

PI Controller for Automatic Generation Control Based on Performance Indices

Kalyan Chatterjee¹

Abstract—The optimal design of PI controller for Automatic Generation Control in two area is presented in this paper. The concept of Dual mode control is applied in the PI controller, such that the proportional mode is made active when the rate of change of the error is sufficiently larger than a specified limit otherwise switched to the integral mode. A digital simulation is used in conjunction with the Hooke-Jeeve's optimization technique to determine the optimum parameters (individual gain of proportional and integral controller) of the PI controller. Integrated Square of the Error (ISE), Integrated Time multiplied by Absolute Error (ITAE), and Integrated Absolute Error (IAE) performance indices are considered to measure the appropriateness of the designed controller. The proposed controller are tested for a two area single nonreheat thermal system considering the practical aspect of the problem such as Deadband and Generation Rate Constraint (GRC). Simulation results show that dual mode with optimized values of the gains improved the control performance than the commonly used Variable Structure .

Keywords—Load Frequency Control, Area Control Error (ACE), Dual Mode PI Controller, Performance Index,

I. INTRODUCTION

THE analysis and design of Automatic Generation Control (AGC) system of individual generators eventually controlling large interconnections between different control areas play a vital role in automation of power system. The sensitivity of any power plant depends upon the response time taken by the automatic generation controller to take care of the frequency change. The purposes of AGC are to maintain system frequency very close to a specified nominal value, to maintain generation of individual unit at the most economic value, to keep the correct value of the line power between different control areas. If the load is increased, AGC system increases the mechanical torque by increasing the steam flow rate to turbine to compensate the load by increasing the generator's output economically in an area. This process must be repeated constantly on a power system because the load changes constantly. The conventional control strategy for the AGC problem is to take the integral of the control error as the control signal. By the way of using integral controller, zero steady-state frequency deviation can be achieved but the dynamic performance of such controllers is unsatisfactory. Variable structure concept has been used by some of the investigators [1-3] to cope with the Load Frequency Control

(LFC) problem. The concept of dual-mode control is applied in the PI controller such that the proportional mode is made active when the rate of change of the error is sufficiently larger than a specified limit otherwise switched to the integral mode. A digital simulation is used in conjunction with the Hooke-Jeeve's optimization technique to determine the optimum parameters (individual gain of proportional and integral controller) of the PI controller. Three different types of performance indices are considered to measure the appropriateness of the designed controller. The concept of dual mode with optimized values of the gains improves the performance of the controller and reduces the overshoot and settling time of the system response.

II. ANALYSIS IN THE TIME DOMAIN

The design of linear control systems can be carried out in either the time or the frequency domain. Design in the time domain using performance specifications as rise time, delay time, settling time, maximum overshoot and so on, is feasible analytically only for second order systems or systems that can be approximated by second order systems. General design procedures using time - domain specifications are difficult to establish for systems with order higher than the second. But, the development and availability of high -powered and user-friendly computer software is rapidly changing the practice of control system design. With modern computer software tools, the designer can go through a large number of design runs using the time-domain specifications within a matter of minutes. This considerably diminishes the historical edge of the frequency- domain design, which is based on the convenience of performing graphical design manually. In addition, it is generally difficult, except for the experienced, to select a meaningful set of frequency- domain specifications that will correspond to the desired time domain performance requirements. In this work, the secondary controller is designed in time domain specifications.

III. TWO-AREA WITH INTEGRAL CONTROLLER

The guiding principle in pool operation is that each area in normal steady state should supply its own load and such portions of other areas load as had been agreed upon .It is required that the steady-state tie-line power deviation following load changes must be brought to zero. For making the steady state error zero, integral controller is used as a supplementary controller.

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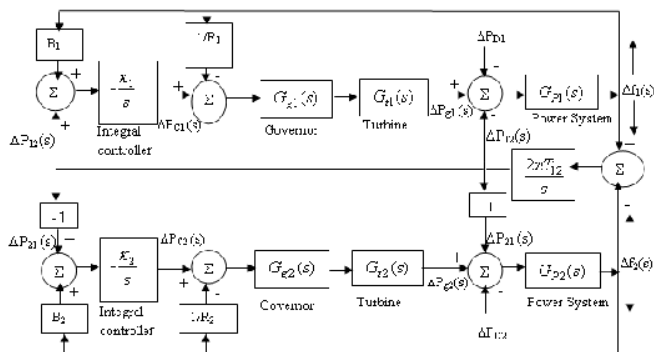


Fig.1 Complete Block Diagram of Two-Area System with Integral Controller

From this Fig.1 the command signals P_{Ci} ($i=1, 2$) will be of the form

$$\Delta P_{c1} = -\kappa_1 \int (\Delta P_{12} + B_1 \Delta f_1) dt \quad (1)$$

$$\Delta P_{c2} = -\kappa_2 \int (\Delta P_{21} + B_2 \Delta f_2) dt \quad (2)$$

The constant κ_1 and κ_2 are integrator gains, and the constants B_1 and B_2 are the frequency bias –settings. The type of control is known as the tie-line bias control. The static response of the system shows that the steady state frequency response and tie line power deviation can be eliminate with integral controller.

IV. THE PI CONTROLLER

One of the most widely used control laws in thermal power station governing systems is the PI type controller. Proportional controller is used to reach the steady state condition much quicker because of the faster transient response with proportional controller. The proportional term of the controller produces a control signal proportional to the error in the system, so that $u(t) = \kappa_p e(t)$. Typically, given a step change of load demand, low values of κ_p give rise to stable responses with large steady-state errors. Higher values of κ_p give better steady-state performance, but worse transient response. Therefore, the higher value of κ_p is used to reduce the steady state error, although increasing the gain κ_p decreases the system time constant and damping. Therefore it is evident to choose the optimum value of κ_p .

The proportional action can never eliminate the steady state error in the system because some (small) error must be present in order to produce a control output. A common way of reducing the steady state error is by incorporating integral action into the controller. Here, the control signal generated is proportional to the integral of the error signal, that is $u(t) = \kappa_i \int e(t) dt$, where κ_i is the integral gain. While an error exists, the integrator tends to increase control action, thus driving the plant output towards the demand output. Then, when the error disappears, the continuing integrator output can

be used to maintain the control action necessary for steady-state conditions. But, if the gain of integrator κ_i is sufficiently high, overshoot will occur increasing sharply as a function of the gain, this is highly undesirable. Lower value of κ_i reduce overshoot but increase rise time of the system. Based upon discussion it is required to design both the κ_p and κ_i properly.

It is well known that if the control law employs integral control the system has no steady state error. However, it increases the type of system by one. Therefore, the response with the integral control is slow during the transient period as shown in Fig.2. In the absence of the integral control when only proportional controller will act, gain of closed loop system can be increased significantly thereby improving the transient response. Therefore, the system reaches steady state much quicker because of the faster transient response. This can be observed from the response with proportional controller in Fig.2. However, the disadvantage with the proportional controller is that the system displays a steady state error. From these studies, one may draw the conclusion that the control law should be based on a compromise between the proportional and integral controller. The result of this compromise is also given in Fig.2 for the case of the PI control. It is seen that with the integral control system approaches steady state at a faster rate than with the PI control. It means that PI compromise does not eliminate the conflict between the static and dynamic performance of the system. The PI control strategy has slightly smaller deviation at the first peak than integral control strategy but settling time for only integral control is less. Also the response with the PI controller is more oscillatory than the integral controller [6].

Based upon the above-mentioned facts, it is desirable to introduce a dual concept involving both proportional and integral controller. The proportional controller will act during the transient period when rate of change of the error is sufficiently larger, whereas the integral controller would be the better option when the rate of change of the error is small.

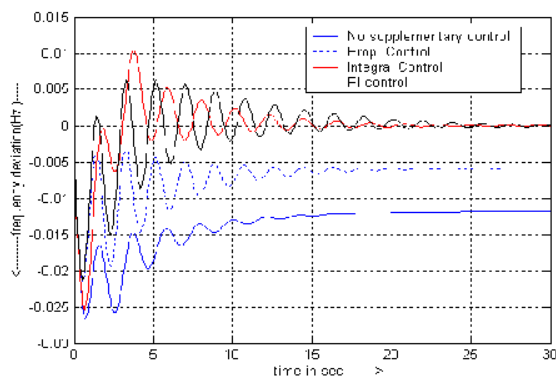


Fig. 2 Time Domain Response for Area 1

V. THE PROPOSED APPROACH

The structure of the Dual Mode controller changes depending

on the rate of change of error shown in the Fig.3 . That is, when the error is large one might choose one control strategy and for sufficiently small error another control strategy. It is thus a discontinuous mode of operation. When the error is sufficiently small and remains small the control structure is not changed. It may be called the continuous mode of operation.

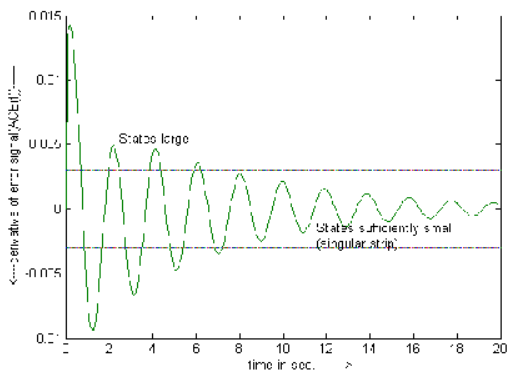


Fig. 3 Error Signal

VI. PROPOSED AUTOMATIC GENERATION CONTROL STRATEGY

As mentioned in the beginning of this section the control algorithm in the proposed approaches has two modes of operation, i.e. continuous and discontinuous. The control is based on the conventional techniques during the continuous mode. It is proposed that the control structure be switched during the discontinuous mode. The type of structure to be used during the discontinuous mode depends upon the particular problem and switching can be performed on a simple criterion such as rate of change of the error staying within a singular strip. A suitable control algorithm based on such variable structure control scheme is developed in Automatic Generation Control problem.

A. Discontinuous Mode

The control system will operate in this mode when the rate of change of the error signal, as shown in Fig.3 exceeds specified limit. In the discontinuous mode, the control should switch between two different control algorithms in the feedback loop until the rate of change of the error signal trajectory enters the singular strip permanently. The time at which these changes occur is determined in accordance with the current value of the derivative of the error signal. Based on the properties of the proportional and the integral control, the system response can be improved by employing a variable structure concept that combines useful properties of both the control action during the discontinuous mode. The control law employed during the transient period that is the discontinuous mode is switched between equations (3) and (4) depending upon the magnitude of the rate of change of the error signal.

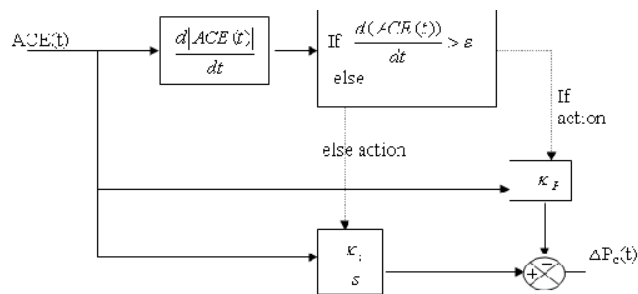


Fig. 4 Block Diagram for the Proposed Controller

$$\text{For } \left| \frac{d(ACE(t))}{dt} \right| > \epsilon$$

$$\Delta P_c(t) = -K_p ACE(t) \quad (3)$$

Where $ACE(t)$ is an error signal at a particular instant and $\epsilon > 0$ is some constant indicating the specified limit of rate of change of the error signal.

$$\text{and for } \left| \frac{d(ACE(t))}{dt} \right| \leq \epsilon$$

$$\Delta P_c(t) = -K_i \int ACE(t) dt \quad (4)$$

Then if the parameters K_p, K_i and ϵ are suitably selected, one can ensure a high quality transient response. By choosing a suitable value of K_p , one makes sure that speed of the system is high. Whenever the rate of change of error falls within the specified error bound ($\left| \frac{d(ACE(t))}{dt} \right| < \epsilon$), the integrator starts accumulating the error. But if the error exceeds the bound the integrator resets to zero.

This continuous switching between the proportional and integral control strategies quickly brings the system to the continuous mode when $\left| \frac{d(ACE(t))}{dt} \right| < \epsilon$.

B. Continuous Mode

When the rate of change of the error signal remains within the specified limit i.e. $\left| \frac{d(ACE(t))}{dt} \right| < \epsilon$, the system will operate in the continuous mode. The integral control strategy is best able to meet the LFC requirements when the system enters the continuous mode. Thus the control law during the continuous mode would be

$$\Delta P_c(t) = -K_i \int_{t_\epsilon}^t ACE(t) dt \quad (5)$$

Where $t_\epsilon < t$ is the time at which the error enters the region $\left| \frac{d(ACE(t))}{dt} \right| < \epsilon$ and remains in this region. The integral control will then eliminate the steady state error remaining in the system. The proposed control scheme is shown in Fig.4.

C. Performance with the proposed control

For the proposed control scheme, the control law is taken as

$$\Delta P_{c1}(t) = -\kappa_{p1}[ACE_1(t)] \quad \text{for } \left| \frac{d(ACE_1(t))}{dt} \right| > \varepsilon_1$$

$$\Delta P_{c1}(t) = -\kappa_{i1}[\int ACE_1(t)dt] \quad \text{for } \left| \frac{d(ACE_1(t))}{dt} \right| \leq \varepsilon_1$$

$$\Delta P_{c2}(t) = -\kappa_{p2}[ACE_2(t)] \quad \text{for } \left| \frac{d(ACE_2(t))}{dt} \right| > \varepsilon_2$$

$$\Delta P_{c2}(t) = -\kappa_{i2}[\int ACE_2(t)dt] \quad \text{for } \left| \frac{d(ACE_2(t))}{dt} \right| \leq \varepsilon_2$$

Where $\kappa_{p1} = \kappa_{p2} = \kappa_p$, $\kappa_{i1} = \kappa_{i2} = \kappa_i$, $\varepsilon_1 = \varepsilon_2 = \varepsilon$ and $\Delta P_{c1}(t)$ and $\Delta P_{c2}(t)$ are the controls for area 1 and area 2 respectively.

VII. DESIGN PROCEDURE OF DUAL MODE CONTROLLER

The main objective of the controller is to provide accurate actuating signal to the governor and respond first as well after small load perturbation. The accuracy of the signal depends on the switching and optimal value of κ_p and κ_i . Routh-Hurwitz criteria is used to determine the range of κ_p and κ_i over which the system remains stable. While determining the stability zone, we neglect all non-linearities existing in the system such as governor deadband, GRC and governor valve position of the system as we need only the broad zone of κ_p and κ_i . But we consider all the nonlinearities at the time of searching optimum values of κ_p and κ_i by Hooke-Jeeve's method within the broad stability zone of κ_p and κ_i determined by Routh array. The total designing work of the dual-mode controller [16] has been carried out by the following way:

Step 1:

Find out the overall transfer function (i.e. $\frac{\Delta f_i}{\Delta P_D}$) of the system considered. From this transfer function, derive the characteristic equation (denominator of the transfer function) of the system.

Step 2:

Investigate the upper and lower stability limit of the κ_p and κ_i . Routh-Hurwitz criterion is used here to determine the stability limit of κ_p and κ_i . In our proposed controller, either proportional or integral controller will act at a time depending on the control strategy. Therefore, we have to determine the stability zone of one parameter (either κ_p and κ_i) when the corresponding controller acts only. So we determine the stability zone of κ_p keeping κ_i equals to zero (i.e. no integral action) and the same for κ_i

Step 3:

Find out the optimum values of the parameters κ_p and κ_i as the controller performance depends upon the values of κ_p and κ_i . The optimum values of the parameters κ_p and κ_i , which minimize an array of different performance indices are easily and accurately computed using the Hooke-Jeeve's optimization technique.

VIII. PERFORMANCE INDICES

The design of a control system is an attempt to meet a set of specifications, which define the overall performance of the system in terms of certain measurable quantities. A number of dynamic performance measures i.e. peak overshoot (Po), rise time (t_r), peak time (t_p), settling time (t_s) and steady state error (e_{ss}), have been introduced for step and higher order inputs. These measures have to be satisfied simultaneously in design and hence the design necessarily becomes a trial and error procedure. If, however, a single performance index could be established on the basis of which one may describe the appropriateness of the system response, then the design procedure will become logical and straightforward [8,9]. Therefore performance index is a function of the variable system parameters. The other desirable features of a performance index are its sensitivity, i.e. its ability to clearly distinguish between an optimum and non-optimum system, its sensitivity to parameter variations and the ease of its analytical computation or its on-line analogical or digital determination [9].

The following performance indices in this study considered here [8,9] to measure the appropriateness of the system, are of the form,

a) Integrated Square of the error. It is defined as,

$$ISE = \int_0^{\infty} ((\Delta P_{tie})^2 + \alpha(\Delta f_1)^2 + \gamma(\Delta f_2)^2) dt$$

b) Integrated time multiplied by absolute error (ITAE).

It is defined as,

$$ITAE = \int_0^{\infty} t |(\Delta P_{tie}) + \alpha(\Delta f_1) + \gamma(\Delta f_2)| dt$$

c) Integrated absolute error (IAE). It is defined as

$$IAE = \int_0^{\infty} |(\Delta P_{tie}) + \alpha(\Delta f_1) + \gamma(\Delta f_2)| dt$$

Here α and γ are the penalty factors for the frequency deviation in both areas. Both the values equal to 0.065 are considered here [6]. The responses of errors (i.e. ΔP_{tie} , Δf_1 and Δf_2) improve with the accurate values of controller parameters, κ_i and κ_p .

IX. RESULTS AND DISCUSSION

The simulation of proposed dual mode PI controller is carried out using MATLAB[®] SIMULATION TOOLBOX. To simplify the analysis, the two inter connected areas are considered identical. For comparative study between the VSS controller [1] and the proposed controller, the same values of the system parameters [7] are used as given in Table 1. The performance of the controller is investigated considering nonreheat turbines only. The unit step input disturbance reveals useful information about the speed of response of the system. Therefore, a step load change is considered for evaluating the transient performance of the system.

TABLE I INPUT SYSTEM PARAMETERS

$D_1 = D_2 = 8.33 \times 10^{-3} \text{ p.u. Mw/Hz}$ $H_1 = H_2 = 5 \text{ sec};$ $P_r = 2000 \text{ Mw (area rated capacity);}$ $P_{\text{tie max}} = 200 \text{ Mw (tie line capacity);}$ $T_{11} = 2\pi \left(\frac{P_{\text{tie max}}}{P_r} \cos 30^\circ \right);$ $R_1 = R_2 = 2.4 \text{ Hz/p.u. Mw}$ $T_d = T_{d2} = 0.08 \text{ sec}; T_d = T_{d1} = 0.3 \text{ sec};$ $B_1 = B_2 = 0.425;$ $K_H = K_{H2} = 120 \text{ Hz/p.u. M W}$ $T_{PI} = T_{PI2} = 20 \text{ sec}$

The proposed control algorithm or switching scheme (SS) is simulated by using SIMULINK model as shown in Fig.5. The switching scheme given in Fig.5 works by switching between proportional controller and integral controller depending on the specified value, ϵ , of rate of change of the error signal. The optimum values of ϵ , κ_p and κ_i are determined off line. The optimum values of above parameters are determined by considering different performance indices.

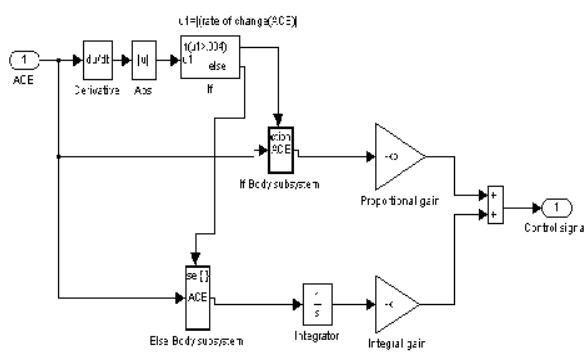


Fig. 5 Dual Mode Switching Scheme Simulated by the help of Simulation Toolbox

A. Nonreheat Turbine

All the data from the Table 1 have been used here Nonreheat turbine is considered first without any physical constraints and then with physical constraints.

1) Nonreheat Turbine without Physical Constraints

In this study, no physical constraints are imposed on the system variables while finding the system response after a load change. Two load changes are considered in area 1 to investigate the performance of the proposed controller

Case 1: A step load disturbance 0.005 p.u. in area 1

Case 2: A step load disturbance 0.01 p.u. in area 1

Case 1 (Load change 0.005 p.u in area 1):

The optimum values of ϵ , κ_p and κ_i for nonreheat turbine without physical constraints at different performance indices are studied and results are shown in Table 2 to Table 4. Table 2 indicates the values of different time response parameters i.e. t_p (peak time), P_o (maximum overshoot) and t_s (settling time) of the response of frequency in area 1 (Δf_1) and optimum values of κ_p and κ_i at different ϵ values when ISE is considered as Performance index. Though the values of peak time and peak overshoot are almost same at different ϵ but settling time

becomes minimum when ϵ is 0.004. The same investigation is carried out where performance indices are ITAE and IAE. The results are shown in Table 3 and Table 4. For both the cases, $\epsilon = 0.004$ is found to give best result as indicated in Table 3 and Table 4. Comparing the three performance indices at $\epsilon = 0.004$, it is observed that ISE gives best dynamic response in respect to overshoot and settling time. The dynamic responses for Δf_1 , Δf_2 , ΔP_{tie} , ΔP_{g1} , ΔP_{g2} and control signal (area 1) at optimum values of $\epsilon=0.004$, $\kappa_p=0.14$ and $\kappa_i=0.65$ are shown in Fig.6.

Case 2 (Load change 0.01 p.u in area 1):

A simulation study similar to case 1 is carried out for a step load disturbance of 0.01 p.u. to test the system performance. The different performance indices are studied and results are shown in Table 5 to Table 7.

It is observed from the tables that $\epsilon = 0.005$ gives the best response. ISE is the best choice as performance index as compared to other two performance indices in respect to overshoot and settling time

TABLE II DIFFERENT VALUES OF TIME RESPONSE PARAMETERS AND OPTIMUM VALUES OF CONTROLLER PARAMETERS AT ISE

ϵ	Peak time (t_p) (Sec.)	Peak overshoot (P_o)	Settling time (t_s) (Sec.)	Optimum value of κ_p	Optimum value of κ_i	Performance Index
0.003	0.55	0.0106522	9.90	0.14	0.73	2.20×10^{-5}
0.004	0.55	0.0106098	9.00	0.14	0.55	2.09×10^{-5}
0.005	0.55	0.0105192	11.65	0.18	0.645	2.11×10^{-5}

TABLE III DIFFERENT VALUES OF TIME RESPONSE PARAMETERS AND OPTIMUM VALUES OF CONTROLLER PARAMETERS AT IAE

ϵ	Peak time (t_p) (Sec.)	Peak overshoot (P_o)	Settling time (t_s) (Sec.)	Optimum value of κ_p	Optimum value of κ_i	Performance Index
0.003	0.55	0.0106522	9.80	0.14	0.77	0.0083
0.004	0.55	0.0106030	9.30	0.14	0.70	0.0082
0.005	0.55	0.0105190	11.65	0.18	0.64	0.0082

TABLE IV DIFFERENT VALUES OF TIME RESPONSE PARAMETERS AND OPTIMUM VALUES OF CONTROLLER PARAMETERS AT ITAE.

ϵ	Peak time (t_p) (Sec.)	Peak overshoot (P_o)	Settling time (t_s) (Sec.)	Optimum value of κ_p	Optimum value of κ_i	Performance Index
0.003	0.60	0.010775	9.80	0.103	0.7225	0.0162
0.004	0.55	0.010693	9.30	0.125	0.6575	0.0164
0.005	0.60	0.010587	11.55	0.103	0.6094	0.0179

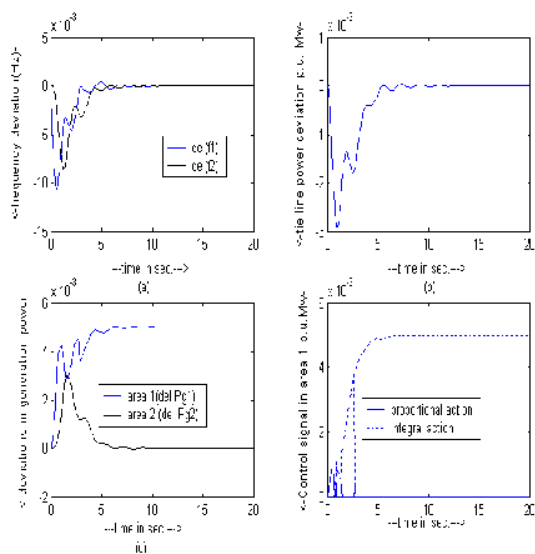


Fig. 6 Dynamic Response for Nonreheat Turbine at Load Change 0.005 p.u. in Area 1 Frequency Deviations area 1 and area 2 (b) Tie line Power Deviation (c) Deviations of Generated Power area 1 and area 2 (d) Control Signal(area 1)

TABLE V DIFFERENT VALUES OF TIME RESPONSE PARAMETERS AND OPTIMUM VALUES OF CONTROLLER PARAMETERS AT ISE

ϵ	Peak time(t_p) (Sec.)	Peak overshoot (Po)	Settling time(t_s) (Sec.)	Optimum value of κ_p	Optimum value of κ_i	Performance Index
0.004	0.60	0.0216998	9.55	0.08	0.62	1.14×10^{-4}
0.005	0.55	0.0208191	9.30	0.22	0.80	8.80×10^{-5}
0.006	0.55	0.0213045	9.90	0.14	0.73	9.20×10^{-5}

TABLE VI DIFFERENT VALUES OF TIME RESPONSE PARAMETERS AND OPTIMUM VALUES OF CONTROLLER PARAMETERS AT IAE

ϵ	Peak time(t_p) (Sec.)	Peak overshoot (Po)	Settling time(t_s) (Sec.)	Optimum value of κ_p	Optimum value of κ_i	Performance Index
0.004	0.60	0.0218251	10.55	0.675	0.6125	0.0209
0.005	0.55	0.0210612	6.15	0.18	0.8000	0.0164
0.006	0.55	0.0213045	9.90	0.14	0.7300	0.0170

TABLE VII DIFFERENT VALUES OF TIME RESPONSE PARAMETERS AND OPTIMUM VALUES OF CONTROLLER PARAMETERS AT ITAE

ϵ	Peak time(t_p) (Sec.)	Peak overshoot (Po)	Settling time(t_s) (Sec.)	Optimum value of κ_p	Optimum value of κ_i	Performance Index
0.004	0.6	0.02172870	9.55 sec.	0.103	0.7225	0.0522
0.005	0.6	0.02220387	6.55 sec.	0.125	0.6575	0.0366
0.006	0.6	0.02155003	9.10 sec.	0.100	0.6094	0.0323

Fig. 7 shows the dynamic responses of Δf_1 , Δf_2 , ΔP_{tie} , ΔP_{g1} , ΔP_{g2} and control signal (area 1) at optimum values of $\epsilon = 0.005$, $\kappa_p = 0.22$ and $\kappa_i = 0.8$.

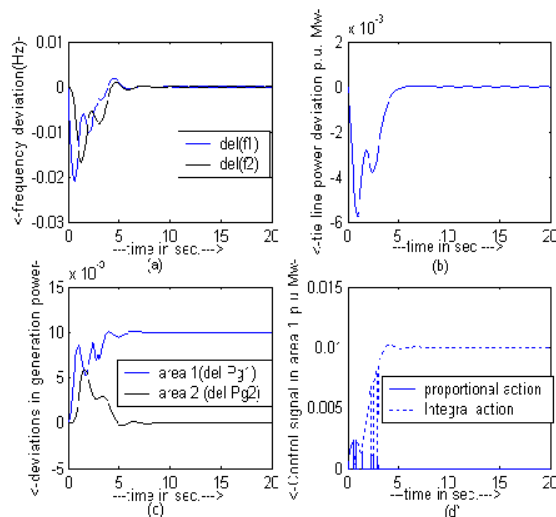


Fig.7 Dynamic Response for nonreheat Turbine at Load change 0.01 p.u. in Area 1 (a)Frequency Deviations area 1 and area 2 (b) Tie Line Power Deviation (c) Deviations of Generated power area 1 and area 2 (d) Control Signal (area 1)

2) Nonreheat turbine with GRC

In the presence of Generation rate constraint, (10% per minute is considered) a step load change of 0.005 p.u. in area 1 is assumed. The optimum values of ϵ , κ_p and κ_i for the nonreheat turbine with GRC at different performance indices are studied. The optimum values of $\epsilon = 0.004$ is found best and ISE gives better dynamic response as compared to IAE and ITAE. Table 8 shows the dynamic response parameters of frequency deviation in area 1 and optimal value of κ_p and κ_i at ISE. Fig.8 shows the dynamic responses (Δf_1 , Δf_2 , ΔP_{tie} , ΔP_{g1} and ΔP_{g2}) and control signal with GRC for a step load change 0.005 p.u. in the area 1 with $\epsilon = 0.004$, $\kappa_p = 0.24$ and $\kappa_i = 0.8$.

TABLE VIII DIFFERENT VALUES OF TIME RESPONSE PARAMETERS AND OPTIMUM VALUES OF CONTROLLER PARAMETERS AT ISE

ϵ	Peak time(t_p) (Sec.)	Peak overshoot (Po)	Settling time(t_s) (Sec.)	Optimum value of κ_p	Optimum value of κ_i	Performance Index
0.003	0.6	0.0110454	10.0	0.26	0.80	2.40×10^{-5}
0.004	0.6	0.0110437	9.0	0.24	0.80	2.22×10^{-5}
0.005	0.6	0.0110525	14.0	0.23	0.80	2.30×10^{-5}

Table 9 compares the results obtained from the proposed controller and the same of Variable Structure Scheme (VSS) controller reported in reference [3]. It can be observed that great improvements in system performance have been obtained by using the proposed dual mode control scheme.

TABLE IX COMPARISON OF PERFORMANCE FOR THE CASE OF NONREHEAT TURBINE WITH GENERATION RATE CONSTRAINT WITH VSS

	Δf_1		Δf_2	
	Settling time (sec)	Max. deviation (Hz)	Settling time (sec.)	Max. deviation (Hz)
Variable Structure Scheme(VSS)	16.00	-0.0140 +0.0080	14.50	-0.0190 +0.0060
Dual mode controller	5.00	-0.0110 +0.0001	12.00	-0.0090 +0.0001

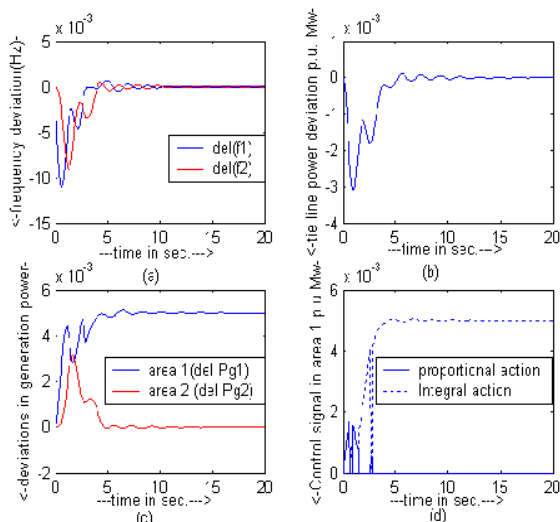


Fig. 8 Dynamic Response for Nonreheat Turbine with GRC at Load Change 0.005 p.u. area 1. (a) Frequency Deviations area 1 and area 2 (b) Tie line Power Deviation (c) Deviations of Generated Power area 1 and area 2 (d) Control Signal (area 1)

3) Nonreheat turbine with GRC and Governor Deadband

Similar simulation studies have been performed at nonreheat turbine with GRC and Governor Deadband. Governor Deadband is considered to avoid excessive operation of the Governor. The limiting value of governor deadband is specified as $\pm 0.06\%$. Table 10 shows the time response parameters of frequency deviation in area 1 (Δf_1) for a load change 0.005 p.u. when ISE is considered as performance index and dynamic responses are shown in Fig.9.

By comparing the values of overshoot and settling time in Table 2, Table 8 and Table 10, it can be observed that the responses are deteriorating with the increase in the number of physical constraints. It is obvious because GRC and governor deadband are restricting the magnitude of input signal when the input violates the limit of GRC and deadband. As a result, the output of the signal from controller does not correspond to the actual input signal. The same observation can be drawn from the graphical representation in Fig.6, Fig.8 and Fig.9.

TABLE X DIFFERENT VALUES OF TIME RESPONSE PARAMETERS AND OPTIMUM VALUES OF CONTROLLER PARAMETERS AT ISE

ε	Peak time(t) (Sec.)	Peak overshoot (Po)	Settling time(t) (Sec.)	Optimum value of K_p K_i	Performance Index
0.003	0.65	0.0118825	12.00	0.08 0.78	3.2×10^{-1}
0.004	0.65	0.0115448	10.45	0.26 0.80	2.5×10^{-1}
0.005	0.65	0.0115421	13.00	0.30 0.80	2.7×10^{-1}

X. CONCLUSIONS

A control algorithm based on the dual mode concept has been investigated for Load frequency control of interconnected power systems. By properly selecting the control parameters of the Dual mode controller, the frequency deviations and the tie

line power can effectively be controlled in the presence of generation rate constraint and Governor deadband. Hooke-Jeeve's method is used for optimizing the control parameters. The proposed control concept gives better response in comparison to Variable Structure System (VSS). Moreover, VSS controller requires knowledge of all the state variables and thus practical realization of the controllers is more involved and expensive, requiring state estimators and inter area data transfer over long distances. Whereas, the proposed control algorithm is very simple in structure and easy to implement, as it requires only one variable i.e. rate of change of the area control error which is already available in the system.

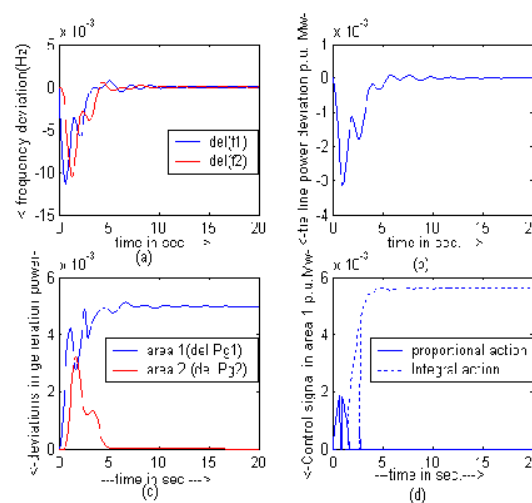


Fig. 9 Dynamic Response for Nonreheat turbine with GRC and Governor Deadband at Load Change 0.005 p.u. in Area 1 (a) Frequency Deviations area 1 and area 2 (b) Tie Line Power Deviation (c) Deviations of Generated Power Area 1 and Area 2 (d) Control Signal (area 1)

XI. APPENDIX

- ΔP_{gi} = incremental generation change,
- ΔX_{Ei} = incremental governor valve position change
- ΔP_{Di} = incremental load demand change
- Δf_i = incremental frequency deviation
- ΔP_{tiei} = incremental change in tie-line power
- ΔP_{Ci} = incremental change in speed changer position
- f = nominal system frequency
- H_i = inertia constant
- D_i = load frequency constant

$$(K_{pi} = \frac{1}{D_i}, T_{pi} = \frac{2H_i}{fD_i})$$

- T_{ij}^0 = synchronizing coefficient
- R_i = speed regulation parameter
- T_{gi} = governor time-constant
- T_{ti} = turbine time constant
- K_{ri}, T_{ri} = reheat coefficient and reheat time constant
- T_{pi} = Power System time constant

The area control error (ACE) for the i^{th} area is defined as

$$ACE_i = \Delta P_{tiei} + B_i \Delta f_i \quad (A.1)$$

Where, B_i is the frequency bias constant. The conventional automatic generation controller has a linear integral control strategy of the form

$$\Delta P_{ci} = -K_{Ii} \int (\Delta P_{tie-i} + B_i \Delta f_i) dt \quad (A.2)$$

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REFERENCES

- [1] Wah-Chun Chan and Yuan-Yih Hsu. "Automatic generation control of interconnected power systems using variable-structure controllers", IEE Proceedings Vol. 128 ,Pt.C,No.5,September 1981,pp.269-279.
- [2] Ashok Kumar, O.P.Malik and Prof. G.S.Hope. "Variable-structure-system control applied to AGC of an interconnected power system", IEE Proceedings, Vol. 132 ,Pt.C,No.1,Jan 1985,pp.23-29.
- [3] D.Das, M.L.Kothari, Prof D.P.Kothari and J.Nanda. "Variable structure control strategy to automatic generation control of interconnected reheat thermal system", IEE Proceedings-D, Vol. 138, No.6 November 1991, pp.579-585.
- [4] J.Nanda and B.L.Kaul, "Automatic Generation Control of an interconnected power system," *Proc.IEE*, vol. 125, No.5, pp.385-390.
- [5] N.N.Benjamin and W.C.chan, "Variable Structure Control of Electric Power Generation," *IEEE Transactions on power Apparatus and Systems*, Vol. PAS-101, No2, 1982, pp.376-380.
- [6] O.P.Malik, Ashok Kumar and G.S.Hope, "A Load Frequency control algorithm based on a generalized approach," *IEEE Transactions on power systems*, vol. 3, No.1, May 1988
- [7] Y.L.Abdel-Magid and M.M.Dawood, "Genetic algorithm applications in Load frequency control", *Genetic Algorithms in Engineering Systems: Innovations and Applications*, 12-14th September 1995, conference publication, No.414, IEE 1995.
- [8] I.J.Nagrath and M.Gopal, "Control System Engineering", 1999, New Age International Publisher, pp-215-219.
- [9] Eronini Umez, "System Dynamics and Control", Thomson Asia Pte Ltd. 1999.
- [10] A.J.wood and Woolenberg, "Power System generation, operation and control", 1998 Jhon Wiley, New York.
- [11] Kalyanmoy Deb, "Optimisation for engineering design", Prentise Hall of India, New Delhi, 1998
- [12] O.E.Elegerd, "Electric Energy Systems Theory", second edition, New York: McGrawHill, Inc. 1982, pp 315-389
- [13] IEEE Committee Report, "Dynamic models for steam and hydro turbines in power system studies," *IEEE Transactions on power Apparatus and Systems*, Vol.92, No.6, 1973, pp.1904-1915.
- [14] Kundur. P, "Power System Stability and Control", McGraw Hill, New York, 1994.
- [15] "Dynamic Models for steam and Hydro Turbines in Power system studies", IEEE committee report. Transactions in Power Apparatus & Systems Vol.92, No.6, Nov./Dec. 1973, pp.1904-915.
- [16] Chatterjee, Kalyan (2010) "Design of Dual Mode PI Controller for Load Frequency Control," *International Journal of Emerging Electric Power Systems*: Vol. 11 : Iss. 4, Article 3.



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