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Optimal Regulator for AGC of Multi-Area Interconnected Power System with AC/DC Link

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Abstract: In this paper Automatic Generation Control of multi-area interconnected power system consisting of reheat type turbines has been studied. As a consequence of continually load fluctuation the frequency deviate over time and these transients are to be minimized to zero in terms of Area Control Error using optimal linear quadratic regulator. An optimal regulator has been designed to ascertain zero steady state frequency deviation deviation under all operating conditions. The performance of the proposed optimal regulator with conventional integral regulator has been compared. The simulation results reveals that better control performance in terms of overshoot and settling time can be obtained by optimal regulator. System is also studied with AC Tie-line only and DC Link parallel with AC Tie-line.

Keywords: Automatic Generation Control (AGC), Area Control Error (ACE), Optimal Linear Quadratic Regulator (LQR), DC Link

NOMENCLATURE

DESCRIPTION OF ABBREVIATIONS

ΔF_i :	Incremental change in frequency
	subscript referring to area (i=1,2,3; j=1,2,3)
ΔP_{gi}:	Incremental change in generator power output
ΔP_{di} :	Incremental change in load demand
ΔX_{gi}:	Incremental change in governor valve position
$\Delta P_{tiei,j}$:	Incremental change in tie-line power (MW)
T_p:	Electric system time constants
R_i :	Speed regulation parameter, Hz/p.u.MW
K_i:	Integral gain constant
T_{gi}:	Speed governor time constant of area, s
K_{ri},T_{ri}:	Reheat coefficient's & reheat time's
B_i :	Frequency bias constant (p.u.MW/Hz)
ΔACE_i:	Change in Area control error's
T_{ti}:	Turbine time constants
K_{gi}:	Speed governor gain
K_{t1}:	Reheat thermal turbine gain constant
$T_{i,j}$:	Synchronizing coefficient of ac tie-line
A, B, C, Γ:	System matrices associated with state, control, output and disturbance vectors respectively
X, U, Y, Pd:	State, control, output and disturbance vectors respectively

I. INTRODUCTION

AGC regulates the power output of electric generators within prescribed area in response to changes in system frequency, tie-line loading, and relation of these to each other. This maintains the scheduled system frequency and established interchange with other areas within predetermined limits.

The operation and control of these interconnected power systems is no longer a simple task for power engineers. In the event of availability of a suitable AGC scheme, the selection of proper approach for its effective implementation has a vital role [1-3].

Regulator design for interconnected power system AGC function is a multivariable system design problem and its effective study can be justified using modern control techniques for investigations [4-7]. The recent advancement in optimal control theory and availability of high speed digital computers coupled with enormous capability of handling large amount of data motivated the power system engineers/researchers to devise advanced AGC strategies. Through various research publications, it has been established that with optimal control strategies designed using linear regulator theory, ameliorated system dynamic performance with greater stability margins as compared to that obtained with conventional AGC regulators can be achieved [10].

The requirements and benefits of using parallel AC/DC transmission links as system interconnection are highlighted [8, 9].

This paper is dedicated to represent the optimal AGC regulator designs based on an optimal Linear Quadratic Regulator theory. The optimal AGC regulator is designed for a multi-area interconnected reheat type power system with AC Tie-line only and DC Link parallel with AC transmission lines considering 0.01 p.u.MW perturbation in one of the area are considered for the study. Power system dynamic performance has been studied by investigating the response plots of the disturbed areas ΔF_1, ΔF_2, ΔF_3, ΔACE_1, ΔACE_2 and ΔACE_3, with nominal system parameters.

II. MULTI-AREA INTERCONNECTED POWER SYSTEM MODEL

A multi-area interconnected power system consisting of equal plants with reheat type thermal turbines interconnected with AC Tie-line only and DC Link parallel with AC Tie-line in Fig.1, 2. The investigated power systems model is shown in Fig.3.

The power system dynamic equations in state space for this model can be given as:

System State, Control, Disturbance Vector:

$$[X] = [\Delta F_1\ \Delta P_{g1}\ \Delta P_{r1}\ \Delta X_{g1}\ \Delta F_2\ \Delta P_{g2}\ \Delta P_{r2}\ \Delta X_{g2}\ \Delta F_3\ \Delta P_{g3}\ \Delta P_{r3}\ X_{g3}\ \Delta P_{tie12}\ \Delta P_{tie23}\ \Delta P_{tie31}\ \textstyle\int ACE_1 dt\ \int ACE_2 dt\ \int ACE_3 dt]^T$$

$$[U] = [U_1\ U_2\ U_3]^T$$

$$[P_d] = [P_{d1}\ P_{d2}\ P_{d3}]^T$$

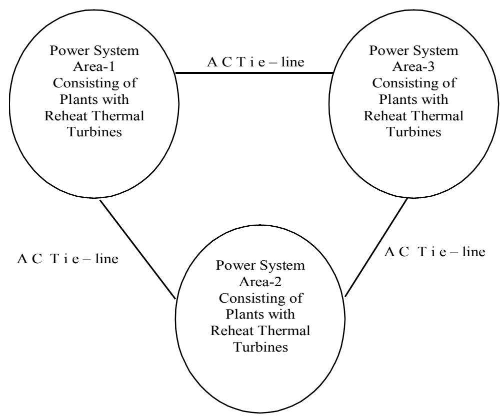

Fig.1 Block diagram of multi-area interconnected power system with AC Tie-line only

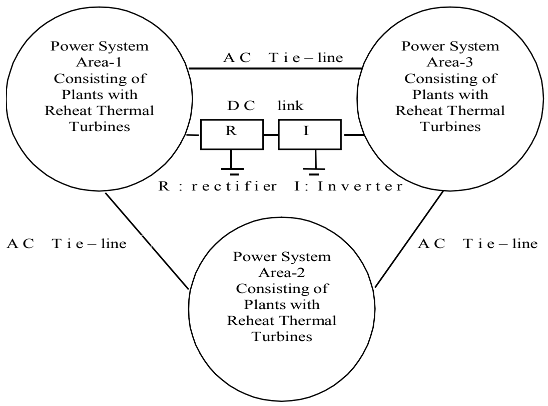

Fig.2 Block diagram of multi-area interconnected power system DC Link parallel with AC Tie-line

The system output, which depends on area control error (ACE) shown as

$\underline{Y} = [ACE_1\ ACE_2\ ACE_3] = C\ \underline{X}$

where; $ACE_i = B_i\ \Delta F_i + \Delta P_{tie,i,\ j}$

Where Bi is the frequency bias constant, ΔF_i is the frequency deviation and $\Delta P_{tie,i}$ is the change in tie-line power transfer for areas i, j. C is the output matrix. The simulation study has been performed using MATLAB-7.8 version. The SIMULINK TOOLBOX is also used to achieve the results and their investigations.

System model is described in the following state equations:

From the block diagram,

$$\dot{} = -\frac{}{} + \frac{}{} - \frac{}{} - \frac{}{}\Delta \quad (1)$$

$$\dot{} = \frac{}{} + \frac{}{} - \frac{}{} \quad (2)$$

$$\dot{} = -\frac{}{} + \frac{}{} \quad (3)$$

$$\dot{} = -\frac{1}{} - \frac{1}{} + \frac{1}{} \quad (4)$$

$$\dot{} = -\frac{}{} - \frac{}{} - \frac{}{} - \frac{}{}\Delta \quad (5)$$

$$\dot{} = \frac{}{} + \frac{}{} - \frac{}{} \quad (6)$$

$$\dot{} = \frac{}{} - \frac{}{} \quad (7)$$

$$\dot{} = -\frac{1}{} - \frac{1}{} + \frac{1}{} \quad (8)$$

$$\dot{} = \frac{}{} - \frac{}{} - \frac{}{} - \frac{}{}\Delta \quad (9)$$

$$\dot{} = \frac{}{} + \frac{}{} - \frac{}{} \quad (10)$$

$$\dot{} = \frac{}{} - \frac{}{} \quad (11)$$

$$\dot{} = -\frac{1}{} - \frac{1}{} + \frac{1}{} \quad (12)$$

$$\dot{} = (2 \quad + 2 \quad) \quad - 2 \quad - 2 \quad (13)$$

$$\dot{} = (2 \quad + 2 \quad) \quad - 2 \quad - 2 \quad (14)$$

$$\dot{} = (2 \quad + 2 \quad) \quad - 2 \quad - 2 \quad (15)$$

$$\dot{} = \quad + \quad (16)$$

$$\dot{} = \quad + \quad (17)$$

$$\dot{} = \quad + \quad (18)$$

DC Link model: The DC Link is presented as a time delay as discussed by [8]. Fig.4 (b) shows the DC link model.

Changes in the power system model for replacing the AC Tie-line between areas 1 and 3 with an AC-DC parallel Tie-lines are:

$$\dot{} = \frac{}{} + 2 \quad + 2 \quad - 2 \quad - \frac{}{} + 2 \quad - \frac{1}{} \quad (13)$$

$$\dot{} = \frac{}{} + 2 \quad + 2 \quad - 2 \quad - \frac{}{} + 2 \quad - \frac{1}{} \quad (15)$$

The AC Tie-line model is shown in Fig. 4 (a).

III. CONVENTIONAL INTEGRAL REGULATOR

Regulator input is taking as Area Control Error (ACE), the control vectors for the conventional Integral regulators, respectively can be given in the following ways:

$$U_i = -\int K_i\ (ACE_i)dt$$
$$= -\int K_i\ (B_i\ \Delta F_i + \Delta P_{tie,i})dt$$

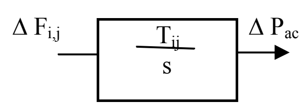

Fig. 4(a) Model for AC Tie-line

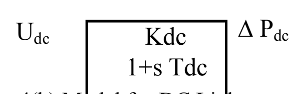

Fig. 4(b) Model for DC Link

IV. OPTIMAL LINEAR QUADRATIC REGULATOR DESIGN

In the optimal control scheme the control inputs U_1, U_2 and U_3 are generated by means of feedback from all the states with feedback gains (K) constants to be determined in accordance with an optimal criterion [7].

For full state feedback, the control vector U is constructed by a linear combination of all states, i.e.

$$U = -KX \quad (i)$$

where K is the feedback matrix.

The feedback matrix K is to be determined so that a certain performance index J is minimized. In MATLAB, this can be obtained by LQR (Linear Quadratic Regulator) by the following function

$$K = lqr(A, B, Q, R) \qquad \text{(ii)}$$

The state-feedback law $U = -KX$ minimizes the cost function (J)

$$J = -\left(\int^{\infty} X' \; Q X' + U' \;\; R U'\right)dt \qquad \text{(iii)}$$

where, X ' and U ' are transient state terms.

The state cost weighting matrix 'Q' and control cost weighting matrix 'R' has been selected as an identity matrix of compatible dimensions respectively.

$$A = \begin{bmatrix}
-1/Tp_1 & Kp_1/Tp_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -Kp_1/Tp_1 & 0 & 0 & 0 & 0 & 0 \\
0 & -1/Tr_1 & (1/Tr_1)+Kr_1*Tr_1/Tr_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1/Tt_1 & 1/Tt_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1/R_1*Tg_1 & 0 & 0 & -1/Tg_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1/Tp_2 & Kp_2/Tp_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -Kp_2/Tp_2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -1/Tr_2 & (1/Tr_2)+Kr_2*Tr_2/Tr_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1/Tt_2 & 1/Tt_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1/R_2*Tg_2 & 0 & 0 & -1/Tg_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/Tp_3 & Kp_3/Tp_3 & 0 & 0 & 0 & 0 & -Kp_3/Tp_3 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/Tr_3 & (1/Tr_3)+Kr_3*Tr_3/Tr_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/Tt_3 & 1/Tt_3 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/R_3*Tg_3 & 0 & 0 & -1/Tg_3 & 0 & 0 & 0 & 0 & 0 & 0 \\
2*pi*T_{13}+2*pi*T_{12} & 0 & 0 & 0 & -2*pi*T_{12} & 0 & 0 & 0 & -2*pi*T_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-2*pi*T_{12} & 0 & 0 & 0 & 2*pi*T_{21}+2*pi*T_{23} & 0 & 0 & 0 & -2*pi*T_{23} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-2*pi*T_{31} & 0 & 0 & 0 & -2*pi*T_{32} & 0 & 0 & 0 & 2*pi*T_{32}+2*pi*T_{31} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
B_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & B_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_3 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0
\end{bmatrix}$$

$$B^T = \begin{bmatrix}
0 & 0 & 0 & — & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & — & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & — & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\qquad
\Gamma^T = \begin{bmatrix}
-— & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -— & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -— & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

V. COMPUTATIONAL RESULTS

In the present study, optimal AGC regulator based on full state vector feedback control strategy is designed. This study considers interconnected power system with AC Tie-line only and DC Link parallel with AC Tie-line. The optimal closed loop system eigenvalues (TABLE-1) and state feedback gains (TABLE-2) are also computed to investigate the stability of the system.

The dynamic response plots with this regulator considering 1% step load disturbance in Area-1 are plotted for frequency deviation of ΔF_1, ΔF_2, ΔF_3 and area control error ΔACE_1, ΔACE_2, ΔACE_3 of are shown in Fig. 5-10.

It is found that parameters obtained by using LQR theory, give dynamic response in which oscillations and settling time in frequency deviations and area control errors are lesser as compared Integral control theory.

These investigations also reveal that the implementation of DC Link in the transmission lines is beneficial for the damping out the oscillations.

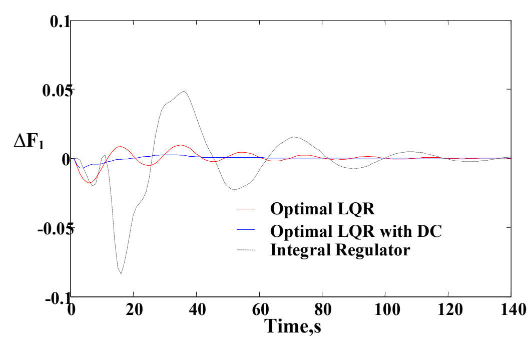

Fig. 5 Dynamic Response of ΔF_1

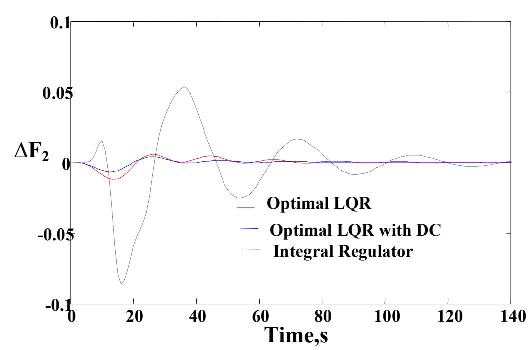

Fig. 6 Dynamic Response of ΔF_2

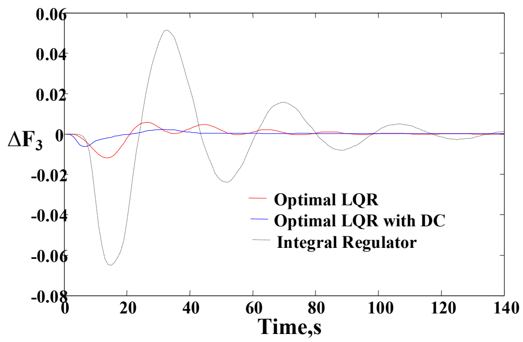

Fig. 7 Dynamic Response of ΔF_3

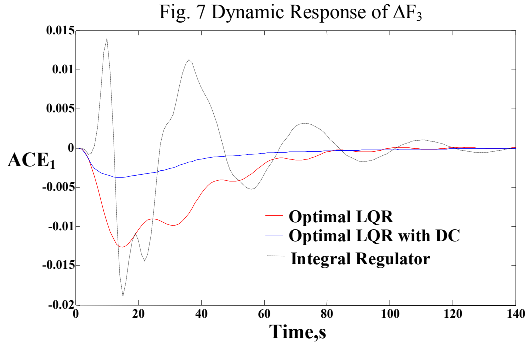

Fig. 8 Dynamic Response of ACE_1

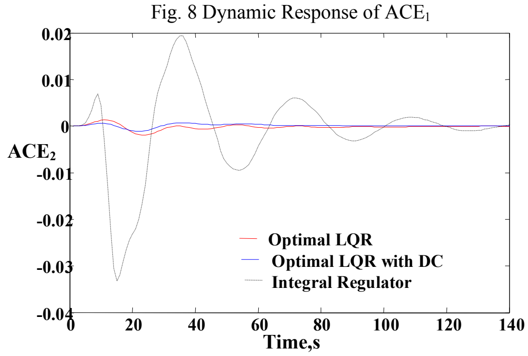

Fig. 9 Dynamic Response of ACE_2

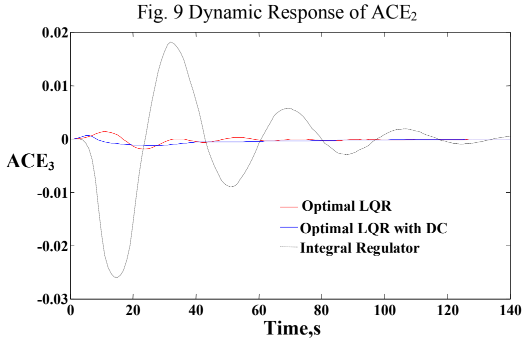

Fig. 10 Dynamic Response of ACE_3

VI. CONCLUSION

The system dynamic performance in the wake of load disturbance in either of the area of interconnected power system has been investigated. The optimal AGC regulator using LQR control strategy is designed and their feasibility is studied. This proposed optimal LQR gives much better results than the Integral regulator. The power system dynamic performance of reheat thermal power plants can be compensated effectively by incorporating DC link in parallel with AC Tie-line in place of AC Tie-line only as area interconnection between power system areas.

SYSTEM DATA:

Power System Parameters:
Nominal system frequency = 50Hz
$Pr_1 = Pr_2 = Pr_3 = 2000$, $B_1 = B_2 = B_3 = 0.425$, $R_1 = R_2 = R_3 = 2.4$, $K_{g1} = K_{g2} = K_{g3} = 1$, $T_{g1} = T_{g2} = T_{g3} = 0.08$, $K_{r1} = K_{r2} = K_{r3} = 0.5$, $T_{r1} = T_{r2} = T_{r3} = 10$, $K_{t1} = K_{t2} = K_{t3} = 1$, $T_{t1} = T_{t2} = T_{t3} = 0.3$, $K_{p1} = K_{p2} = K_{p3} = 120$, $T_{p1} = T_{p2} = T_{p3} = 20$, $2\pi T_{12} = 2\pi T_{23} = 2\pi T_{31} = 0.545$, $\Delta Pd_1 = 0.01$, $K_{dc} = 1$, $T_{dc} = 0.2$.

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TABLE-1

Optimal Close Loop System Eigenvalues	
AC Tie-line only	DC Link parallel with AC Tie-line
-17.5108	-17.6624
-17.5108	-17.6593
-17.5108	-17.6598
-4.1391	-2.5149 + 7.9542i
-4.1178	-2.5149 - 7.9542i
-4.1178	-4.3274
-0.9782 + 1.0560i	-3.7362
-0.9782 - 1.0560i	-3.6024
-0.2918 + 3.1677i	-3.2514
-0.2918 - 3.1677i	-0.4744 + 2.8448i
-0.2918 + 3.1677i	-0.4744 - 2.8448i
-0.2918 - 3.1677i	-1.0395 + 1.3321i
-0.4245	-1.0395 - 1.3321i
-0.4831 + 0.3220i	-0.6418 + 0.3220i
-0.4831 - 0.3220i	-0.6418 - 0.3220i
-0.4831 + 0.3220i	-0.5786 + 0.2571i
-0.4831 - 0.3220i	-0.5786 - 0.2571i
-0.0000	-0.2974

TABLE – 2

K	$\begin{bmatrix} 0.338 & 6.019 & 1.042 & 0.598 & 0.555 & 1.343 & 0.137 & 0.022 & 0.555 & 1.343 & 0.137 & 0.022 & -3.283 & -1.158 & -1.158 & 1.000 & 0.000 & 0.000 \\ 0.555 & 1.343 & 0.137 & 0.022 & 0.338 & 6.019 & 1.042 & 0.598 & 0.555 & 1.343 & 0.137 & 0.022 & -1.158 & -3.283 & -1.158 & 0.000 & 1.000 & -0.000 \\ 0.555 & 1.343 & 0.137 & 0.022 & 0.555 & 1.343 & 0.137 & 0.022 & 0.338 & 6.019 & 1.042 & 0.598 & -1.158 & -1.158 & -3.283 & -0.000 & -0.000 & 1.000 \end{bmatrix}$

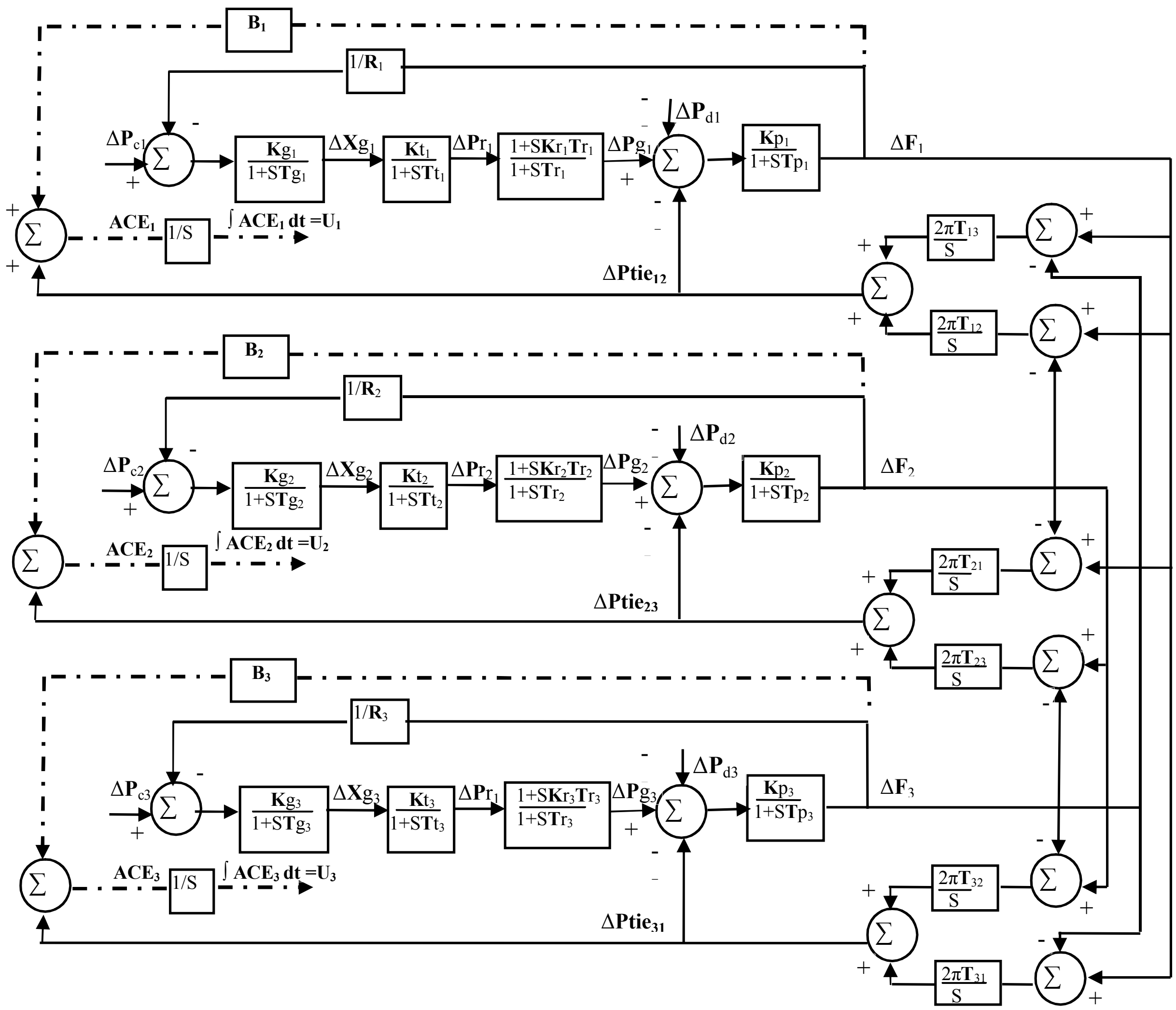

Fig.3 Transfer function model of multi-area reheat type power system model