with the optimal controller in MATLAB R2010a. To perform the study, the optimal gains of controller are obtained for (i) AC link and (ii) AC/DC parallel links with the help of Riccatii equation and these optimal feedback gain matrices are stated in Table 1. The eigenvalues for the systems under study are given in Table 2 for both the systems without and with AC-DC links. The comprehensive study of Table 2 reveals that all three power systems are stable in nature, as all eigenvalues lie in the left half of s-plane. However, for all the systems, some of the important eigenvalues with AC-DC links have more negative real parts. This indicate, stability margins of the power system interconnected via AC-DC in comparison to the system interconnected via AC link only, is better.

Table 1: Optimal feedback gain matrices [K*] of optimal PI controller

AC link only $[K^*]_{[2\times17]}$	[0.6377	0.0998	-1.5770	5.1949	2.0432	0.4447	0.1477	-1.6747	3.8398
	-0.2020	0.8697	0.4525	-0.0042	0.0015	-0.6063	1.0000	0.0000;	
	0.0998	0.6377	1.5770	0.4447	0.1477	5.1949	2.0432	-0.2020	0.8697
	-1.6747	3.8398	0.0015	-0.6063	0.4525	-0.0042	-0.0000	1.0000]	
AC-DC links $[K^*]_{[2\times18]}$	[0.4054	0.3321	-0.1323	4.4442	1.3625	1.1955	0.8284	-1.5487	3.1050
	-0.3280	1.6045	0.3925	0.5985	0.0616	-1.2091	1.0000	-0.0000	-0.0150;
	0.3321	0.4054	-0.1323	1.1955	0.8284	4.4442	1.3625	-0.3280	1.6045
	-1.5487	-3.1050	0.0616	-1.2091	0.3925	0.5985	0.0000	1.0000	0.0150]

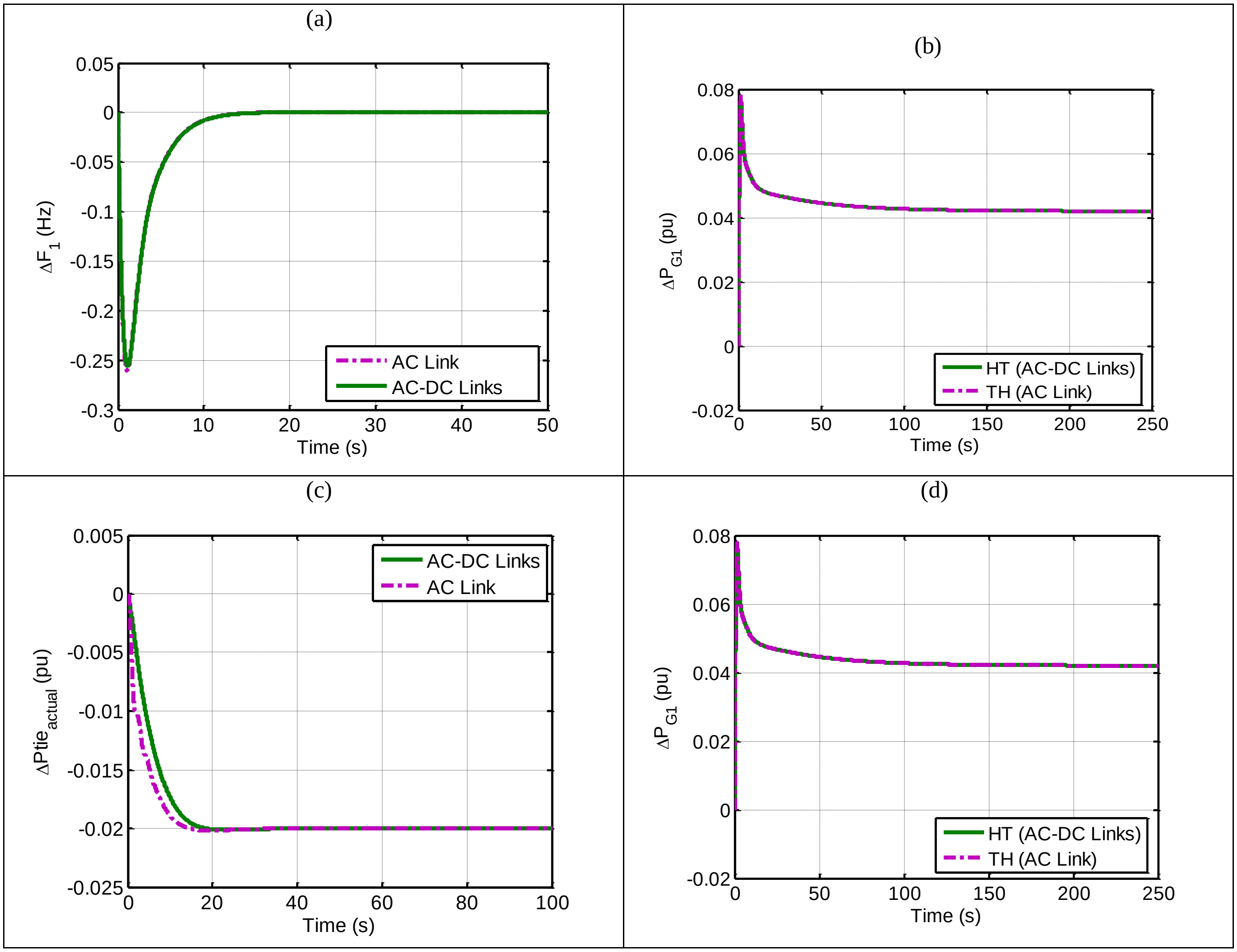
Table 2: Pattern of eigenvalues with optimal controller for two-area restructured power systems

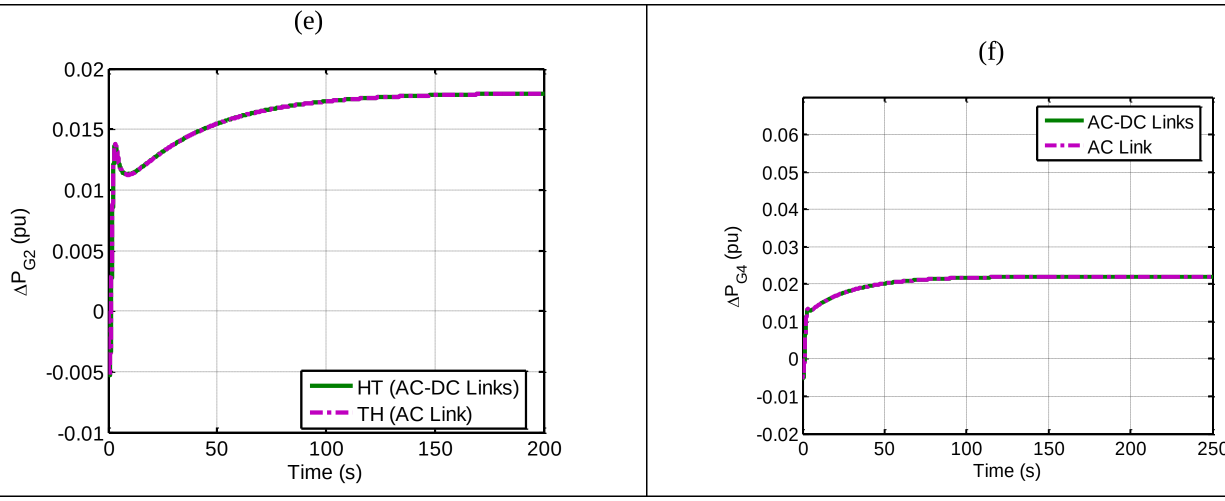
AC link		AC-DC links	
-14.2014	-1.3844	-14.2014	-3.8493
-14.1913	-0.3358	-14.0921	-0.3358
-0.5098 ± 2.8635i	-0.1971 + 0.0839i	-2.1269 ± 7.8181i	-0.1944 + 0.0812i
-2.8423 + 0.8174i	-0.1971 - 0.0839i	-2.823 + 0.8174i	-0.1944 - 0.0812i
-2.8423 - 0.8174i	-0.0347	-2.823 - 0.8174i	-0.1973
-2.8358 + 0.4309i	-0.0348	-1.9871 + 0.3153i	-0.0348
-2.8358 - 0.4309i	-0.0347	-1.9871 - 0.3153i	-0.0347
-1.1819 ± 1.2571i		-1.1819 ±1.2571i	-0.4905

The following contracts are selected:

$$DPM = \begin{bmatrix} 0.5 & 0.25 & 0.0 & 0.3 \\ 0.2 & 0.25 & 0.0 & 0.0 \\ 0.0 & 0.25 & 1.0 & 0.7 \\ 0.3 & 0.25 & 0.0 & 0.0 \end{bmatrix} \qquad (17)$$

Let each DISCO demands 0.04 pu power from GENCOs as per the pattern of cpfs shown in the DPM of Eq. (17) and apfs selected for this case are: apf1 = 0.75, apf2 = 0.25, apf3 = apf4 = 0.5. Hence, area demands are: ΔPD1 = ΔPD2 = 0.08 pu. Using Eq. (5), ΔPtiescheduled = –0.02 pu. The simulation results for the systems in the presence of AC/DC parallel links are shown in Fig. 2. The actual tie-line power settle to the desired value of –0.02 pu (shown in Figs. 5(c-d)), which is ΔPtiescheduled in the steady state. The steady state desired values of power generations in area-1 and 2 are: ΔPG1 = 0.042 pu, ΔPG2 = 0.018 pu, ΔPG3 = 0.078 pu, ΔPG4 = 0.022 pu. These generations are verified from the simulation results shown in Figs. 5(e–f). The desired dynamic responses of deviation in frequencies of area-1 and area-2 are displayed in Figs. 5(a–b) for all the system models under study.




(e)

(f)

Fig. 2: Dynamic performance of two-area restructured TH power system with AC/DC and AC parallel links (a) ΔF_1 (Hz) vs. Time (b) ΔF_2 (Hz) vs. Time (c) $\Delta Ptie_{actual}$ (pu) vs. Time (d) ΔP_{G1} (pu) vs. Time (e) ΔP_{G2} (pu) vs. Time (f) ΔP_{G4} (pu) vs. Time.

VI. CONCLUSIONS

AGC of restructured two-area hydro-thermal systems interconnected via AC/DC and AC link is considered and compared. Robust optimal PI structured controller is designed using all state feedback vector control strategy to incorporate all power contracts possible between GENCOs and DISCOs in a deregulated power environment. A decisive comparative performance analysis is done for poolco and bilateral contracts. It is observed from eigenvalues analysis that with both AC link and AC/DC parallel links, all systems are stable. However, it can be observed that stability margins of the systems with AC/DC parallel links increases in comparison to AC link.

Appendix: System parameters [6-7]

Rated area capacity = 2000MW, nominal loading = 50%, $T_{gi} = 0.08$ s, $T_{ti} = 0.3$ s, $K_{ri} = 0.5$, $T_{ri} = 10$ s, $K_{PSi} = 120$, $T_{PSi} = 20$ s, $2\pi T_{12} = 0.545$ puMW/Hz, $R_i = 2.4$ Hz/puMW, $\beta_i = 0.425$ puMW/Hz, $T_{RHi} = 48.7$ s, $T_{Ri} = 5$ s, $T_{GHi} = 0.513$ s, $T_{Wi} = 1$ s, $\alpha_{12} = -1$, $K_{dc} = 1$, $T_{dc} = 0.2$ s.

VII. REFERENCES

[1] Arya Y, Kumar N. Optimal control strategy-based AGC of electrical power systems: A comparative performance analysis. Optimal Contr Appl Methods 2017; DOI 10.1002/oca.2304.

[2] Donde V, Pai MA, Hiskens IA. Simulation and optimization in an AGC system after deregulation. IEEE Trans Power Syst 2001;16(3):481–489.

[3] Demiroren A, Zeynelgil HL. GA application to optimization of AGC in three-area power system after deregulation. Int J Elect Power Energy Syst 2007;29(3):230–240.

[4] Sinha S, Patel R, Prasad R. Application of AI supported optimal controller for automatic generation control of a restructured power system with parallel AC-DC tie lines. Euro Trans Elect Power 2012; 22(5):645–661.

[5] Arya Y, Kumar N. Optimal AGC with redox flow batteries in multi-area restructured power systems," Eng Sc Tech, an Int J 2016;19(3):1145–1159.

[6] Arya Y, Kumar N, Ibraheem. AGC of a two-area multi-source power system interconnected via AC/DC parallel links under restructured power environment. Optimal Contr Appl Methods 2016;37 (4):590–607.

[7] Arya Y, Kumar N. Fuzzy gain scheduling controllers for AGC of two-area interconnected electrical power systems. Elect Power Compon Syst 2016;44(7):737–751.

[8] Tyagi B, Srivastava SC. A decentralized automatic generation control scheme for competitive electricity markets. IEEE Trans Power Syst 2006;21(1):312–320.

[9] Shayeghi H. A robust decentralized power system load frequency control. J Electr Eng 2008; 59(6):281–293.

[10] Deepak M, Abraham RJ. Load following in a deregulated power system with thyristor controlled series compensator. Int J Elect Power Energy Syst 2015; 65:136–145.

[11] Shayeghi H, Shayanfar HA, Malik OP. Robust decentralized neural networks based LFC in a deregulated power system. Elect Power Syst Res 2007;77(3– 4):241–251.

[12] Sekhar GTC, Sahu RK, Baliarsingh AK, Panda S. Load frequency control of power system under deregulated environment using optimal firefly algorithm. Int J Electr Power Energy Syst 2016; 74:195–211.

[13] Shree SB, Kamaraj N. Hybrid neuro fuzzy approach for automatic generation control in restructured power system. Int J Elect Power Energy Syst 2016;74:274–285.

[14] Selvaraju RK, Somaskandan G. ACS algorithm tuned ANFIS-based controller for LFC in deregulated environment. J Applied Res Tech 2017; 15(2):152–166.