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Comparative Study of Dynamic Performance of Multi-Area Interconnected Power Systems with EHVAC/HVDC Links

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Abstract*: This paper presents comparative study of dynamic performance of 3-area interconnected Hydro-Thermal power systems when subjected to small step load perturbations. For the present study, power system model-1 consists of one area with reheat thermal power plants and other two areas with hydro power plants having identical capacity and power system model-2 consists of two areas with reheat thermal power plants and other area with hydro power plants having identical capacity . The system interconnection is considered namely (I) EHVAC transmission link only (II) EHVAC in parallel with HVDC transmission link. 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. To carry out the investigations, optimal AGC regulators are designed using proportional-plus-integral control strategy and implemented on the system under consideration in the wake of 1% step load perturbation in thermal/hydro area. The system responses have been simulated in Mat lab. Responses of deviation in frequencies, deviation in tie line powers ac as well as dc and integral of area control errors have been plotted for three areas for both power system models. Thus, on the basis of these responses, the comparative study of dynamic performance of the systems has been studied. Besides this, to study the closed loop system stability, the closed loop system eigen values are computed.*

Keywords*: Interconnected power systems; System dynamic performance; EHVAC//HVDC Transmission link; Optimal AGC regulator.*

I. Introduction

The normal operation of interconnected power systems requires that each area maintains the load and generation balance. The change in frequency and voltage from their nominal values, when there is any mismatch in real and reactive power generations and demands. Generally, the power systems are frequently subjected to varying load demands. For an efficient and successful power system operation in the wake of area load changes and abnormal conditions, such as outages of generation, leading mismatches have to be corrected via supplementary control. Automatic Generation Control (AGC) of interconnected power systems is defined as the regulation of power output of generators within a prescribed area, in response to change in system frequency, tie-line loading, or the relation of these to each other, so as to maintain scheduled system frequency and/or established interchange with other areas within predetermined limits. Thus optimal AGC is a very important issue in the operation of power systems to supply sufficient & reliable electric power with good quality. The good quality of power means consistency of frequency, voltage and level of reliability. In real practice power system components are nonlinear. Therefore linearization around a nominal operating point is usually performed to get a linear system model, which is used in the controllers design process. The number of control engineers Fosha, Elgerd[1], Calovic[2], Carpentier, M.L.Kothari, J. Nanda & Prabhat Kumar[5] have presented their pioneer work on optimal AGC regulator design using modern optimal control theory. 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 system model-1&2 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(comparative) the system's dynamic performance.

(b) To study the closed loop system stability, the closed loop system eigen values have been computed for the power systems model-1&2 with EHVAC/HVDC inter-ties.

II. Power System Model:

Power system model-1 consists of one area with reheat thermal power plants and other two areas with hydro power plants having identical capacity and power system model-2 consists of two areas with reheat thermal power plants and other area with hydro power plants having identical capacity . The system interconnection is considered namely (I) EHVAC transmission link only (II) EHVAC in parallel with HVDC transmission link.

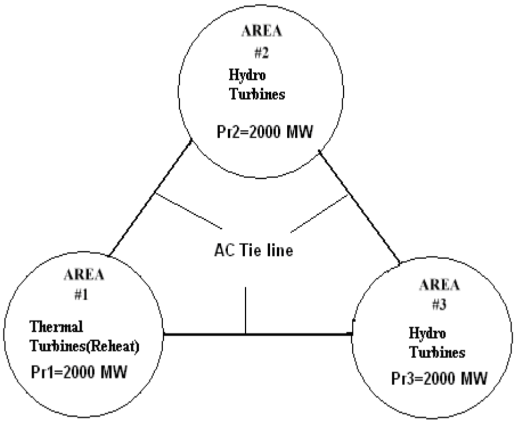


Fig 1 Power System Model -1(1-T & 2-H) With EHVAC Tie lines only

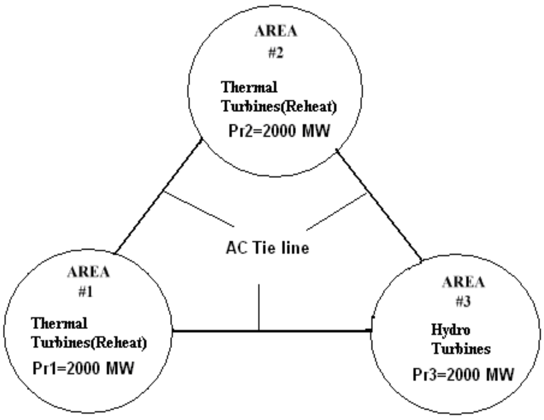
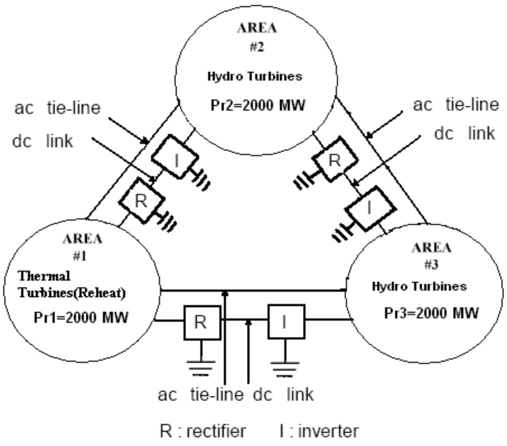


Fig 3 Power System Model-2 (2-T &1-H) With EHVAC Tie lines only



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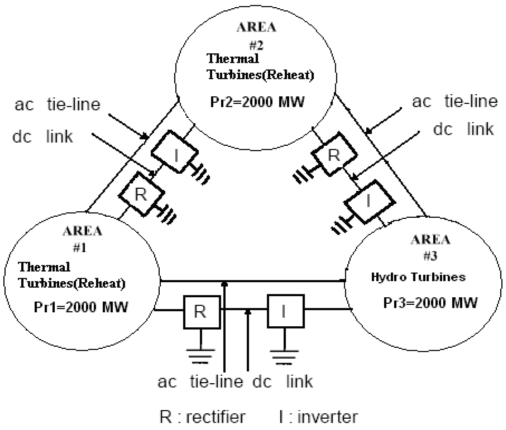


Fig 2 Power System Model -1 (1- Thermal & 2- Hydro) with parallel EHVAC/HVDC Links

Fig 4 Power System Model -2 (2- Thermal & 1- Hydro) with parallel EHVAC/HVDC Links

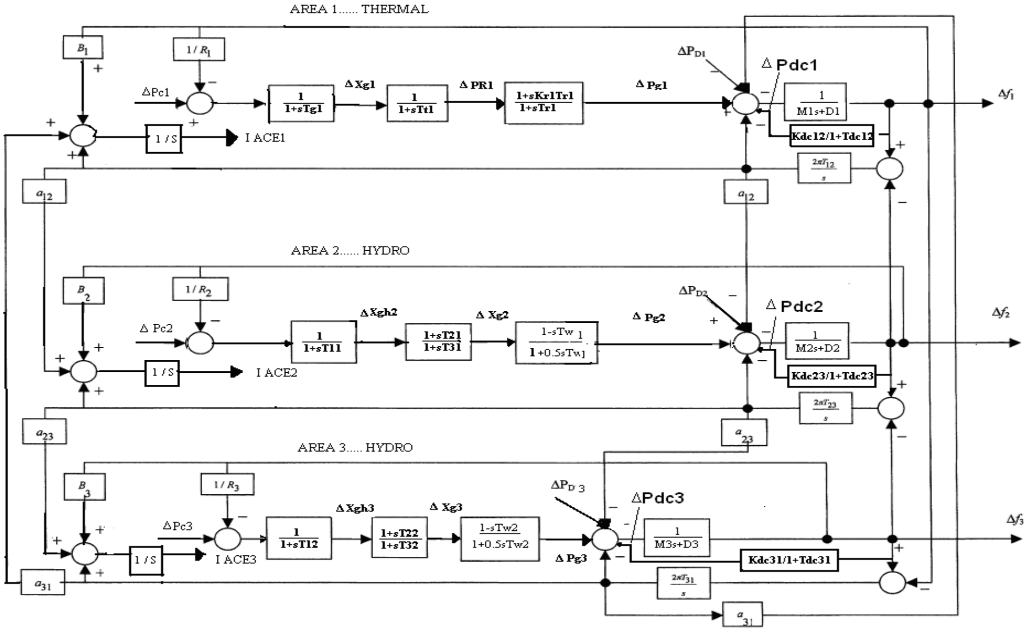


Fig. 5: BLOCK DIAGRAM OF 1-THERMAL & 2-HYDRO AREA INTERCONNECTED HYDROTHERMAL POWER SYSTEMS

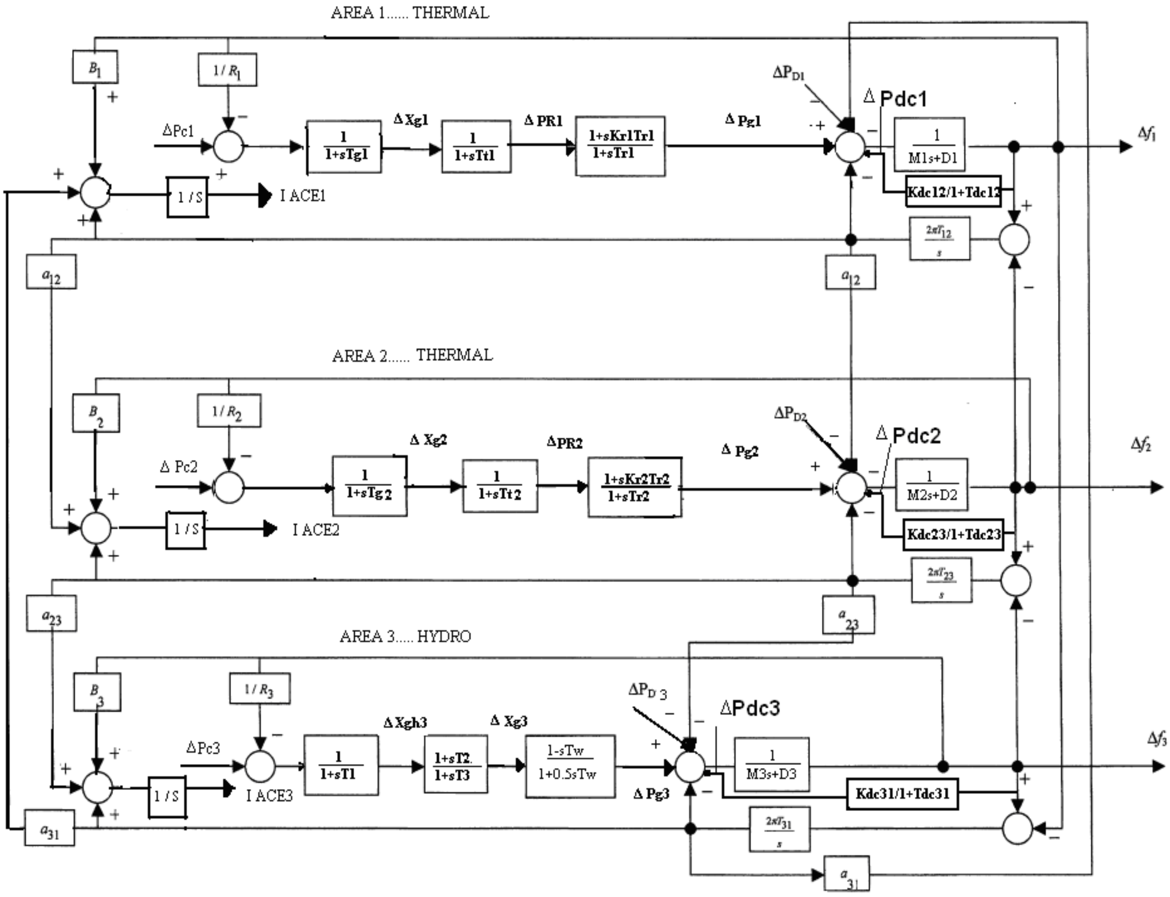


Fig. 6: BLOCK DIAGRAM OF 2-THERMAL & 1-HYDRO AREA INTERCONNECTED HYDROTHERMAL POWER SYSTEMS

III. OPTIMAL AGC REGULATOR DESIGN WITH FULL STATE VECTOR FEED-BACK [4]

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

$$\dot{\underline{X}} = A\,\underline{X} + B\,\underline{U} + Fd\,\underline{Pd} \tag{1.1}$$

$$\underline{Y} = C\,\underline{X} \tag{1.2}$$

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

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

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;

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

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

$\underline{U}^* = -K^* \underline{X}$ (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 equation is to be solved (The inbuilt LQR command has been used):

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

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

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

Hence, the desired optimal feedback gain matrix will be

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

State Variable Model

The state space representation is described by Equations (1.1) and (1.2). The structures of state, control, and disturbance vectors for all case studies are given as follows.

Power System Model-1

Case Study b1 :(EHVAC Transmission Link)

State vector:

$[XI] = [\Delta f1, \Delta Pg1, \Delta PR1, \Delta Xg1, \Delta f2, \Delta Pg2, \Delta PR2, \Delta Xg2, \Delta f3, \Delta Pg3, \Delta Xg3, \Delta Xgh3, \Delta Ptie1, \Delta Ptie2, \Delta Ptie3, IACE1, IACE2, IACE3]^T$

Control vector:

$[UI] = [U1\ U2\ U3]\ T = [\Delta Pc1, \Delta Pc2, \Delta Pc3]^T$

Distribution vector:

$[PdI] = [\Delta Pd1, \Delta Pd2, \Delta Pd3]^T$

Case Study b2 :(Parallel EHVAC/HVDC Transmission Link)

State vector:

$[XII] = [XI\ \Delta Pdc1\ \Delta Pdc2\ \Delta Pdc3]^T$

Control vector:

[UII] = [UI]

Distribution vector:

[PdII] = [PdI]

Power System Model-2

Case Study c1:(EHVAC Transmission Link)

State vector:

$[XIII] = [\Delta f1, \Delta Pg1, \Delta PR1, \Delta Xg1, \Delta f2, \Delta Pg2, \Delta Xg2, \Delta Xgh2, \Delta f3, \Delta Pg3, \Delta Xg3, \Delta Xgh3, \Delta Ptie1, \Delta Ptie2, \Delta Ptie3, IACE1, IACE2, IACE3]^T$

Control vector:

$[UIII] = [U1\ U2\ U3]^T = [\Delta Pc1, \Delta Pc2, \Delta Pc3]^T$

Distribution vector:

$[PdIII] = [\Delta Pd1, \Delta Pd2, \Delta Pd3]^T$

Case Study c2: :(Parallel EHVAC/HVDC Transmission Link)

State vector:

$[XIV] = [XIII\ \Delta Pdc1\ \Delta Pdc2\ \Delta Pdc3]^T$

Control vector:

[UIV] = [UIII]

Distribution vector:

[Pd IV] = [Pd III]

IV. SIMULATION RESULTS

The system responses have been simulated in Mat lab. In the present study, Optimal AGC regulators based on full state vector feedback control strategy are designed. The closed loop system eigen values are computed to investigate the systems stability and the same are presented in Table.

TABLE: Optimal Closed-loop system eigen values.

Power System Model-1

CASE STUDY (b1):

-41.4388
-41.4555
-0.3327 ± 3.2146i

-0.3188 ± 3.1051i
-3.5272
-3.1568
-2.6479
-1.9087
-1.2534 ± 0.7453i
-0.4609
-0.3314
-0.1955 ± 0.0717i
-0.1150

CASE STUDY (b2):

-57.2633
-57.2813
-2.2648 ± 9.6325i
-2.2798 ± 9.5847i
-3.6623
-5.0000
-2.7957
-2.4751 ± 0.5362i
-1.1923 ± 0.6144i
-0.5093
-0.4576
-0.4861
-0.2638
-0.1636 ± 0.0687i
-0.1149

Power System Model-2

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

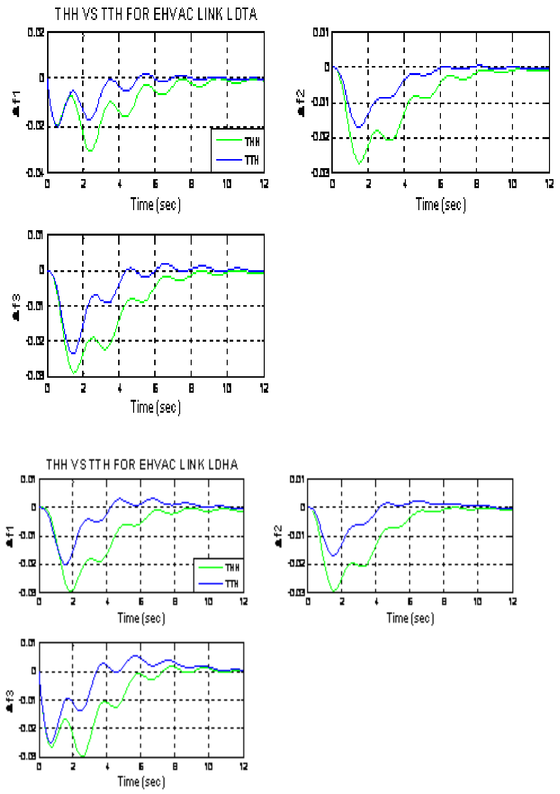


FIG: 7(a & b)

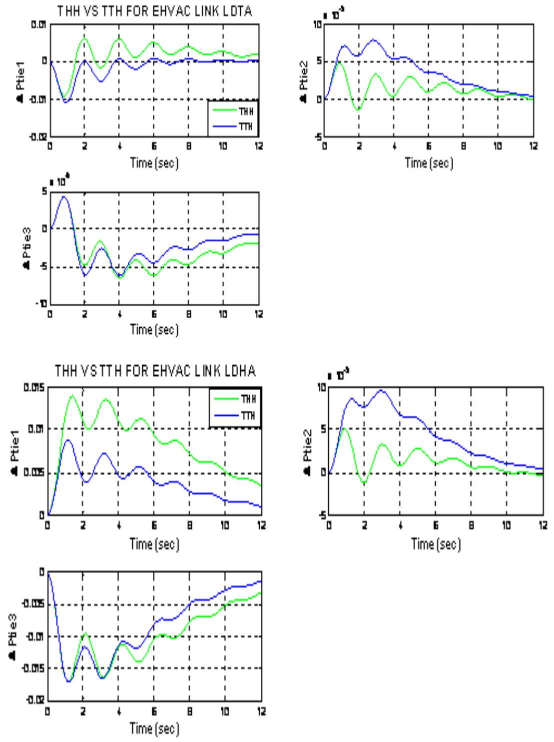


FIG: 8(a & b)

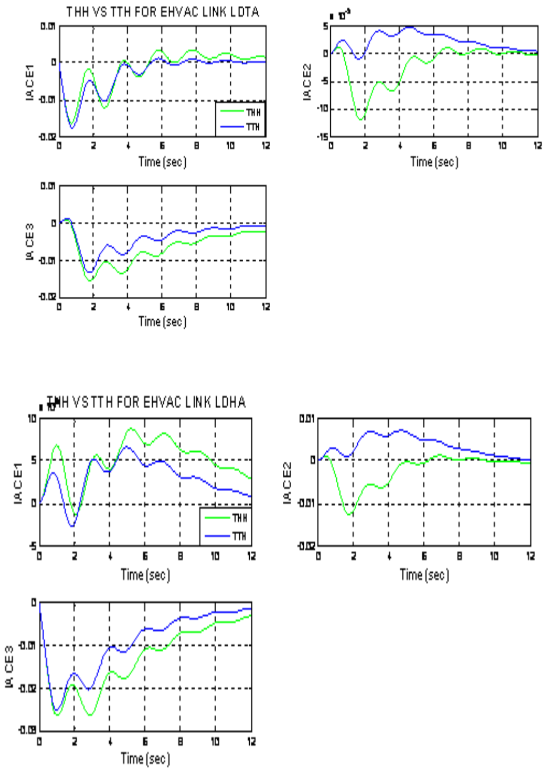


FIG: 9 (a & b)

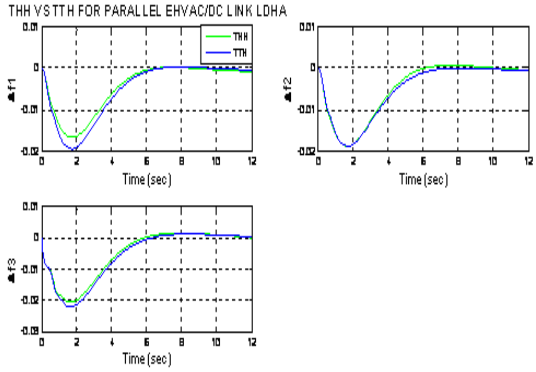
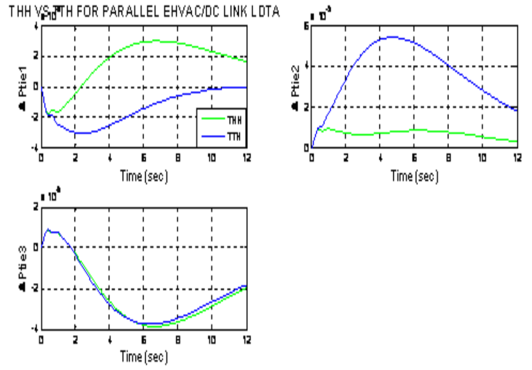


FIG: 10 (a & b)



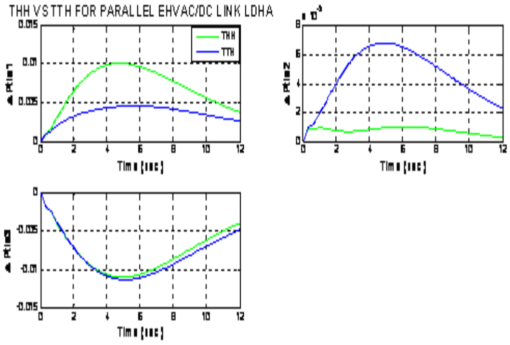


FIG: 11(a & b)

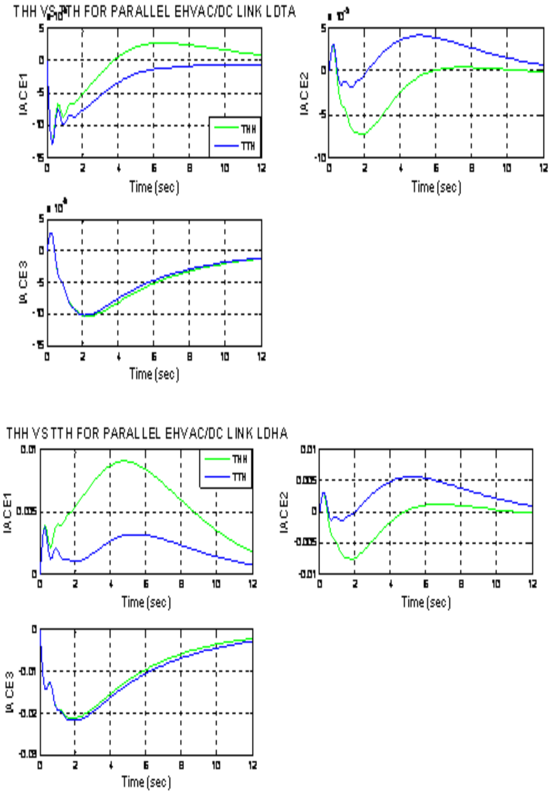


FIG: 13 (a & b)

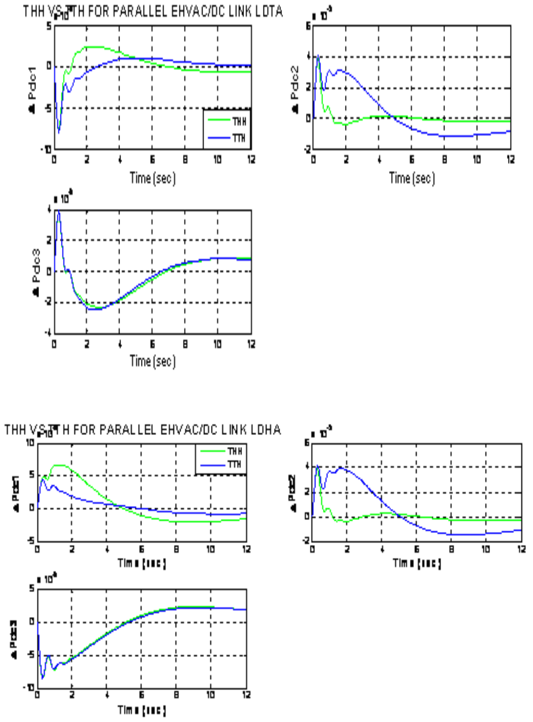


FIG: 12 (a & b)

Fig (7) shows that response plots of deviation in frequencies in area -1, 2 and 3 subjected to 1% step load disturbance in thermal/hydro area, with higher number of oscillations and large settling time. The magnitude of overshoot and settling time is high in case of THH. It is inferred that TTH have better dynamic performance in all aspects of system responses in all areas subjected to 1% step load disturbance either in thermal or hydro area.

Fig (8) shows that response plots of deviation in tie line powers in area -1, 2 and 3 subjected to 1% step load disturbance in thermal/hydro area with higher number of oscillations, large settling time. The settling time is high in case of THH. It is inferred that TTH have better dynamic performance in all aspects of system responses excluding area-2 subjected to 1% step load disturbance either in thermal or hydro area.

Fig (9) shows that response plots of integral of area control errors in area -1, 2 and 3 subjected to 1% step load disturbance in thermal/hydro area with higher number of oscillations, large settling time. The magnitude of overshoot and settling time is high in case of integral of area control error for THH. It is inferred that TTH have better dynamic performance in all aspects of system responses in all areas subjected to 1% step load disturbance either in thermal or hydro area.

Fig (10) shows that response plots of deviation in frequencies in area -1, 2 and 3. This trend of response is exhibited for 1% step load disturbance in thermal/hydro area. The magnitude of overshoot and settling time is high in case of THH. It is inferred that TTH have better dynamic performance in all aspects of system responses in all areas subjected to 1% step load disturbance either in thermal or hydro area.

Fig (11) shows that response plots of deviation in ac tie line power's in area -1,2 and 3 subjected to 1% step load disturbance in thermal/hydro area with higher magnitude of overshoot, large settling time and higher value of steady state error even after 15 s of time. It is clear that TTH have better dynamic performance in all aspects of system responses excluding area-2 subjected to 1% step load disturbance either in thermal or hydro area.

Fig (12) shows that response plots of deviation in dc tie line powers in area –1, 2 and 3 subjected to 1% step load disturbance in thermal/hydro area with higher magnitude of overshoot, large settling time and higher value of steady state error even after 15 s of time. It is clear that, in case of responses of delta Pdc1 (LDTA), delta Pdc2 (either in LDTA or LDHA) for THH have better dynamic performance in all aspects. In case of response of delta Pdc1 for TTH have better dynamic response subjected to 1% step load disturbance in hydro area. But the response of delta Pdc3 is nearly same for both cases (i.e. THH &TTH) subjected to 1% step load disturbance either in thermal or hydro area.

Fig (13) shows that response plots of integral of area control errors in area -1, 2 and 3 subjected to 1% step load disturbance in thermal/hydro area with higher number of oscillations, large settling time and steady error exits even after 15 s of time, The magnitude of overshoot is high in case of integral of area control error for hydro area. The response of IACE1 is better for TTH .But the response of IACE3 is nearly same for both cases (i.e. THH &TTH) subjected to 1% step load disturbance either in thermal or hydro area.

V. CONCLUSION

The paper presents comparative study of dynamic performance of 3-area interconnected hydro-thermal power systems when subjected to 1% step load disturbance in thermal/hydro area. It is clear that TTH (power system model-2) have better dynamic performance in all aspects of system responses excluding deviation in ac tie line power in area-2 subjected to 1% step load disturbance in thermal/hydro area. In case of responses of delta Pdc1 (LDTA), delta Pdc2 (either in LDTA or LDHA) for THH (power system model-1) has better dynamic performance in all aspects. In case of response of delta Pdc1 for TTH (power system model-2) have better dynamic response subjected to 1% step load disturbance in hydro area. But the response of delta Pdc3 is nearly same for both cases (i.e. THH &TTH) subjected to 1% step load disturbance either in thermal or hydro area. The response of IACE1 is better for TTH .But the response of IACE3 is nearly same for both cases (i.e. THH &TTH) subjected to 1% step load disturbance either in thermal or hydro area. In case of IACE2, for TTH has reduction in overshoot as compared to THH case. However, small value of steady state error exists.

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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= Rated power output of ith area
Δi= 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= Time constants representing hydro governor
Tw= Water inertia time constant
K =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
LDHA=Load disturbance in hydro area

APPENDIX A

Numerical data: Power System Model-1: For Reheat Thermal Plants; Pr1 =Pr2= 2000 MW; H1 = H2=5 Sec; D1 =D2= 0.00833 p.u. MW/Hz; M1=M2=0.167pu MW/Hz; R1 =R2= 2.4 Hz p.u.MW; B1 =B2= 0.425 p.u.MW/Hz; Tg1 =Tg2= 0.08 Sec; Tt1 =Tt2= 0.3 sec; a12 = -1; ΔPd1 = 0.01; ΔPd2 = 0.00; Kr1 =Kr2= 0.5; Tr1 =Tr2= 10 Sec;**For Hydro plant** Pr3=2000 MW; H3=5 Sec; D3=.00833 p.u.MW/HZ; M3=0.167pu MW/Hz; R3 =2.4 Hz p.u.MW;B3=0.425p.u.MW/Hz;T1=0.513Sec;T2=5 Sec; T3=48.7 Sec; Tw=1.0 Sec; ΔPd3= 0.00;**For AC& DC Link** Pmax = 200 MW (10%of Rated Power);2*pi*T12=2*pi*T23=2*pi*T31=0.545a = δ1- δ2 = δ2- δ3 =δ3-δ1=30°;Kdc1=Kdc2=Kdc3=1.0;Tdc1=Tdc2=Tdc3=0.2Sec;**Power System Model-2: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;**For Hydro plant** Pr2=Pr3=2000 MW; H2=H3=5 sec;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;