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Optimal Agc of Deregulated Interconnected Power System with Parallel Ac/Dc Link

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Abstract : *This paper presents optimal AGC regulator design of deregulated power system based on the full state feedback control strategy. The two-area interconnected power system of identical nature consisting of non-reheat turbine is considered for the investigations. The area-interconnection of the power system via parallel EHVAC/HVDC transmission link is considered. The proposed controller is applied to two-area interconnected power system and its feasibility is demonstrated by investigating the dynamic response plots obtained various system states of the power system models under consideration. The patterns of closed-loop eigenvalues are obtained to analyze the stability of the power system models.*

Keywords*- AGC, Deregulated power system, interconnected power system, parallel EHVAC/HVDC*.

I. INTRODUCTION

The electric power industry is in transitional phase moving from centrally regulated utilities to deregulated environment that will inject competition in the power sector among all the companies to sale the unbundled power at very reasonable rates to the distribution companies. The restructuring and deregulation of power sector is to create a competitive environment where generation and transmission services are bought and sold under demand and supply market conditions. This has unbundled the electric utility services into its basic components and offering each component separately for the sale with separate rates. The unbundling of the vertical entity creates the separate entity for generation, transmission and distribution for the transaction of electric power. Before deregulation ancillary services were provided by a single entity possessing owns generating resources, transmission and distribution capacities located within its territories.

The deregulated power system will have the generating power station separated from transmission and distribution entities. All the power generating stations will be recognized as independent power producers (IPPs). These will be known as GENCOs which will have a free market to compete each other to sell the electrical power. The retail consumers are supposed to buy the electrical power from the distribution companies known as DISCOs. There is also a third player between the GENCOs and DISCOs for wheeling the between them which is designated as TRANSCOs. So in the deregulated power system instead of having single vertical entity it will have three players as GENCOs, DISCOs and TRANSCOs operating separately with their own set functionalities. To supply the regulation between Disco and Genco, a contract will be established between these entities. In the deregulated power system structure, a distribution company has the freedom to have a contract with any generation companies for purpose of transaction of power. The different companies may have the bilateral transactions and these will have to be monitored through an independent system operator which will control the number of ancillary services.

The main task of automatic generation control is to maintain the reliability of the system at the desired frequency even to the varying load demand. The generation companies in deregulated environment may or may not participate in the AGC task. As far as the optimal AGC schemes for interconnected power systems operating in deregulated environment are concerned, a considerable work has been reported in literature [1-5]. V. Donde et al. in [5] have presented an AGC of interconnected power systems in deregulated environment. The distribution companies may contract for the transaction of power with generation companies in its area or other areas. This transaction of power among the generation and distribution companies is done under the supervision of the independent system operators.

The frame work of the deregulated power system is as follows:

1. Unbundling of electrical power system separating Vertically Integrated Utility into GENCOs, TRANSCOs and DISCOs as independent entities.
2. Annulling of exclusive rights
3. Third party shall get access to transmission or supply grids.

However, in all the above articles power system models interconnected via EHV AC transmission links only. But due to the obvious of merits of HVDC transmission line, the interconnection with HVDC link has been utilized for the power system model under consideration. One of the most useful applications of HVDC link is its operation in parallel with EHVAC transmission line between two power networks. This makes the system makes the more stable. The HVDC transmission link an area interconnection has also been demonstrated as a viable tool to improve dynamic performance of the system [6-9].

In the work presented in this paper, optimal controllers are designed and compared based on the interconnected between the two areas. In one power system model the AC tie-line is considered and in the second power system model a parallel AC/DC tie line is considered. The dynamic performance of the power system models considered is analyzed for the designed regulators.

II. Power System Model

A two-area interconnected power system operating under deregulated environment with parallel EHVAC/HVDC for exchanging of power between control areas is considered for investigation. The structure of power system model consists of two identical non-reheat thermal power plants as GENCOs and two distribution system as DISCOs.

The transfer function model of power system model under investigation is developed and presented in Fig. 8. In this model, the actual and scheduled steady state power flows on the tie line are given by;

$\Delta P_{tie12}^{scheduled}$ =(Demand of DISCOs in area-2 from GENCOs in area-1) - (Demand of DISCOs in area-1 from GENCOs in area-2) (1)

$$\Delta Ptie_{12,schedule} = \sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\Delta P_{Lj} - \sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\Delta P_{Lj} \quad (2)$$

The tie line power error ($\Delta Ptie_{12,\ error}$) is defined by;

$$\Delta Ptie_{12,error} = \Delta Ptie_{12,actual} - \Delta Ptie_{12,scheduled} \quad (3)$$

The area control errors (ACEs) in deregulated environment in both areas are defined as;

$$ACE_1 = B_1\Delta f_1 + \Delta Ptie_{12,error} \quad (4)$$

$$ACE_2 = B_2\Delta f_2 + \alpha_{12}\Delta Ptie_{12,error} \quad (5)$$

As there may be many GENCOs in each area, the ACE signal is being distribute among them and their ACE participation factor (apf) for automatic generation control and also sum of all apfs in a particular area should be unity.

In steady state, the demand of DISCOs in contract with GENCOs generation must be matched and expressed as:

$$\Delta P_{L1,Loc} = \Delta P_{L1} + \Delta P_{L2} \quad (8)$$

$$\Delta P_{L1,Loc} = \Delta P_{L1} + \Delta P_{L2} \quad (9)$$

$$\Delta P_{L2,Loc} = \Delta P_{L3} + \Delta P_{L4} \quad (9)$$

$$\Delta P_{L2,Loc} = \Delta P_{L3} + \Delta P_{L4} \quad (10)$$

$$\Delta P_2 = cpf_{21}\Delta P_{L1} + cpf_{22}\Delta P_{L2} + cpf_{23}\Delta P_{L3} + cpf_{24}\Delta P_{L4} \quad (11)$$

$$\Delta P_3 = cpf_{31}\Delta P_{L1} + cpf_{32}\Delta P_{L2} + cpf_{33}\Delta P_{L3} + cpf_{34}\Delta P_{L4} \quad (12)$$

$$\Delta P_4 = cpf_{41}\Delta P_{L1} + cpf_{42}\Delta P_{L2} + cpf_{43}\Delta P_{L3} + cpf_{44}\Delta P_{L4} \quad (13)$$

ΔPUC1 and ΔPUC2 are disturbance signal for un-contracted load in case of contract violation. In case un-contracted loads are absent, ΔPUC1 and ΔPUC2 are zero.

2.1. Case Study

In the present work, two different power system models are identified as follows:

Power system Model-I: Two- area interconnected power system consisting of non-reheat turbine via EHVAC tie-line only.

Power system Model-II: Two area interconnected power system of non-reheat turbine via parallel EHVAC/HVDC tie-line.

III. State Variable Model

The two-area power system model operating under deregulated environment is shown in Fig. 8 can be described by the following controllable and observable linear time-invariant state space representation;

$$\frac{d}{dt}\underline{x} = A\underline{x} + B\underline{u} + \Gamma \underline{P_d} \quad (14)$$

$$Y = Cx \quad (15)$$

For power system model under investigation, the system state, control and disturbance vectors are selected as follows:

- **State vector**

X=[Δf1, Δf2, ΔPtie12, ΔPg1, ΔXg1, ΔPg2, ΔXg2, ΔPg3, ΔXg3, ΔPg4, ΔXg4, ∫ACE1dt, ∫ACE2dt]

- **Control vector**

$$u = [\Delta P_{C1} \quad \Delta P_{C2}]^T$$

- **Disturbance vector**

$$P_d = [\Delta P_{L1} \quad \Delta P_{L2} \quad \Delta P_{L3} \quad \Delta P_{L4} \quad \Delta P_{UC1} \quad \Delta P_{UC2}]^T$$

System Matrices

The structure of system matrices A, B, Γ_d and C can be obtained from the transfer function model shown in fig8.

IV. Design of Optimal AGC Regulator

The design of optimal AGC regulators reported in literature [10]. The continuous time dynamic model in the state variable form is given as;

$$\frac{d}{dt}\underline{x} = A\underline{x} + B\underline{u} + \Gamma \underline{P_d} \quad (16)$$

$$\underline{y} = C\underline{x} \quad (17)$$

Where, x, u, P_d and y are state, control, disturbance and output vector respectively. A, B, C and Γ are system, control, output and disturbance matrices of compatible dimensions.

In the application of optimal control theory, the term in equation (16) is eliminated by redefining the states and controls in terms of their steady-state values occurring after the disturbance. It can be rewritten as;

$$\frac{d}{dt}\underline{x} = A\underline{x} + B\underline{u}, \ \underline{x}(0) = x_0 \quad (18)$$

Moreover eq. (17) will remain the same. The control signal u is such that to minimize the performance index (J):

$$J = \int_0^{\infty}\frac{1}{2}[\underline{x}^T Q\underline{x} + \underline{u}^T R\underline{u}]dt \quad (19)$$

Where, Q and R are weighting matrices for the state variables and the input variables. This optimal control problem is referred to as the linear quadratic regulator design problem. To solve this LQ optimal control problem, let us first construct a Hamiltonian function.

$$J = -\frac{1}{2}[\underline{x}^T Q\underline{x} + \underline{u}^T R\underline{u}]dt + \underline{\lambda}^T[A\underline{x} + B\underline{u}] \quad (20)$$

When there is no constraint on the input signal, the optimal (in this case, the minimum) value can be solved by taking the derivative of H with respect to u and then solving the following equation;

$$\frac{\partial H}{\partial \underline{u}} = -R\underline{u} + B^T\underline{\lambda} = 0 \quad (21)$$

Denote by u* the optimal control signal u. Then, u* can be explicitly written in the following form:

$$\underline{u}^* = R^{-1}B^T\underline{\lambda} \quad (22)$$

On the other hand Lagrangian Multiplier (λ) can be written as; $\underline{\lambda} = S\underline{x}$ (23)

Where, S is the symmetrical solution of the well known DRE.

$$\frac{dS}{dt} = -SA - A^T S + SBR^{-1}B^T S - Q \quad (24)$$

The solution matrix S will tend to a constant matrix i.e. dS/dt=0, In this case DRE reduced to so called algebraic Riccatti Equation:

$$SA + A^T S - SBR^{-1}B^T S + Q = 0 \qquad (25)$$

Now (22) can be written as;

$$\underline{u}^* = R^{-1}B^T S x \qquad (26)$$

With a full state vector feedback control problem, a control law is stated as;

$$\underline{u}^* = -\Psi^* \underline{x} \qquad (27)$$

Using (26) and (27), the desired optimal feedback gain matrix (Ψ*) is given by;

$$\Psi^* = R^{-1}B^T S \qquad (28)$$

How to determine the feedback gain matrix [Ψ*], which minimizes the values of J is an important optimization problem. The value of [Ψ*] is usually obtained from the solution of matrix Riccati equation [11]

V. Simulation Results

The optimal gains of AGC regulators are obtained by using MATLAB software. The patterns of closed loop eigenvalues is reported in Table-1 where as the optimal gains of AGC regulators designed and performance index obtained are presented in Table-2 and Table-3 respectively. The dynamic response plots with the implementation of optimal AGC regulators are shown by Figs. (1-7).

VI. Discussion of Results

The MATLAB software is used to obtain pattern of closed-loop eigenvalues, optimal gains of AGC regulators, performance index and dynamic response plots for both the models. The inspection of closed-loop eigenvalues as shown in Tables-1 inferred that all the eigenvalues have negative real part, thereby ensuring the system stability in closed-loop fashion.

The response curves of Figs. (1-2) represent frequency deviations of respective areas. Observations carried out from these plots reveal that the proposed optimal AGC regulators are capable to mitigate the deviations in frequency of both areas caused due to instantaneous load demands from DISCOs. The tie line power deviation settles to a zero value. The proposed AGC regulators are found to demonstrate their ability to bring the system state deviation as per the desired ones in an effective manner.

The response curves in Figs. (4-7) show the deviations in power generation by GENCOs of respective areas. From the inspection of these Figs., it has been inferred that the proposed optimal AGC regulators are effective in settling the change in power generation to the required value in reasonably small time.

Table-1 Pattern of Closed-loop Eigenvalues

Power system model-I	Power system model-II
-4.6020	-4.6020
-4.3400	-2.5000
-0.7696 ± 3.2987i	-2.7225 ± 1.0381i
-2.5000	-2.1035 ± 7.6681i
-2.5000	-1.6667
-1.6667	-1.6667
-1.6667	-1.1371 ± 2.4201i
-1.1371 ±.4201i	-0.4096 ± 0.2931i
-0.6925 ± 0.2596i	-0.3228
-0.3228	

Table-2 Optimal Gains of AGC Regulator

P.S. Model-I	0.5190 0.1524 -2.2802 2.5248 1.2060 2.5248 1.2060 -0.0431 -0.0130 -0.0431 -0.0130 1.0 0.0
P.S. Model-II-	0.1524 0.5190 2.2802 -0.0431 -0.0130 -0.0431 -0.0130 2.5248 1.2060 2.5248 1.2060 0.0 1.0

Table-3 Performance Index

Model-I	34.4470
Model-II	28.9270

VII. Conclusions

In this paper, the gains of optimal AGC regulators are obtained using modern control theory through state space model technique. The patterns of closed-loop eigenvalues are obtained for power system models in deregulated environment and their investigation reveals that system is stable. The responses are associated with more number of oscillations coupled with larger settling time degraded the system dynamic response in case of power system model-I having AC tie line only are reduced tremendously in the power system model-II with AC/DC parallel tie lines.

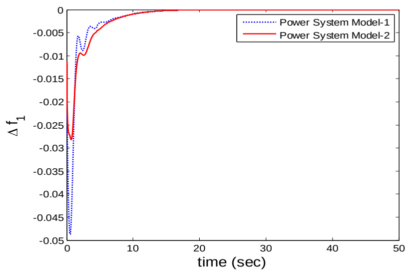

Fig. 3 Change in Frequency (ΔF1)

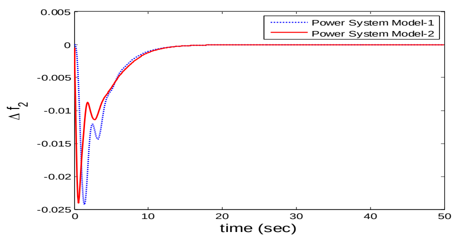

Fig. 4 Change in Frequency (ΔF2)

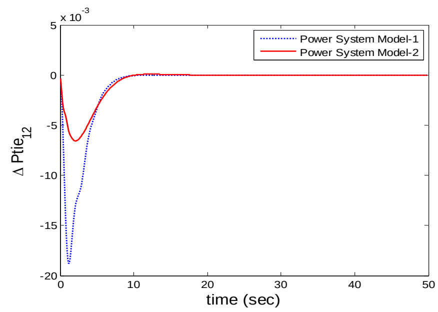

Fig. 5 Change in Tie-line power (ΔPtie12)

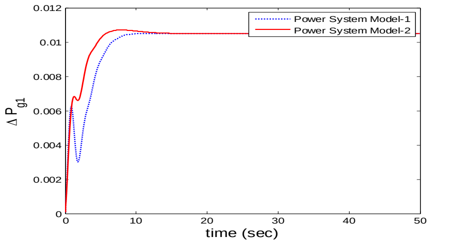

Fig. 6 Change in Power generated (Pg1)

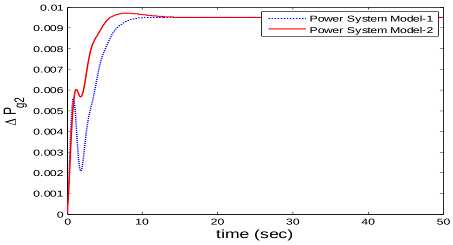

Fig. 7 Change in Power generated (Pg2)

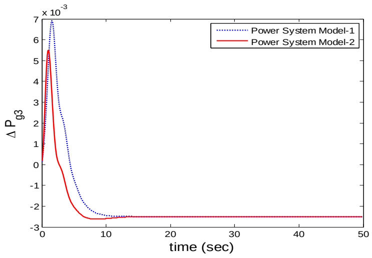

Fig. 8 Change in Power generated (Pg3)

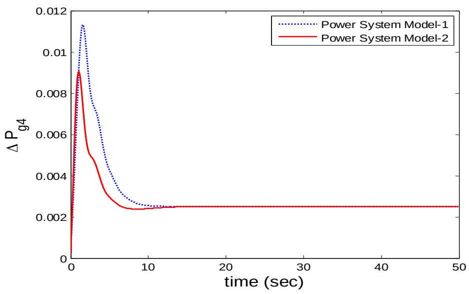

Fig. 9 Change in Power generated (Pg4)

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Numerical Data:

L1=0.01;PL2=0.01;PL3=0.0;PL4=0.0; M=2; L=13; W=4; TOL=0.00001; alpha=0.005;T12=0.0867; b1=0.4249;b2=0.4249; a12=-1;Tp1=20;Kp1=120;Tp2=20;Kp2=120;Kdc=1;Tdc=0.2; Tt1=0.6; Tg1=0.4; Tr1=5;Kr1=0.3;R1=2.4;Tt2=0.6; Tg2=0.4; Tr2=5; Kr2=0.3; R2=2.4;Tt3=0.6; Tg3=0.4; Tr3=5; Kr3=0.3; R3=2.4;Tt4=0.6; Tg4=0.4; Tr4=5; Kr4=0.3; R4=2.4;apf1=0.5; apf2=0.5;apf3=0.5;apf4=0.5;cpf11=0.1;cpf12=0.0;cpf13=0.0; cpf14=0.6; cpf21=0.0; cpf22=0.0; cpf23=0.0; cpf24=0.4; cpf31=0.7;cpf32=0.0;cpf33=0.1;cpf34=0.0;cpf41=0.2;cpf42=1;
cpf43=0.0; cpf44=0.0;

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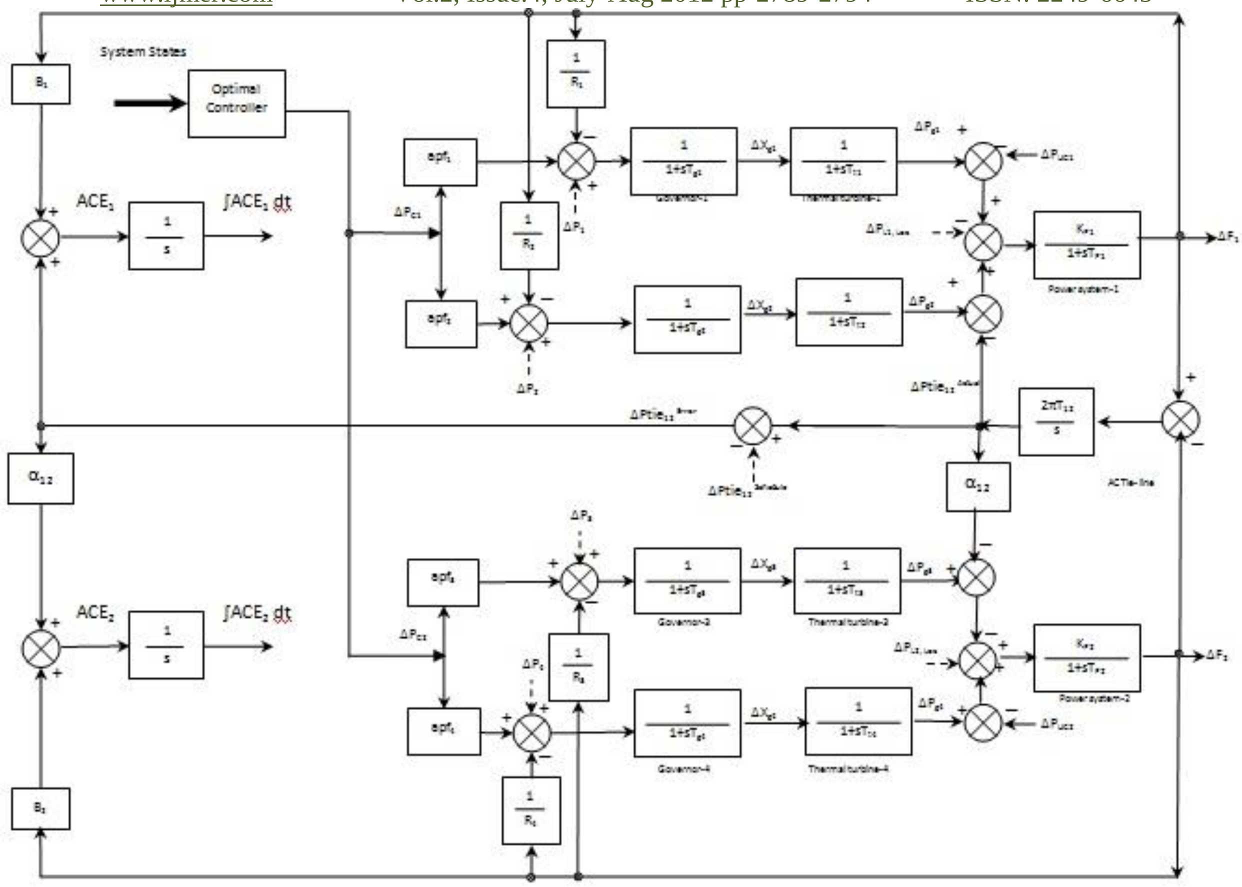

Fig. 3.2 Transfer function model of two-area interconnected power system under deregulated environment

- **System Matrix 'A_1'**

$$
A_1=\begin{bmatrix}
-\frac{1}{T_{Ps1}} & 0 & \frac{-K_{Ps1}}{T_{Ps1}} & \frac{K_{Ps1}}{T_{Ps1}} & 0 & \frac{K_{Ps1}}{T_{Ps1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{1}{T_{Ps2}} & \frac{K_{Ps2}}{T_{Ps2}} & 0 & 0 & 0 & 0 & \frac{K_{Ps2}}{T_{Ps2}} & 0 & \frac{K_{Ps2}}{T_{Ps2}} & 0 & 0 & 0 \\
2\pi T_{12} & -2\pi T_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{T_{tps1}} & \frac{1}{T_{tps1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{1}{R_1 T_{gps1}} & 0 & 0 & 0 & -\frac{1}{T_{gps1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{tps2}} & -\frac{1}{T_{tps2}} & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{1}{R_2 T_{gps2}} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{gps2}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{tps3}} & \frac{1}{T_{tps3}} & 0 & 0 & 0 & 0 \\
0 & -\frac{1}{R_3 T_{gps3}} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{gps3}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{tps4}} & \frac{1}{T_{tps4}} & 0 & 0 \\
0 & -\frac{1}{R_4 T_{gps4}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{gps4}} & 0 & 0 \\
b_1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & b_2 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

- **Control Matrix 'B_1'**

$$B_1^T = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{apf_1}{T_{g1}} & 0 & \frac{apf_2}{T_{g2}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{apf_3}{T_{g3}} & 0 & \frac{apf_4}{T_{g4}} & 0 & 0 \end{bmatrix}$$

- **Disturbance Matrix 'Fd_1'**

$$F_{d1}^T = \begin{bmatrix} -\frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & \frac{cpf_{11}}{T_{g1}} & 0 & \frac{cpf_{21}}{T_{g2}} & 0 & \frac{cpf_{31}}{T_{g3}} & 0 & \frac{cpf_{41}}{T_{g4}} & 0 & 0 \\ -\frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & \frac{cpf_{12}}{T_{g1}} & 0 & \frac{cpf_{22}}{T_{g2}} & 0 & \frac{cpf_{32}}{T_{g3}} & 0 & \frac{cpf_{42}}{T_{g4}} & 0 & 0 \\ 0 & -\frac{K_{P2}}{T_{P2}} & 0 & 0 & \frac{cpf_{13}}{T_{g1}} & 0 & \frac{cpf_{23}}{T_{g2}} & 0 & \frac{cpf_{33}}{T_{g3}} & 0 & \frac{cpf_{43}}{T_{g4}} & 0 & 0 \\ 0 & -\frac{K_{P2}}{T_{P2}} & 0 & 0 & \frac{cpf_{14}}{T_{g1}} & 0 & \frac{cpf_{24}}{T_{g2}} & 0 & \frac{cpf_{34}}{T_{g3}} & 0 & \frac{cpf_{44}}{T_{g4}} & 0 & 0 \end{bmatrix}$$