OPTIMAL FEEDBACK CONTROLLER WITH IMPROVED SENSITIVITY TO PARAMETER UNCERTAINTIES TO SUIT THERMAL POWER PLANTS

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ABSTRACT

In this paper, the problem of optimal feedback controllers of linear dynamic systems with quadratic performance index is considered. The selection of quadratic performance index leads to convenient mathematical manipulations in the solution of optimal control problem. The sensitivity of the system performance to off-nominal parameters values may cause a degraded optimal control performance. Consequently, a rational approach is to improve the sensitivity of the optimal performance developed. The developed scheme is applied to power frequency control problem for two interconnected thermal areas (units) with single reheat turbine in thermal power generation plant. The linear state space model represent this practical problem is developed. Emphasize is made on the role of associated mechanical items (speed governor and reheat turbine). To achieve the required calculations to implement developed scheme, a computation code is developed. Results obtained from the numerical computation showed that some state variables are more sensitive system parameters (speed governor time constant ... etc) than other states (speed regulator parameter ... etc). Also numerical results showed that the system is more sensitive to speed regulator parameter, speed governor time constant and reheat time constant than other states. The optimal solution found here satisfies the necessary conditions of thermal power plant dynamical response. The approach considered in this paper is useful for both performance analysis and design problems. It can give a better understanding of the impact of different system parameters on the overall performance of the system.

NOMENCLATURE

A	nxn dimensional state weighing matrix.
A'	n(r+1)xn(r+1) dimensional augmented state weighing matrix.
b	Frequency bias parameter for area control error.
B	m×m dimensional control weighing matrix.
B'	mxm dimensional augmented control weighing matrix.
C	m×n dimensional optimal feedback gain matrix.
C'	m×n(r+1) dimensional augmented optimal feedback gain matrix.
D	P dimensional disturbance vector.
f_o	Instantaneous frequency.
F	n×n dimensional state coefficient matrix.
F'	n(r+1)xn(n+1) dimensional augmented state coefficient matrix.
F_{hp}	Fraction represent portion of turbine in high pressure stage.
F_{ip}	Fraction represent portion of turbine in intermediate stage.
F_{lp}	Fraction represent portion of turbine in low pressure.
G	n×n dimensional control coefficient matrix.
G'	n(r+1)× m dimensional augmented control coefficient matrix.
J	Quadratic performance index.
K_g	Static gain of speed governor mechanism.
K_p	Generator gain constant.
N	n(r+1) dimensional state (trajectory) sensitivity vector.
P	n(r+1)×n(r+1) dimensional symmetric matrix of augmented system given by a Riccati equation.
P_r	Rated power of the area (power capacity).
Q	n×n dimensional symmetric matrix given by a sensitivity Riccati equation with respect to the sensitivity parameters.
R	Speed regulator parameter.
S	n×n dimensional symmetric matrix of the system given by a Riccati equation.
s	Laplace operator.
T	Transpose a matrix or a vector.
T_{ch}	Time constant of steam chest.
T_{co}	Time constant of cross over piping.

T_g Time constant of speed governor mechanism.
T_p Generator time constant.
T_{12} Synchronizing power coefficient of the tie line connected between the two areas.
T_{rh} Time constant of the reheater in single reheat turbine.
U m dimensional optimal control vector.
U_{ss} m dimensional steady state optimal control vector.
V n(r+1) dimensional augmented state vector.
X n dimensional state vector.
X_{ss} n dimensional steady state vector.
Y n×p dimensional disturbance coefficient matrix.
Z Sensitivity parameter.
Δ Small deviation of a state variable.
Δp_{gv} Incremental change in steam valve position.
Δp_c Incremental change in speed change position.
Δp_d Incremental change in load demand.
Δp_m Incremental change in output turbine power.
Δp_{r1} Incremental change in power deviation between steam control.
Δp_{tie} Incremental change in tie line power between the first area.
$\int$ ACE Integral of area control error.

1. INTRODUCTION

It worth mentioning that the recent trends in the development of modern control system have been in the direction of optimization. It is often referred to as the modern design procedure. and is rapidly becoming the major technique for the design of automatic control system. The application of modern control theory to problems of power generation has been considered recently by many authors. The results of the linear quadratic feedback control theory were extensively used to synthesis optimal controllers in the area of power frequency control problem in thermal power generation plants. In this system, the control inputs are the incremental change in governor valve position. The reheat steam turbine and governors for all practical purposes can be represented by first order models [1].

In the modern speed governing system may involve electronic apparatus to perform a lower function associated with speed sensing and droop compensation. (The electronic apparatus provides greater flexibility and improved performance, in both dead band and dead time). Neglecting the nonlinearities, the transfer function for hydraulic governor may equally well represent the electri governor [2]. Gopal, ...etc.[3] synthesized a constant gai feedback controller with reduced trajectory sensitivity t small parameter variations. Their controller ensured th prescribed degree of stability but for discrete tim dynamic systems.

In this paper, the objective is mainly to synthesize a optimal controller for thermal power plants, such that th controlled system has improved sensitivity to paramete errors. The block diagram representation of the tw identical interconnected thermal areas is shown in Figure (1), where a mechanical speed governor system and single reheat turbine are considered [4].

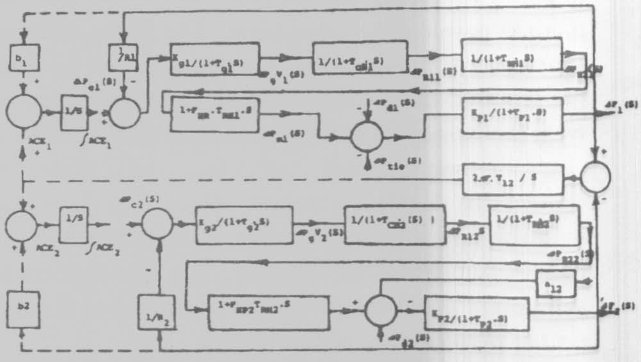

Figure 1. Transfer function block diagram of two identical interconnected thermal areas.

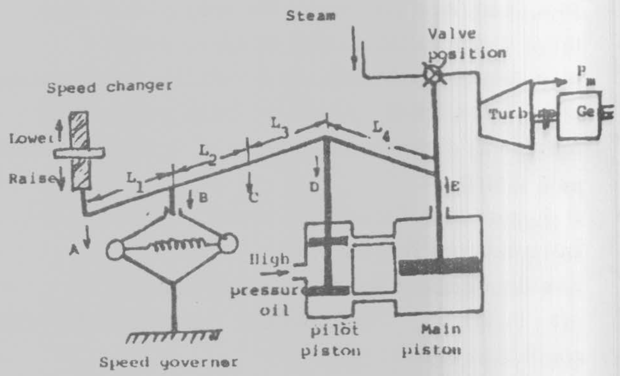

Figure (2-a). Schematic diagram of speed governing system.

system and Figure (2-b) represent transfer function of such governor [2]. The transfer function of the reheat turbine is given in Figure (3-a). Reducing the block diagram of Figure (3-b) and neglecting time constant of crossover (T_{co}), the model simplify and the transfer function is given by:

$$\Delta Pm(s)/\Delta Pgv(s) = \frac{(1 + FhbTrhS)}{(1 + TchS)(1 + Trh)} \quad (1)$$

The energy balance of the interconnected control area may expressed as [4].

$$\Delta F(s) = \frac{Kp}{(1 + TpS)}[\Delta pm(s) - \Delta Pd(s) - \Delta Ptio(s)] \quad (2)$$

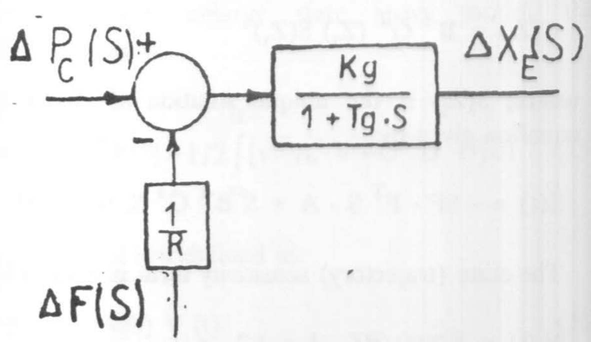

Figure (2;b) Transfer function block diagram of speed governor.

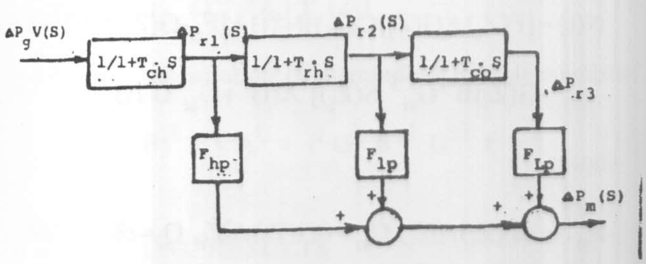

Figure (3.a). Transfer function block diagram of single reheat turbine.

The total incremental power exported from the first area to the second ΔP_{tio} equals the sum of all out following incremental line power in the lines connecting areas,[4].

$$\text{i.e } \Delta P_{tie}(S) = 2\pi T_{12}[\Delta F_i(s) - \Delta F_2(s)] \quad (3)$$

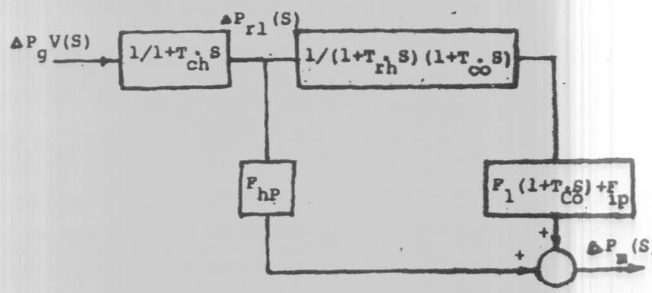

Figure 3-b. Reduced transfer function block diagram of Figure (3.a).

Area control Error (ACE): the ACE is to be linear combination of incremental frequency and tie line power. That is to force the steady state tie line power to almost zero. The ACE for i^{th} areas is defined as:

$$ACE = \Delta P_{tie,i} + bi\,\Delta F_i \quad (4)$$

where:

$$\Delta P_{tie,j} = a_{ij}\,\Delta P_{tie,i} \quad , a_{ij} = \frac{\Delta P_{ri}}{\Delta P_{rj}} \quad (5)$$

Equations governed the overall state space model are presented in appendix (A).

Suppose that the dynamics of the interconnected units is described by the state equation:

$$\dot{X} = F X + GU + YD \quad (6)$$

where:

$X^T = [\Delta P_{gv1}, \Delta Pr_{11}, \Delta P_{r21}, \Delta P_{r21}, \Delta P_{m1}, \Delta F_1,$

$\int ACE_1, \Delta Ptie, \Delta Pgv2$

$\Delta P_{r12}, \Delta P_{r22}, \Delta P_{m2}, \Delta F_2, \int ACE_2]$ is the state vector

$U_T = [\Delta P_{c1}\ \Delta P_{c2}]$ is the control vector

$D_T = [\Delta P_{d1}\ \Delta P_{d2}$ is the load disturbance vector

The state equation (6) can be written in a more convenient form:

$$\dot{X} = F X + G U \quad , \quad X(to) = -X_{ss} \quad (7)$$

Where the new state vector equals the old vector minus its steady state values X_{ss}.

The nominal system parameters are used:
f^o = normal frequency = 50 HZ, $2\pi T_{12}$-0.545 PU.MWS/rad

$K_{p1} = K_{p2} = 100$ rad/P.U.MWS, $R_1 = R_2 = 2.4$HZ/PU.MWS

$P_{r1} = P_{r2} = 2000$ MW, $T_{rh1} = T_{rh2} = 10$ second

$T_{p1} = T_{P2} = 20$ second, $T_{g1} = T_{g2} = 0.08$ second

$F_{p1} = F_{p2} = 0.3$, $T_{ch1} = T_{ch2} = 0.3$ second

$K_{g1} = K_{g2} = 1.0$, $b_1 = b_2 = 0.425$, $a_{12} = -1.0$

Then the corresponding system matrices are given by:

$$F = \begin{bmatrix} -12.5 & 0 & 0 & 0 & 5.208 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3.33 & -3.33 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.1 & -0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -0.9 & 0 & -0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 5 & -0.05 & 0 & 5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.425 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.545 & 0 & 0 & 0 & 0 & 0 & 0 & -0.545 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3.33 & -3.33 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1 & -0.1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -0.9 & 0 & -0.1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 5 & 0 & 0 & 0 & 5 & -0.05 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0.425 & 0 \end{bmatrix}$$

$$G = \begin{bmatrix} 12.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12.5 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

2-SYNTHESIZE OF OPTIMAL FEEDBACK CONTROLLER WITH IMPROVED PERFORMANCE SENSITIVITIES

A major drawback to implement the optimal control schemes is that the resulting optimal performance was found to be highly sensitive to system parameters assumed in the optimal control synthesize. The sensitivity of the system performance to off nominal parameter values may cause a degraded optimal controller performance. Consequently, a rational approach in the synthesize of optimal feedback controllers is to be improve the sensitivity of the optimal performance to parameter errors, uncertainties and inaccuracies. The developed scheme is based upon the generation of system states sensitivit trajectory. This trajectory is then incorporated in a augmented optimal linear control problem with a augmented quadratic performance index.

The linear system is given by:

$$\dot{X}(t) = F(Z_i)\, X(t) + G(Zi)\, U(t)\ ,\ X(_o) \text{ given} \qquad (8)$$

where; Z_i is the uncertainties parameter vector,

$$Z_i = [Z_1, Z_2, \ldots\ldots, Z_r]$$

The control signal U is defined by:

$$U(t) = -\, C(z_i)\, X(t) \qquad (9)$$

where; $C(Z_i)$ is the optimal feedback gain matrix

$$C(Z_i) = B^{-1}\, G^T\, (Z_i)\, S(Z_i) \qquad (10)$$

where; $S(Z_i)$ is the unique solution of matrix Riccat equation given by:

$$\dot{S}(t) = -\, SF - F^T S - A + S\, B^{-1}\, G^T\, S,\ S(t_f) = Sf \qquad (11)$$

The state (trajectory) sensitivity term is defined by:

$$\dot{N}_i(t) = \partial\, \dot{X}(t)/\partial Z_i\ ,\ i = 1,2,\ldots r$$

The sensitivity term with respect to Z_i is expressed by:

$$\dot{N}(t) = [F(Z_i) + G(Z_i)C(Z_i)]N_i(t) + [F_{zi} - G(Z_i)B^{-1}G^T(Z_i)Q_i$$
$$-G(Z_i)B^{-1}G_{zi}{}^T\, S(Z_i)]\, X(t) + G_{zi}\, U\,(t) \qquad (12)$$

where;

$$F_{zi} = \partial F(Z_i)/\partial Z_i,\ G_{zi} = \partial G(Z_i)/\partial Z_i,\ Q_i = \partial S(Z_i)/\partial Z_i$$

and the term Q_i is obtained through the solution of Liaponuv like equation:

$$Q_i(t) = W_i - Q_i\, E_i - E_i{}^T\, Q_i \qquad (13)$$

where;

$$W_i = -S(Z_i)\, F_{zi} - F_{zi}{}^T + S(Z_i)\, G(Z_i)\, B^{-1}\, G_{zi}{}^T\, S(zi)$$
$$+ S(Z_i)\, G_{zi}\, B^{-1}\, G(Z_i)^T\, S(Z_i)$$

and

$$E_i = F(Z_i) - G(Z_i)\, B^{-1}\, G^T\, (Z_i)\, S(Z_i)$$

The augmented state vector V (t) is defined as follows:

$$\dot{V} = \begin{bmatrix} \dot{X} \\ N_1 \\ \cdot\cdot \\ \cdot\cdot \\ \cdot \\ N_r \end{bmatrix} = \begin{bmatrix} F \\ F_{Z1} - GB^{-1}G^TQ_1 - GB^{-1}G^TZ_1^{*}F - Gc \\ 0 \\ F_{Zr} - GB^{-1}G^TQ_r - GB^{-1}G^TZ_r^{*}F - GC \end{bmatrix} \begin{bmatrix} X \\ N_1 \\ \cdot\cdot \\ \cdot\cdot \\ N_r \end{bmatrix} + \begin{bmatrix} G \\ G_{Z1} \\ \cdot\cdot \\ \cdot\cdot \\ G_{Zr} \end{bmatrix} U$$

or;

$$V(t) = F^{\backslash}\, (Z_1)\, V\, (t) + G^{\backslash}\, (z_1)\, U\, (t) \tag{14}$$

For the above enlarge state space model, the performance index:

$$J^{\backslash} = 1/2\,[v^TPV] + 1/2\int_{to}^{tf} [v^TA^{\backslash}V + U^TB^{\backslash}U]\,\partial t \tag{15}$$

and the control low defined as:

$$U\,(t) = C^{\backslash}\,(Z_i)\, V\,(t) \tag{16}$$

where:

$$C^{\backslash}\,(Z_i) = B^{\backslash -1}\, G^{\backslash T}\,(Z_i)\, P\,(Z_i) \tag{17}$$

and $P(Z_i)$ is the solution of augmented Riccati equation:

$$\dot{P} = P\,F^{\backslash} - F^{\backslash T}\,P - A^{\backslash} + P\,G^{\backslash}\,B^{\backslash -1}\,G^{\backslash T}\,P \tag{18}$$

3- NUMERICAL RESULTS

Performance characteristics of dynamic system are affected considerable by values of system parameters. The computer control scheme for the class of linear continuous dynamic systems under consideration is introduced. The flowchart for the computation code developed for the computer control implementation and the computer program listing is given in ref. [6]. The flowchart code is shown in appendix (B). The code was run on an I.B.M - X T micro computer system.

In a considered case study two identical thermal areas with single reheat turbine of order 13 and the augmented system dimension increases to order 28. Sensitivity parameters are chosen as speed regulator parameter (R), speed governor time constant (T_g) and reheat time constant (T_{rh}). Experience, previous work and published data on the characteristics of the thermal power plants have proved that the above parameters are subjected to uncertainties, inaccuracies and variations from their respective nominal values. The weighing matrices A and B are chosen to be in the form:

A = diag. [0 0 0 1 1 1 0 0 0 0 1 1].

B = I (unit matrix)

(i) without sensitivity consideration : the optimal control law guaranties the desired performance specifications and forces the steady state error of the tie power to an almost zero value.

The steady state values of the optimal control signals are:

$$\Delta P_{c1} = \Delta P_{c2} = -\,0.991435 \text{ P.U}$$

Figures (4-9) present the time histories of the closed loop states and their trajectory time histories under sensitivity consideration to speed regulator parameter (R), reheat time constant (T_{rh}) and speed governor time constant (T_g).

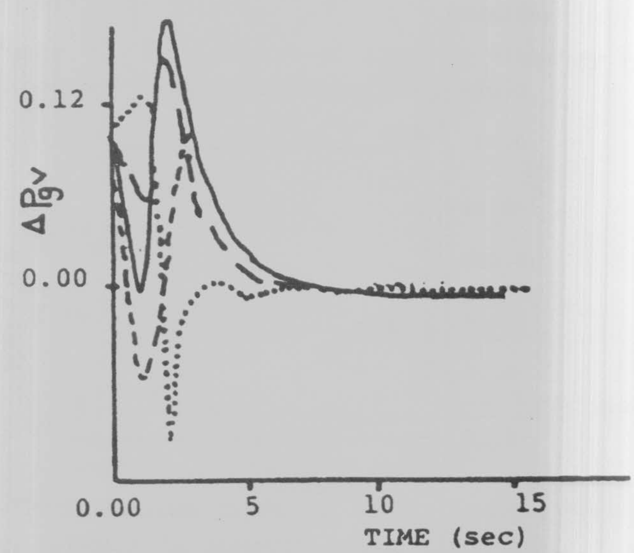

Figure 4. Time history of incremental change in steam valve position.

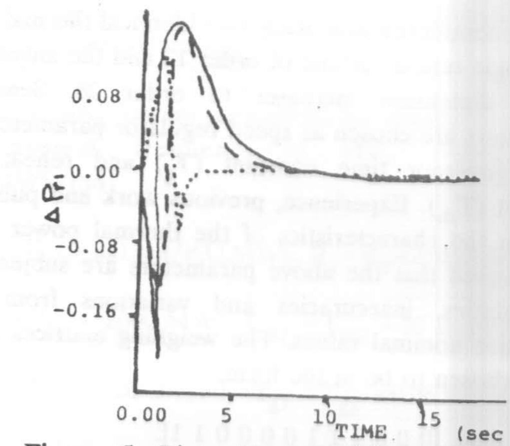

Figure 5. Time history of incremental change in power deviation between steam control valve and H.P.T.

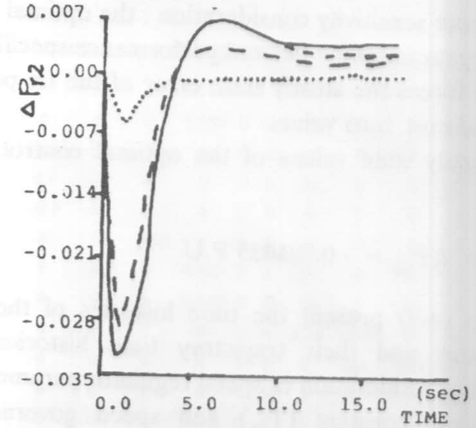

Figure 6. Time history of incremental change in power deviation during reheating.

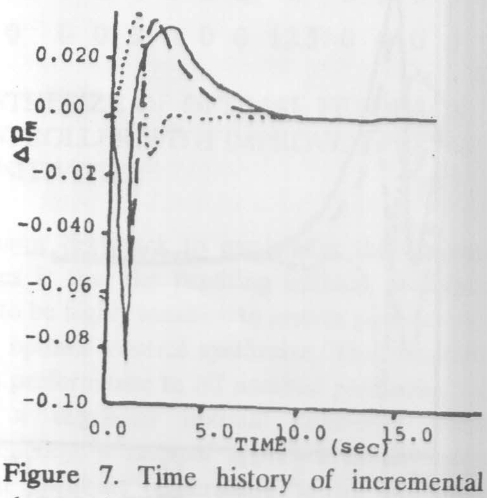

Figure 7. Time history of incremental change in power deviation of output turbine.

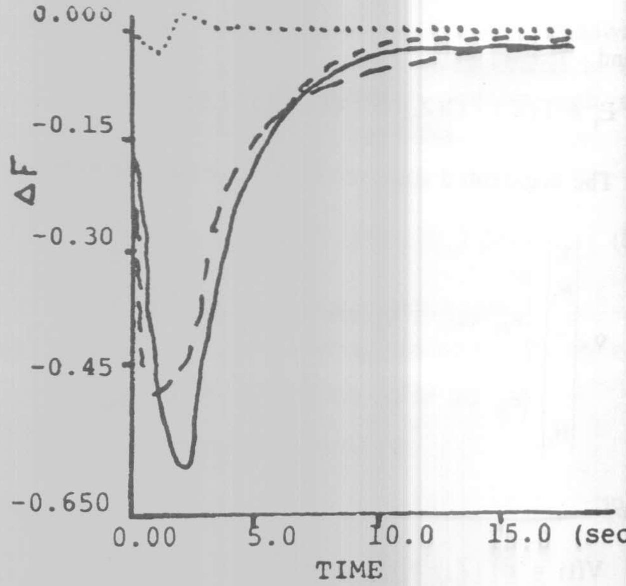

Figure 8. Time history of incremental change in frequency deviation

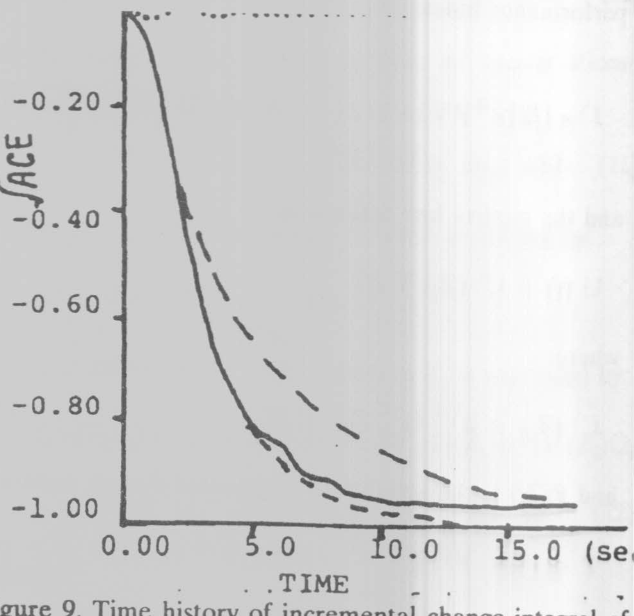

Figure 9. Time history of incremental change integral of Area control error.

Figures (10-15) present the time histories of the sensitivity trajectories of the closed loop states with respect to speed regulator parameter (R), reheat time constant (T_{rh}) and speed governor time constant (T_g) respectively.

(ii) improved sensitivity to speed regulator parameters (R): the major conclusion here is that the deviation in power between the control steam value and high pressure turbine stage (ΔP_{r1}) and the deviation in the steam value position (Δ_{gv}) are relatively the most sensitive state variable to speed regulator parameter (R). The steady state values of optimal control signal are:

$\Delta P_{c1} = \Delta P_{cz} = 0.999498$ P.U.

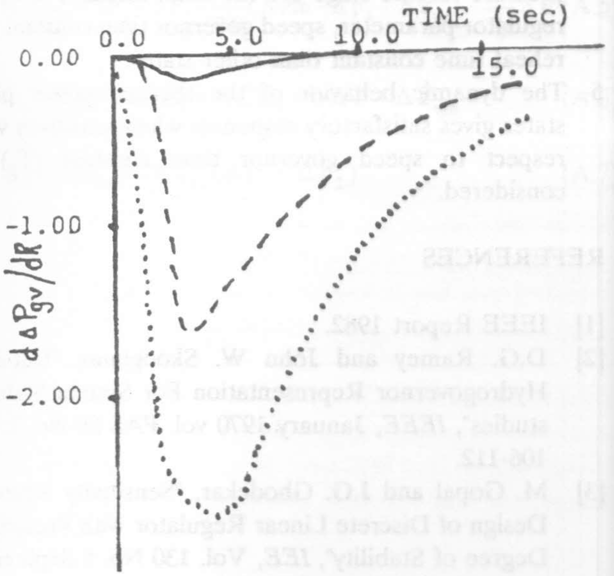

Figure 10. Time history of sensitivity of incremental change in steam valve position.

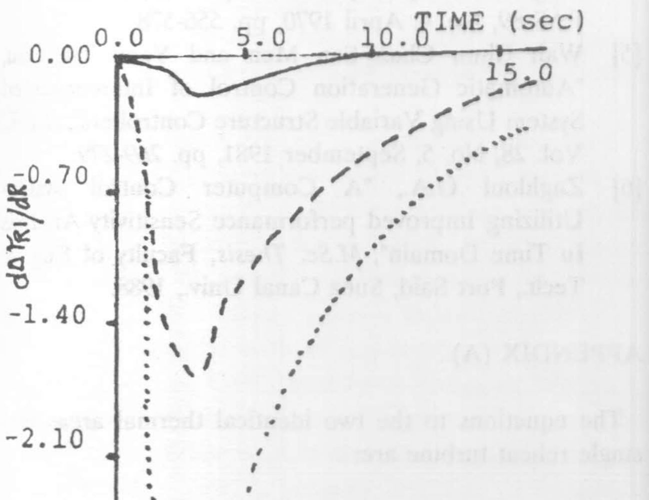

Figure 11. Time history of sensitivity trajectory of incremental change in power deviation between steam control valve and H.P. turbine St.

It is important to note here that, numerically, the value of optimal controller is little longer than its original values.

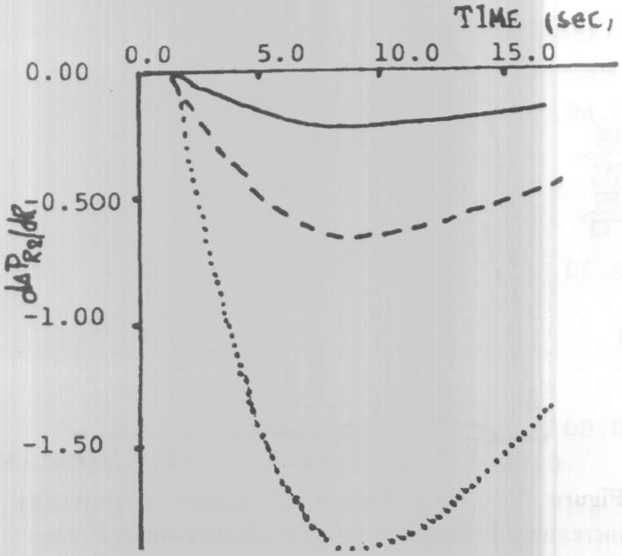

Figure 12. Time history of sensitivity trajectory of incremental change in power deviation during reheating.

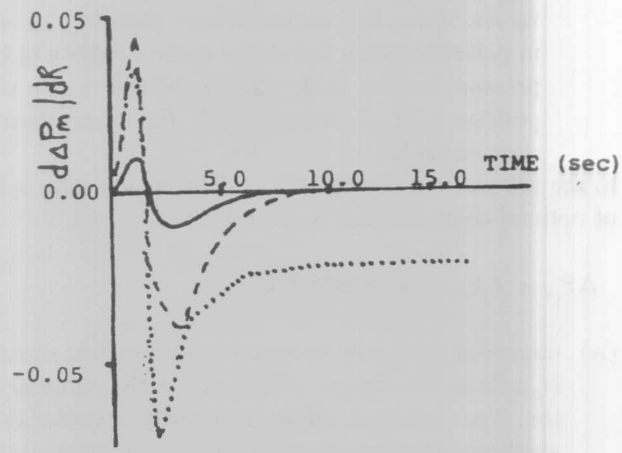

Figure 13. Time history of sensitivity trajectory of incremental change in output turbine power.

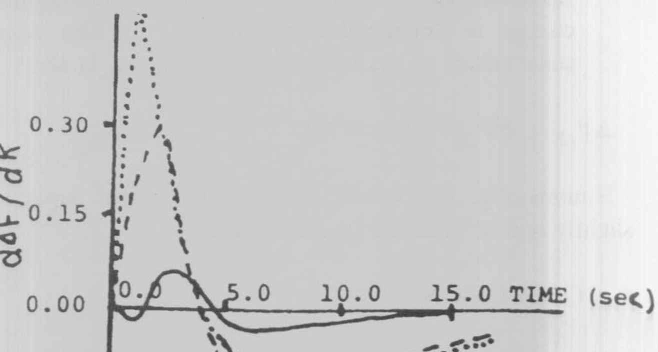

Figure 14. Time history of sensitivity trajectory of incremental change in frequency deviation.

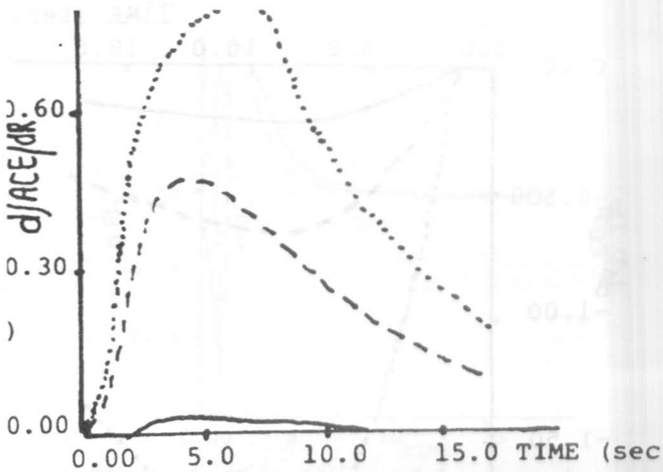

Figure 15. Time history of sensitivity trajectory of incremental change in integral of area control error.

(iii) improved sensitivity to reheat time constant (T_{rh}): it is clear that, the augmented system have negligible deviation from their respective original values. It can be concluded here that the deviation in power between the steam control valve and high pressure turbine stage (ΔP_{r1}) and the steam valve position (ΔP_{gv}) are relatively the most sensitive state variables

to the reheat time constant (T_{rh}). The steady state values of optimal control signal is given by:

$$\Delta P_{ci} = \Delta P_{c2} = 0.985838 \text{ P.U.}$$

(iv) improved sensitivity to speed governor time constant (t_g): from the figures which depict the summary of the time histories ad its sensitivity trajectories of augmented states with respect to speed governor time constant (T_g), the maximum deviation in the state variables sensitivity to T_g results in the incremental change in steam valve position (ΔP_{gv}). The steady state values of the optimal control signal in are:

$$\Delta P_{c1} = \Delta P_{c2} = 1.0008 \text{ P.U}$$

Numerically, the values of optimal control inputs is slightly higher than the original values.

4- CONCLUSION

The outcomes of this paper can be outlined by the following remarks:

1- The thermal power plant is more sensitive to speed governor time constant than its sensitivity to both speed regulator parameter and reheat time constant.
2- The optimal control signal is slightly changed when sensitivity analysis is considered.
3- The dynamic behavior of each area is identical.
4- The deviation of steam valve position and the variation in power between steam control valve and high pressure turbine stage are the most sensitive to speed regulator parameter, speed governor time constant and reheat time constant than other states.
5- The dynamic behavior of the thermal power plant states gives satisfactory responses when sensitivity with respect to speed governor time constant (T_g) is considered.

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APPENDIX (A)

The equations to the two identical thermal areas with single reheat turbine are:

$$\dot{X}_1 = \dot{X}_8 = \Delta \dot{P}_{gv1} = \Delta P_{gv2} = \frac{Kg}{Tg}(\Delta P_c - \Delta P_{gv} - \frac{kg}{Tg}\Delta F \quad \text{(A.1)}$$

$$\dot{X}_2 = \dot{X}_9 = \Delta \dot{P}_{r11} = \Delta P_{r12} = \frac{1}{Tch}(\Delta P_{gv} - \Delta P_{r1}) \quad \text{(A.2)}$$

$$\dot{X}_3 = \dot{X}_{10} = \Delta \dot{P}_{r21} = \Delta P_{r22} = \frac{1}{Tch}(\Delta P_{r1} - \Delta P_{r2}) \quad \text{(A.3)}$$

$$\dot{X}_4 = \dot{X}_{11} = \Delta P_{m1} = \Delta P_{m2} =$$

$$\left(\frac{1}{tch} - \frac{F_{hp}}{Tch}\right)\Delta P_{r1} + \frac{F_{hp}}{T_{ch}}\Delta Pgv - \frac{1}{TRh}\Delta Pm \qquad (A.4)$$

$$\dot{X}_5 = \dot{X}_{12} = \Delta \dot{F}_1 = \Delta \dot{F}_2 = \frac{KP}{TP}(\Delta Pm - \Delta p_d - \Delta P_{tie}) - \frac{1}{Tp}\Delta F \qquad (A.5)$$

$$\dot{X}_6 = \dot{X}_{13} = AGE_1 = ACE_2 = b\,\Delta F + \Delta P_{tie} \qquad (A.6)$$

$$X_7 = \Delta P_{tie} = 2\pi T_{12}(\Delta F_1 - \Delta F_2) \qquad (A.7)$$