Automatic Generation Control of Multi-Area Power Systems with Parallel EHVAC/ HVDC Inter-Ties

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ABSTRACT:- This paper applies the modern control theory to design optimal AGC regulators using full state vector feedback for multi-area interconnected hydro-thermal power systems and implemented under considerations in the wake of 1% step load perturbation in thermal/hydro area. For the present study, power system model consists of one area with reheat thermal power plant and two area with hydro power plants having identical capacity. The system interconnection is considered namely (I) EHVAC inter-ties only (II) EHVAC in parallel with HVDC inter-ties. The dynamic model of incremental power flow through HVDC transmission link is derived based on frequency deviation at both rectifier and inverter ends. Moreover, the HVDC link is considered to be operating in constant current control mode. The system responses have been simulated in Mat lab. Responses of deviation in frequencies, deviation in tie line powers (EHVAC as well as HVDC) and integral of area control errors have been plotted for 3- area. Thus, on the basis of these responses, the dynamic performance of the system has been studied. Besides this, to study the closed loop system stability, the closed loop system eigen values are computed.

Keywords: - Interconnected power systems; HVDC transmission links; System dynamic performance; EHVAC//HVDC transmission link; Optimal AGC regulator.

NOTATIONS

i	Subscript referring to area (i=1,2,3)
ΔXgi	Incremental change in governor valve position of ith area
ΔPci	Incremental change in speed changer position of ith area
ΔPgi	Incremental change in power generation of ith area
ΔPdi	Incremental change in load demand of ith area (p.u. MW/Hz)
ΔFi	Incremental change in frequency of ith area
ΔPtiei	Incremental change in tie-line power flow of ith area (MW)
ΔPdci	Incremental change in DC link power flow of ith area
ΔPri	Incremental change in reheat turbine output of ith area
fo	Nominal system frequency (Hz)
Hi	Per unit inertia constant of ith area (sec)
Di	Load frequency constant of ith area (p.u. MW/Hz)
Ri	Speed regulation parameter of ith area (Hz/p.u. MW)
Bi	Frequency bias constant of ith area (p.u. MW/Hz)
Kgi	Speed governor gain of ith area
Tgi	Speed governor time constant of ith area (sec)
Kri	Reheat turbine gain
Tri	Reheat turbine time constant (sec)
Kdc	DC-Link gain
Tdc	DC-Link time constant (sec)
Pri	
δi	Rated power output of ith area Power angle of ith area
Pmax	Maximum rated power
T12	Synchronizing coefficient of AC link
a12	Area size ratio coefficient
A	System matrix
B	Control matrix
C	Output matrix
fd	Disturbance matrix
X	State vector
Y	Output vector
U	Control vector
Pd	Disturbance vector
J	Performance index value
Q	Positive semi-definite symmetric state cost weighting matrix
R	Positive definite symmetric control cost weighting matrix
P	Positive definite symmetric matrix
T1,T2,T3	
Tw	
K	Time constants representing hydro governor Water inertia time constant Feedback gain matrix
I	Identity matrix
Z	Closed loop system matrix
S	Symmetric cost matrix
MR	Matrix Riccatti
ACE	Area Control Error
IACEi	Integral Area Control Error of ith area.
AGC	Automatic Generation Control
LFC	Load Frequency Control
LQR	Linear Quadratic Regulator
Hz	Hertz
MW	Mega Watt
α	Rectifier Firing Angle
EHVAC	Extra High Voltage Alternating Current
HVDC	High Voltage Direct Current
PI	Proportional Integral Control
THH	One Thermal & two hydro Power Systems
TTH	Two Thermal &one hydro Power Systems
LDTA	Load disturbance in thermal area

I. INTRODUCTION

During last few decades, considerable interest has been shown towards the application of optimal control theory to automatic generation control of interconnected power systems. One of the basic requirements of modern control theory to

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AGC regulator design is the development of dynamic system model in state variable form. The realistic model of any physically realizable complex system like, interconnected power system generally has non-linear characteristics at operating levels. The exact representation of power system dynamics involves a set of large number of non-linear differential equations. The optimal AGC regulator design with non-linear system models poses computationally difficult problems when dealing with higher order complex systems. To cope with this problem, the design engineers propose linearization of system equations about an operating point for optimal system regulator design and apply the linear state-regulator theory to obtain the desired control law. Fosha & Elgerd [1] were the frist to present their pioneer work on optimal AGC regulator design using this concept. A 2-area interconnected power system consisting of two identical power plants of non-reheat thermal turbines was considered for investigations. Bohn& Minisey [17] have studied the optimum LFC of 2-area interconnected power systems. Optimal AGC regulators were designed & implemented on hydro-thermal power system by Calovic [3].An excellent critical review on the application of modern control theory to AGC, has been presented by Carpentier [8]. M.L. Kothari & J. Nanda[4] had highlighted the design of AGC controllers through optimal control strategy for 2-area interconnected hydro-thermal power systems using a new performance index. Prabhat Kumar & Ibraheem [6],[14]&[15] have presented design of AGC regulators using proportional-plus-integral control strategy for 2- area interconnected thermal-thermal, hydro-hydro and hydro-thermal power systems with asynchronous tie-lines. To the best of author’s knowledge, no work have been reported for 3-area hydro-thermal power systems consisting of one area with thermal power plants & other two area with hydro power plants. Thus the main objectives of this piece of work are as under:

(a) To design an optimal AGC controllers for an interconnected 3-area Hydro-Thermal power systems with full state vector feedback control strategy in the wake of 1% step load disturbance in thermal / hydro area incorporating EHVAC/HVDC inter-ties and study the system’s dynamic performance.

(b) To study the closed loop system stability, the closed loop system eigen values has been computed with EHVAC/HVDC inter-ties.

II. DESIGN OF OPTIMAL AGC REGULATOR

An s-area interconnected power system described by a completely controllable and observable linear time-invariant state space representation is considered for the present work. The differential equations of the system in state variable form can be written as

$$\dot{\underline{X}} = A\,\underline{X} + B\,\underline{U} + Fd\,\underline{Pd} \qquad \text{--- (1.1)}$$

$$\underline{Y} = C\,\underline{X} \qquad \text{--- (1.2)}$$

Where: $\underline{X}$, $\underline{U}$, $\underline{Pd}$ and $\underline{Y}$ are the state, control, disturbance and output vectors respectively.

A, B, C and Fd are the matrices of compatible dimensions.

Problem may be stated as find the control U, so as to minimize the performance index

$$J = \int_{\circ}^{\infty} \frac{1}{2}\left[\ \underline{X}^T Q\,\underline{X} + \underline{U}^T R\,\underline{U}\ \right] dt \qquad \text{---- (1.3)}$$

Where,

Q – a positive semi-definite symmetric state cost weighting matrix.

R – a positive definite symmetric control cost weighting matrix.

In the application of optimal control theory, the term Fd $\underline{Pd}$ in eqn (1.1) is eliminated by redefining the states and controls in terms of their steady-state values occurring after the disturbance.

Eqn (1.1) can be rewritten as;

$$\dot{\underline{X}} = A\,\underline{X} + B\,\underline{U}\ ;\ X(0) = X_o \qquad \text{---- (1.4)}$$

Where, $X(0) = X_o$ is the initial condition.

With a full state vector feedback control problem, a control law is stated in the form

$$\underline{U}^* = -K^*\,\underline{X} \qquad \text{--- (1.5)}$$

Hence, in order to design optimal regulator so as to minimize the performance index (1.3), a Matrix- Riccatti (MR) equation given by the following eqn is to be solved (The inbuilt LQR command has been used):

$$A^T P + PA - P B R^{-1} B^T P + Q = 0 \qquad \text{---- (1.6)}$$

By solving this equation, we get positive definite symmetric matrix P such that the optimal control law is calculated as

$$\underline{U}^* = -R^{-1} B^T P\,\underline{X} \qquad \text{---- (1.7)}$$

Hence, the desired optimal feedback gain matrix will be

$$K^* = R^{-1} B^T P \qquad \text{---- (1.8)}$$

III. POWER SYSTEM MODEL

The three area interconnected hydrothermal power systems consisting of one area with reheat thermal power plants and other two area with hydro power plants having identical capacity. The following configurations are identified for power system model;

(I) EHVAC link is used as a system interconnection.

(II)EHVAC link in parallel with HVDC link is used as a system interconnection.

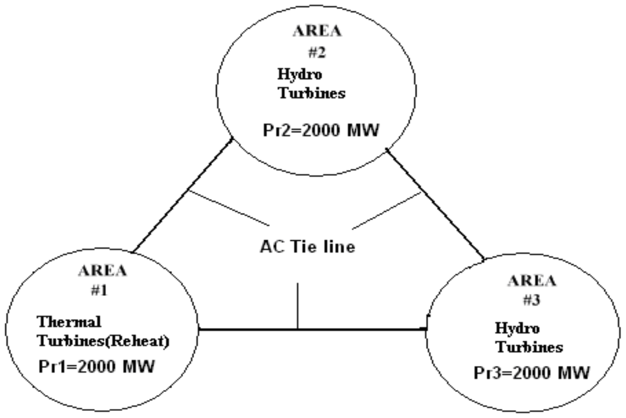


Fig 1 Power System Model (1-T & 2-H) with EHVAC links

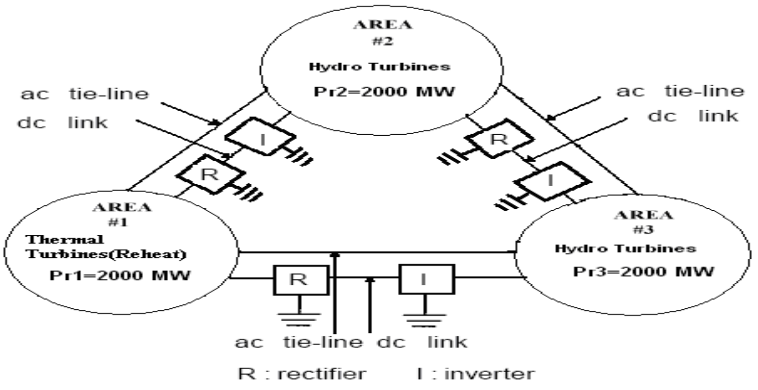


Fig 2 Power System Model(1- Thermal & 2- Hydro) with Parallel EHVAC/DC LINKS

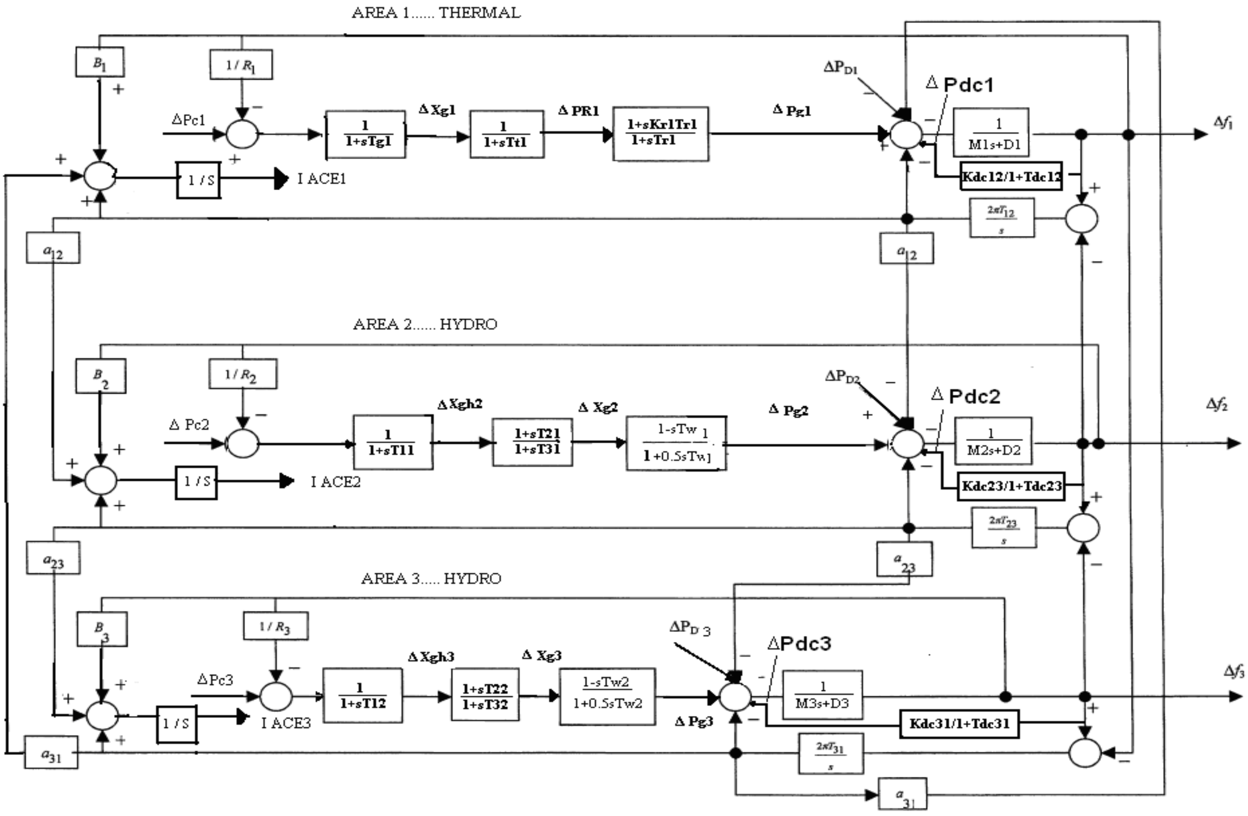


Fig 3: BLOCK DIAGRAM OF 1-THERMAL & 2-HYDRO AREA INTERCONNECTED HYDROTHERMAL POWER SYSTEMS

State Variable Model:

<u>Case Study c1</u>:(with EHVAC inter-ties only)

State vector:

[XIII] = [Δf1,ΔPg1,ΔPR1,ΔXg1,Δf2,ΔPg2,ΔXg2,ΔXgh2,Δf3,ΔPg3,ΔXg3, ΔXgh3, ΔPtie1, ΔPtie2, ΔPtie3, IACE1, IACE2, IACE3] ^{T}

Control vector:

[UIII] = [U1 U2 U3] ^{T} = [ΔPc1, ΔPc2, ΔPc3] ^{T}

Distribution vector:

[PdIII] = [ΔPd1, ΔPd2, ΔPd3] ^{T}

<u>Case Study c2: </u>(with parallel EHVAC/HVDC inter-ties)

State vector:

[XIV] = [XIII ΔPdc1 ΔPdc2 ΔPdc3] ^{T}

Control vector:

[UIV] = [UIII]

Distribution vector:

[Pd IV] = [Pd III]

SYSTEM DATA AND MATRICES:

System Data are given in Appendix A [6], [7].Here matrices for all case study are not reported due to brevity.

IV. SIMULATION RESULTS

The program for simulation has been developed using Matlab package. The program developed considered above all the cases can be access by giving proper input choices during the program execution. All the state, control and disturbance vectors and their corresponding coefficient matrices can also be obtained. The inbuilt LQR command has been used to solve the Matrix- Riccatti equation. Thus, Eigen values and optimum feedback gain matrices have been obtained. After obtaining the required matrices, Matlab functions have been developed for each case. Then to obtain the responses of Δf1, Δf2, Δf3, ΔPtie1, ΔPtie2, ΔPtie3, ΔPdc1, ΔPdc2, ΔPdc3, IACE1 ,I ACE2 and IACE3 Matlab programs using the above said Matlab functions have been developed and plots the required responses. The stability of closed loop system is investigated with the help of closed-loop system eigen values, which are given below. At first glance, it is inferred that with optimal AGC regulators designed, the closed loop system stability is ensured in all cases. The system dynamic performance has also been studied by analysis the response plots obtained for various system variables considering 1% step load disturbance in thermal/hydro area.

Optimal Closed-Loop System Eigen Values:

Case Study (c1):

-57.2634
-3.6275
-0.2716 ± 3.1270i
-0.2986 ± 3.0821i
-2.8832
-2.6398
-1.4447
-0.9643 ± 0.5989i
-0.4835
-0.1893 ± 0.0736i
-0.1471 ± 0.0844i
-0.1152

Case Study (c2):

-41.4382
-2.2693 ± 9.6093i
-2.2819 ± 9.5587i
-3.5931
-5.0000
-2.8122
-1.9946 ± 0.3631i
-1.0121 ± 0.6075i
-0.5147
-0.4991
-0.4529
-0.2105 ± 0.0618i
-0.1530 ± 0.0902i
-0.1150

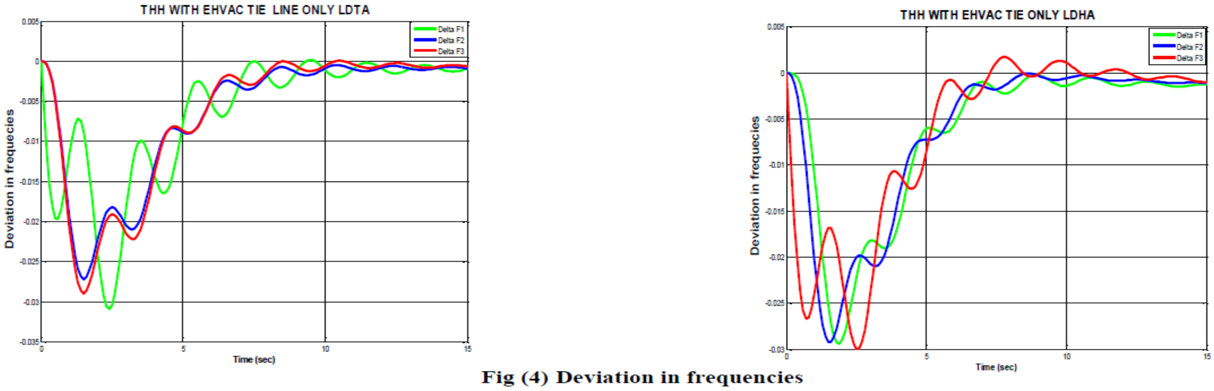


Fig (4) Deviation in frequencies

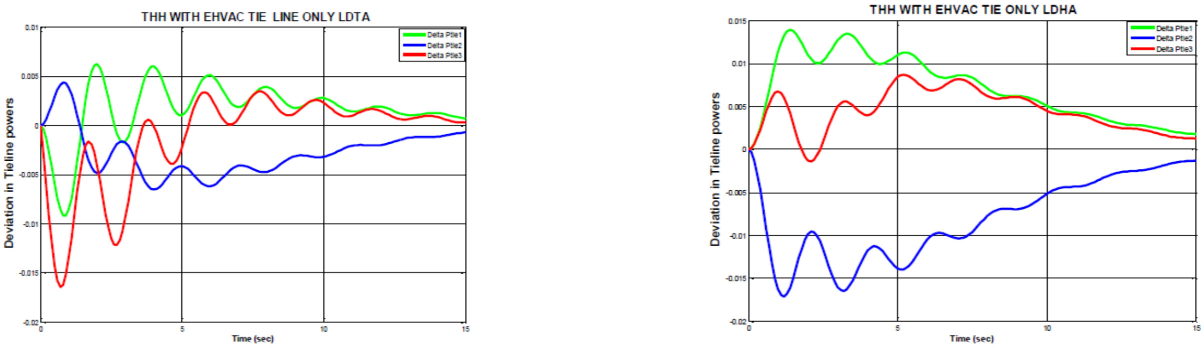


Fig-5 Deviation in tie-line powers

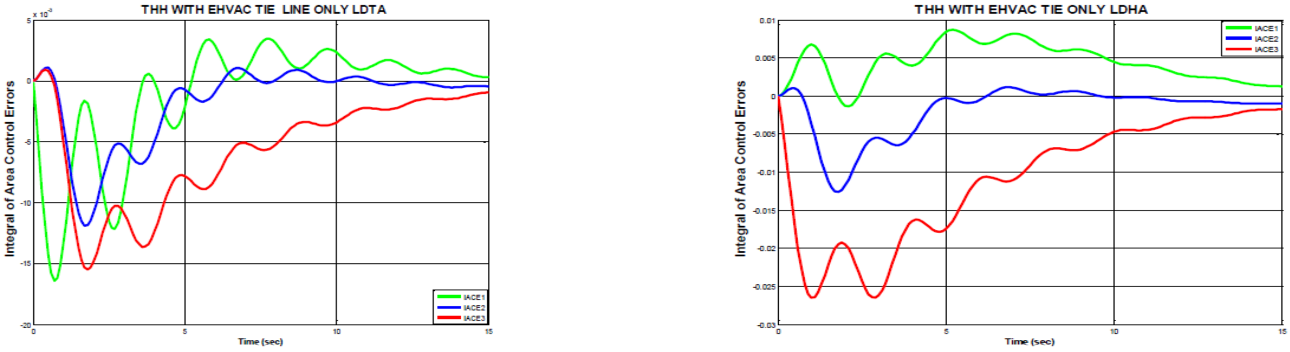


Fig-6 Deviation in integral of area control errors

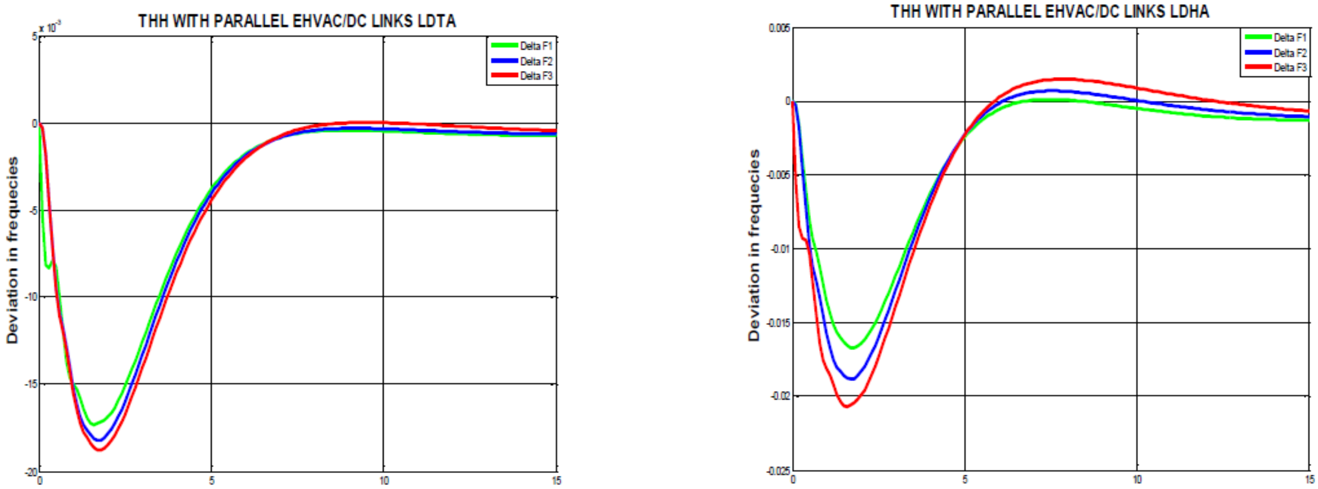


Fig- 7 Deviation in frequencies

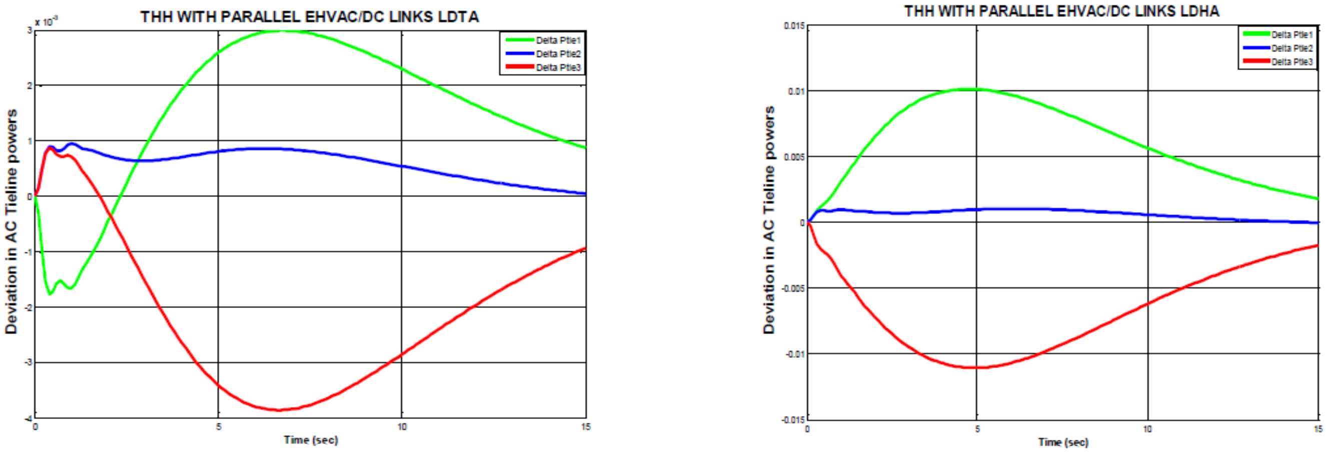


Fig-8 Deviation in AC tie-line powers

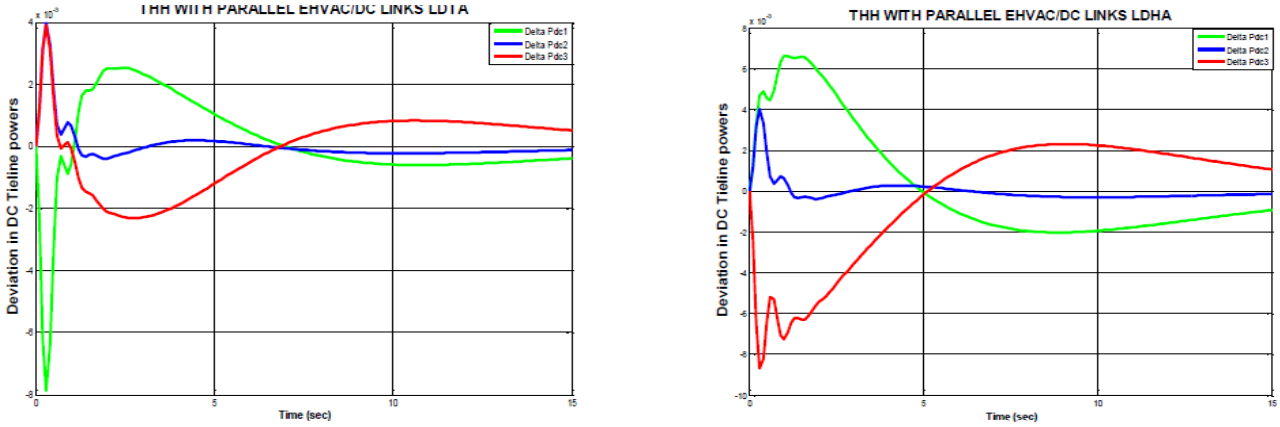


Fig-9 Deviation in DC tie-line powers

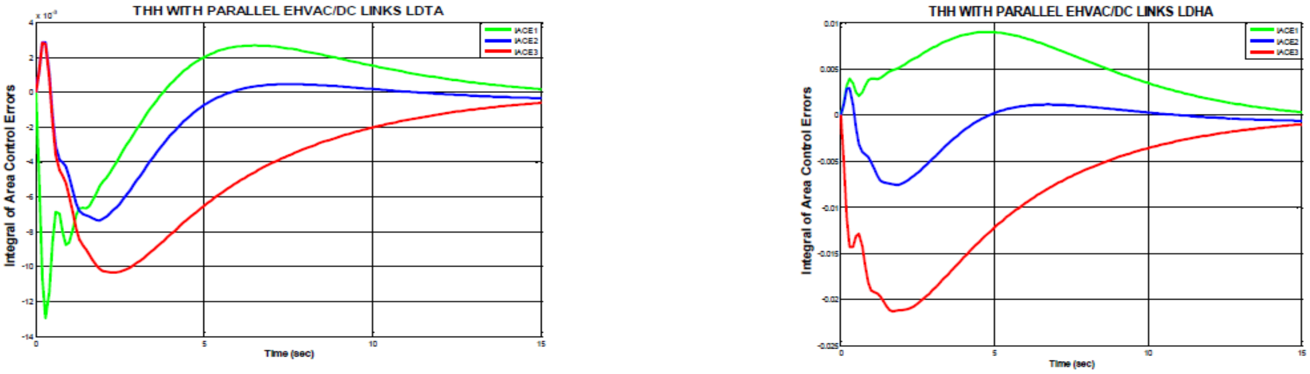
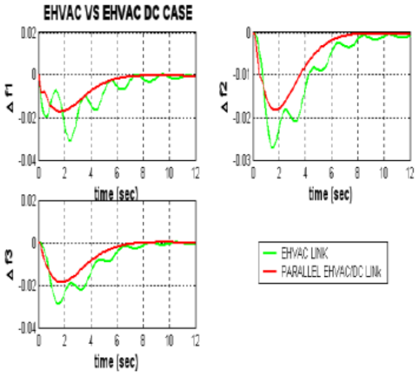
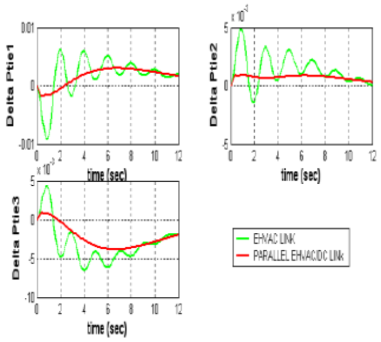


Fig-10 Deviation in integral of area control errors

COMPARATIVE RESPONSES OF EHVAC VS PARALLEL EHVAC/DC LINKS:

(I) 1% Step load disturbance in thermal area





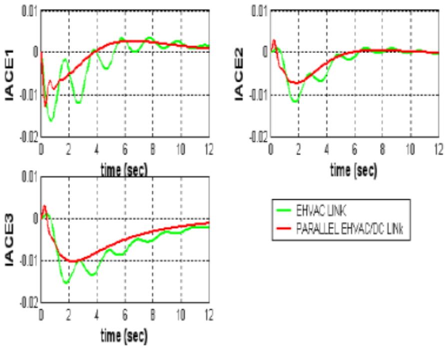
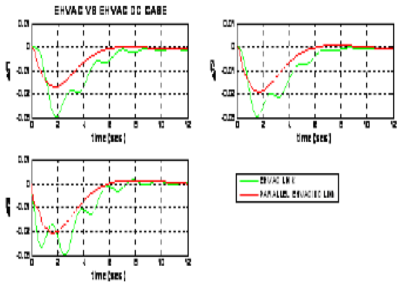


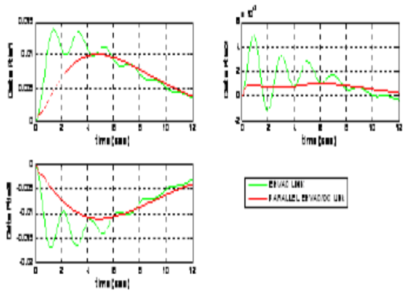
Fig 11

Fig 12

Fig 13

(II) 1% Step load disturbance in hydro area





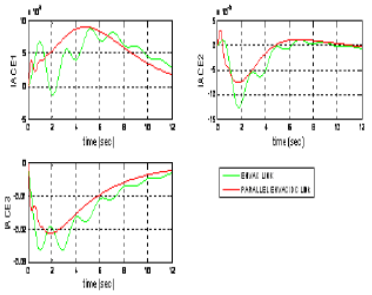


Fig 14

Fig 15

Fig 16

V. RESULT ANALYSIS

The dynamic system performance with optimal AGC regulator design (THH) has been studied. For this purpose, 1% step load disturbance in thermal/hydro area is considered and the response plots for frequency deviations of area-1, area-2 and area-3 (Δf1, Δf2 & Δf3), EHVAC tie-lines power flow deviation (ΔPtie1,ΔPtie2 and ΔPtie3), HVDC tie-line power flow deviation (ΔPdc1, ΔPdc2 & ΔPdc3) and integral of area control error of area 1,2 & 3(IACE1 , IACE2 & IACE3) have been plotted for each case study as shown in above figs. The closed loop system eigen values are obtained. We notice that real part of all the eigen values are negative for all cases (c1&c2), which ensure the stability of closed loop system. The eigen values for above case studies are compared; it is follows that appreciably higher stability margins are achieved, when system interconnection considered as parallel EHVAC/HVDC links (i.e. case study c2).

Fig(4) shows that response plots of deviation in frequencies in area -1,2 and 3, with higher number of oscillations, large settling time and small value of steady state error even after 15 s of time. This trend of response is exhibited for 1%

step load disturbance considered in thermal/hydro area. The magnitude of overshoot is high in that area subjected to 1% step load disturbance in same area.

Fig(5) shows that response plots of deviation in tie line power's in area -1,2 and 3, with higher number of oscillations, large settling time. This trend of response is exhibited for 1% step load disturbance considered in thermal/hydro area. The magnitude of overshoot is high in case of deviation in tie line power for hydro area subjected to 1% step load disturbance either in thermal or hydro area.

Fig(6) shows that response plots of integral of area control errors in area -1,2 and 3, with higher number of oscillations, large settling time. This trend of response is exhibited for 1% step load disturbance considered in thermal/hydro area. The magnitude of overshoot (integral of area control error) is high in that area subjected to load disturbance in same area.

Fig(7) shows that response plots of deviation in frequencies in area -1,2 and 3, with large settling time and small value of steady state error even after 15 s of time. This trend of response is exhibited for 1% step load disturbance considered in thermal/hydro area. The magnitude of overshoot is high in all cases of deviation in frequencies subjected to 1% step load disturbance considered in hydro area.Fig (8) shows that response plots of deviation in ac tie line power's in area -1,2 and 3, with higher magnitude of overshoot, large settling time and higher value of steady state error in two areas(i.e. 1&3) even after 15 s of time subjected to 1% step load disturbance considered either in thermal or hydro area. Fig (9) shows that response plots of deviation in dc tie line power's in area -1,2 and 3, with higher magnitude of overshoot, large settling time and higher value of steady state error in all areas even after 15 s of time subjected to 1% step load disturbance considered either in thermal or hydro area . Fig (10) shows that response plots of integral of area control errors in area -1, 2 and 3, with higher number of oscillations, large settling time, but steady error exits even after 15 s of time in hydro area. This trend of response is exhibited for 1% step load disturbance considered in thermal/hydro area. The magnitude of overshoot (integral of area control error) is high in that area subjected to load disturbance in same area.Fig(11)to(13) shows that response plots of deviation in frequencies, deviation in ac tie line power's and integral of area control errors in area -1,2 and 3 subjected to 1% step load disturbance in thermal area ,Power System Model with parallel EHVAC/DC Link have better dynamic performance in all aspects of systems response.

Fig(14)to(16) shows that response plots of deviation in frequencies, deviation in ac tie line power's and integral of area control errors in area -1,2 and 3 subjected to 1% step load disturbance in hydro area ,Power System Model with parallel EHVAC/DC Link have better dynamic performance in all aspects of systems response.

VI. CONCLUSION

Two cases are studied for 3-area interconnected hydro-thermal power systems. It is inferred that (i) with EHVAC links, all responses namely deviation in frequencies, deviation in tie line powers and integral of area control errors have large overshoot & steady state error subjected to 1% step load disturbance in hydro area instead of thermal area. (ii) With parallel EHVAC/HVDC links, all responses have large overshoot & steady state error subjected to 1% step load disturbance in hydro area instead of thermal area excluding deviation in tie line powers. Also note that overshoot is large in that area subjected to 1% step load disturbance in same area. Moreover, stability margin have improved appreciably with parallel EHVAC/HVDC links.

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APPENDIX A

For Reheat Thermal Plant :Pr1 = 2000 MW; H1 =5 sec; D1 = 0.00833 p.u. MW/Hz; M1=0.167pu MW/Hz; R1 = 2.4 Hz p.u.MW; B1 = 0.425 p.u.MW/Hz; Tg1 = 0.08 Sec; Tt1 = 0.3 sec; a12 = -1; ΔPd1 = 0.01; Kr1 = 0.5; Tr1 = 10 Sec;***ForHydroplant:***Pr2=Pr3=2000MW;H2=H3=5sec;D2=D3=.00833p.u.MW/HZ;M2=M3=0.167puMW/Hz;R2=R3=2.4Hzp.u.MW;B2=B3=0.425p.u.MW/Hz;T11=T12=0.513Sec;T21=T22=5Sec;T31=T32=48.7Sec;Tw1=Tw2=1.0Sec;ΔPd2=ΔPd3=0.00;***For AC& DC Link:*** Pmax = 200 MW (10% of Rated Power); 2*pi*T12=2*pi*T23=2*pi*T31=0.545 puMW,a = δ1- δ2 = δ2- δ3 =δ3- δ1 = 30°; Kdc1= Kdc2=Kdc3=1.0; Tdc1=Tdc2=Tdc3 = 0.2 Sec;