International Journal of Engineering Research
Volume No.4, Issue No.9, pp : 492-497

ISSN:2319-6890)(online),2347-5013(print)
01 Sept. 2015

Modeling of Hydro-Thermal Interconnected System with Conventional and Novel Controller

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Abstract : ***For interconnection of two or more areas in power system, frequency should be maintained within the scheduled value, which can be achieved by employing one of the most prominent techniques called as Automatic Load Frequency Control (ALFC). In ALFC, the frequency can be controlled in three ways, namely Flat frequency regulation, Parallel frequency regulation and Flat tie-line loading. Among these controls, Parallel frequency regulation is commonly used method, because constant frequency can be maintained by equalizing the power generation with the power demand. The main aim is to reduce the oscillations or damping in the frequency and also the changes in tie-line power. In this paper, PI and PID controllers are used to improve both frequency and tie-line power responses for multi-area interconnected power system (which consists of Hydro-thermal generating system) and is developed based on the model predictive control. This paper presents a solution procedure to Load Frequency Control (LFC) of interconnected Hydro-Thermal system with a novel controller (PSO (Particle Swarm Optimization)).***

Keywords**: Automatic Load Frequency Control, Conventional Controllers, PSO technique, Area Control Error (ACE).**

I. INTRODUCTION

Generally, power system consists of three parameters which shall be within the limits for successful operation i.e. Frequency, Voltage and Load angle**,** among these frequency parameter plays vital role [2]. Many different power frequencies were used in the 19th century. Very early isolated ac generating schemes used arbitrary frequencies based on convenience for steam engine, water turbine and electrical generator design. Frequencies between 16⅔ Hz and 133⅓ Hz were used on different systems. The main purpose of a power engineer is to provide power to the consumers reliably and economically with a better quality [4-5]. The frequency and tie-line power should be kept within the limits by equalizing the power generation at the generating end and the power consumption at the load end, because there are two points available throughout the power system for keeping the frequency within the limits, one is at the generating end and the other is at the load end. Load frequency control problem arises when individual generation areas are interconnected by transmission lines called as tie-lines.

The large-scale power systems are liable to performance deterioration due to the presence of sudden small load perturbations [1], parameter uncertainties, structural variations, etc. Due to this, modern control aspects are extremely important in Load Frequency Control (LFC) design of power systems [3]. The main objectives of Load frequency control are i) to maintain constant frequency throughout the system, ii) to preserve the tie-line power at a scheduled level irrespective of load changes in any area, iii) to diminish Area Control Error (ACE) and iv) to minimize Peak time, Peak overshoot and Settling time. When interconnecting two or more areas/regions for providing continuous supply, the complexity of the system increases. Due to the increased complexity of modern power systems, advanced control methods were proposed in ALFC, e.g., Fuzzy logic controller, evolutionary based techniques, decentralized optimal control, pole placement technique, APSO (Accelerated Particle Swarm Optimization) and Quasi Decentralized Functional Observer (QDFOs) [14]. The most important features of two utility interconnected multi-area thermal system is that a) to buy or sell power with neighboring systems, b) to meet sudden requirement of power demand, c) to reduce the installed capacity, d) to possess higher reliability with better quality of supply. The Modeling and the simulation of two area Hydro-thermal interconnected power systems [6] are realized in MATLAB Software.

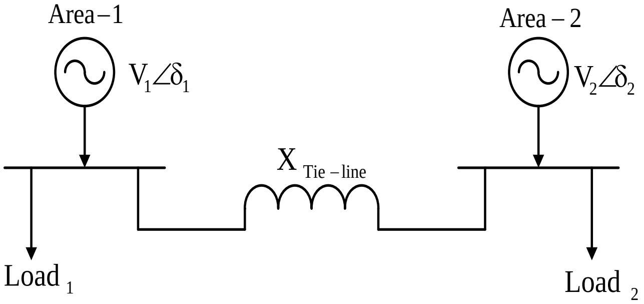


Fig.1 Two interconnected control areas

This paper is organised as follows, section-I explains about the introduction of Load frequency control and how the situation exist in early years of electricity generation. Section-II briefly describes about the system. Section-III illustrates about different control strategies such as conventional controllers, PSO technique. Section-IV describes about mathematical modeling of each and every part of single area load frequency controller with I, PI and PID controller. Section –V gives you about two area hydro-thermal interconnected system using the specified controllers in section-III, and Section-VI shows you the results with comparison of important specifications such as Peak overshoot, settling time, steady state error, etc. of frequency of each area and tie-line power.

II. SYSTEM INVESTIGATED

The LFC of interconnected system consists of two generating areas of equal size; area-1 includes electrical governor hydro system and area-2 make up a reheat thermal system. Fig.3 shows the LFC model of single area thermal system with integral controller and fig.4 shows the ALFC model with electrical governor in hydro area and single stage reheat turbine in thermal area. A frequency bias setting β_i is considered in both hydro and thermal areas. MATLAB/SIMULINK has been used, to obtain dynamic responses for Δf_1 , Δf_2 and $\Delta P_{tie-line}$ for 1% step load perturbation in either area. In the literature, the performance of the electrical governor was found quite superior than the mechanical governor [6]; so that in this paper i included electrical governor only in hydro area. The optimal values of derivative, proportional and integral gains for the electrical governor, speed regulation droops i.e. R_1, R_2, synchronizing coefficient T_{12}, time constant and gains of hydro, thermal turbine and power system have been taken from the work of paper [15].

III. SYSTEM OPTIMIZATION USING PSO

A proportional-integral-derivative controller is a control loop feedback mechanism widely used in industrial control systems. It calculates an error value as the difference between a measured process variable and a desired set point. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point, and the degree of system oscillation.

PSO is an optimization technique which provides an evolutionary based search. This search algorithm was introduced by Dr. Russ Eberhart and Dr. James Kennedy in 1995. It was inspired by the social behavior of bird flocking and fish schooling. The basic concept of this technique that the change in the velocity of each particle towards its P_{best} and g_{best} positions at each step. This means that each particle is try to modify its current position and velocity according to the distance between its current position & P_{best} and the distance between its current position & g_{best}.

The parameters of controller in both the areas have been optimized using integral square error (ISE) technique. The objective function for this technique, to minimize frequency deviations in area-1 & 2 and tie-line power deviations, used is

$$J = \int_0^{t_{sim}} \left[(\Delta f_1)^2 + (\Delta f_2)^2 + (\Delta P_{tie-line})^2\right] dt \qquad (1)$$

Subjected to,

$$K_{i1(min)} < K_{i1} < K_{i1(max)}$$

Where, Δf_1 , Δf_2 and $\Delta P_{tie-line}$ are the incremental changes in frequency of area-1, area-2 and the incremental changes in tie-line power respectively.

PSO allows us to intelligently search the solution space for a global best solution. In contrast to an exhaustive search, PSO significantly reduces the time to optimize response. It was originally developed by biologists to be able to mathematically describe the swarming of birds.

The basic PSO algorithm is composed of two mathematical steps namely i) intelligently update the velocity of the particle and ii) update the position of the particles based on their velocity. The velocity of each particle is update according to the following equation,

$$v_{i+1}^k = wv_i^k + cr_1^k(p_i^k - x_i^k) + sr_2^k(p_g^k - x_i^k) \qquad (2)$$

Where, x_i^k is the position of i^{th} particle at k^{th} iteration

v_i^k is the velocity of i^{th} particle at k^{th} iteration

p_i is the best solution observed by i^{th} particle

p_g is the best solution observed by any particle

w is the inertia coefficient

c is the cognitive coefficient

s is the social coefficient

r is the randomness factor

In the above equation, the first term refers to inertia coefficient which controls how quickly a particle will change direction, the second one represents cognitive coefficient which controls the tendency of a particle to move towards the best solution observed by that particle and the last term expresses about social coefficient which controls the tendency of a particle to move towards the best solution observed by any of the particles.

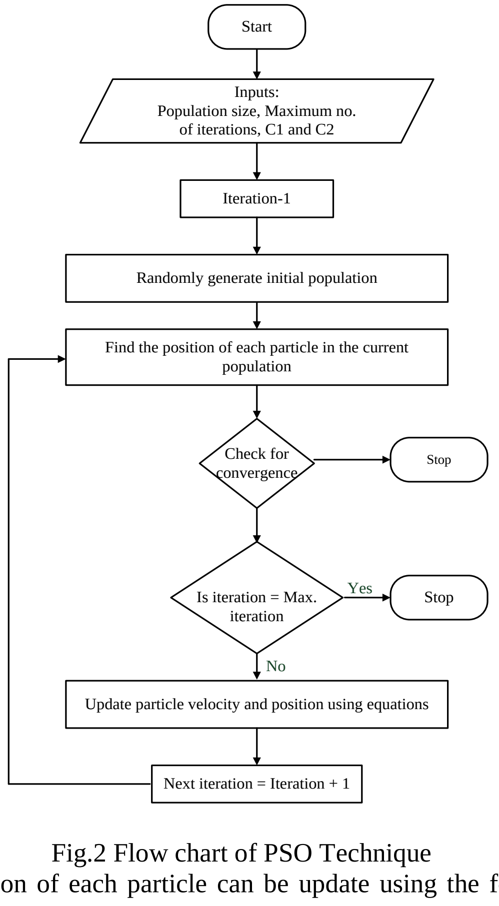


Fig.2 Flow chart of PSO Technique

The position of each particle can be update using the following equation

$$x_i^{k+1} = x_i^k + \chi v_i^{k+1} \qquad (3)$$

Where χ is called as constriction term which is used to tighten up the group towards the end of optimization.

IV. MODEL OF SINGLE AREA LOAD FREQUENCY CONTROL

The system modeling will be developed briefly by considering two assumptions. The first is that the incremental changes in power demand is neglected, the second is that control of real power and frequency, and control of reactive power and voltage, are decoupled and can be considered separately.

A. Speed Governing System:

$$\Delta X_E(S) = f\{\Delta f(S), \Delta P_C(S)\} \tag{4}$$

Calculation of $\Delta X_E(S)$:

$$\Delta X_E(S) = \frac{K_G}{1+ST_G}\left[\Delta P_C(S) - \frac{\Delta F(S)}{R}\right] \tag{5}$$

Where,

Static gain of the governor, $K_G = \frac{K_2 K_3}{K_4}$

Time constant of governor, $T_G = \frac{1}{K_4 K_5}$ and

Regulation of speed governor or droop value, $R = \frac{K_2}{K_1}$

B. Turbine Model:

There are two types steam turbines namely reheat turbine and without reheat turbine.

Rating of high pressure turbine stage is α p.u. say

Both the ratings of intermediate and low pressure turbine stages are $1-\alpha$ p.u.

$\Delta P_V(S)$ is Turbine input

$\Delta P_T(S)$ is Turbine output

Total transfer function of turbine

$$\begin{aligned}\Delta P_T(S) &= \Delta P_{T,HP}(S) + \Delta P_{T,IP,LP}(S)\\ &= \frac{K_T}{1+ST_T}\frac{1+\alpha ST_R}{1+ST_R}\Delta P_V(S)\end{aligned} \tag{6}$$

Where T_R is reheating time constant,
K_T is static gain of turbine,
T_T is turbine time constant

C. Generator model:

Net accelerating torque,

$$\begin{aligned}T_{net} \text{ or } T_a &= T_{mech} - T_{elec.}\\ &= I \times \alpha\end{aligned} \tag{7}$$

Angular momentum of machine, $M = \omega \times I$ (8)

Where, T_{mech} is mechanical input torque in N-m
T_{elec} is electrical output torque in N-m
I is inertia constant or moment of inertia of machine
α is angular acceleration in rad/sec^2
ω is angular speed in rad/secs

$$\Delta P_{mech}(S) - \Delta P_{elec}(S) = MS\Delta\omega(S) \tag{9}$$

D. Model of load:

Change in frequency dependent load, $\Delta P_{Lf} = D \times \Delta\omega$

$D = \frac{\Delta P_{Lf}}{\Delta f}$ MW/Hz or (p.u. MW)/(p.u. Hz)

$$\Delta\omega(S) = \frac{1}{MS}\left[\Delta P_{mech}(S) - \Delta P_L(S) - D\Delta\omega(S)\right] \tag{10}$$

Where D is the damping constant

E. Combined model of Generator and load:

$$G_P(S) = \frac{1}{MS+D} = \frac{K_P}{1+ST_P} \tag{11}$$

Where K_P is power system gain =1/D
T_P is power system time constant in secs =M/D

$$\Delta P_C = -\int K_i \Delta f(t)dt \qquad \Delta P_C(S) = -\frac{K_i}{S}\Delta F(S) \tag{12}$$

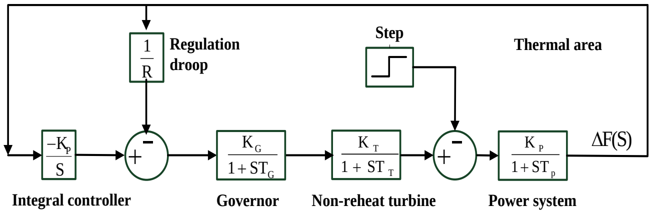


Fig.3 MATLAB/SIMULINK model of Single area thermal system with integral controller

There are two loops in the ALFC namely primary and secondary loops. Primary loop comprises model of Fly ball speed governor, Non–reheat turbine and combined model of generator and load called as power system. Power system consists of both frequency dependent and independent loads, in this paper frequency dependent load only included. After modeling the primary ALFC loop there is always some error present in the output at the steady state.

This error could be eliminated by introducing proportional and integral controller then the overall model can be called as secondary ALFC loop. This error can be reduced with ease using conventional controllers. For single area ALFC, with PID controller the response of frequency could be settled in less time when compared to I and PI controllers.

V. TWO AREA AUTOMATIC LOAD FREQUENCY CONTROL

The frequency should be constant whenever you interconnect two or more areas in AC power systems. For operating these areas simultaneously the variations in the tie-line power should be kept within limits. Care should be taken while designing Tie-line, since it has the capability of carrying over power demand by the neighboring areas. The modeling equations of tie-line power as follows:

Model of Tie-line:

Power flow from area1 to area2 without disturbance

$$P_{12}^0 = \frac{V_1 V_2}{X_{12}}\sin(\delta_1^0 - \delta_2^0) \tag{13}$$

Net power flow from area1 to area2 due to disturbance

$$P_{12} = \frac{V_1 V_2}{X_{12}}\left[\sin(\delta_1^0 - \delta_2^0)\right] + \frac{V_1 V_2}{X_{12}}\left[\cos(\delta_1^0 - \delta_2^0)(\Delta\delta_1 - \Delta\delta_2)\right]$$

$$\Delta P_{12} = T_{12}(\Delta\delta_1 - \Delta\delta_2) \tag{14}$$

Where,

T_{12} is known as synchronizing coefficient $T_{12} = \frac{V_1V_2}{X_{12}}\cos(\delta_1^0 - \delta_2^0)$

(15)

By taking Laplace transform,

$$\Delta P_{12}(S) = \frac{2\pi T_{12}}{S}\left[\Delta F_1(S) - \Delta F_2(S)\right] \qquad (16)$$

The MATLAB/SIMULINK model of two area interconnected Hydro- thermal power system is shown in Fig.6. In this the input to the controller is the sum of tie-line power and the product frequency bias parameter β and change in frequency Δf. i.e.

$$ACE_1 = \Delta P_{12} + \beta_1 \Delta f_1 \qquad (17)$$

$$ACE_2 = -\Delta P_{12} + \beta_2 \Delta f_2 \qquad (18)$$

Where β_1 and β_2 are frequency bias constants of area-1 & 2 respectively and ΔP_{12} is the change in tie-line power between the two areas.

The speed of generator and thus frequency of the overall system with respect to changes in the demand could be achieved by choosing optimum values of frequency bias, regulation droop and the gains of particular controller. In this way the active power generation can be matched with the power demand consumed by the load.

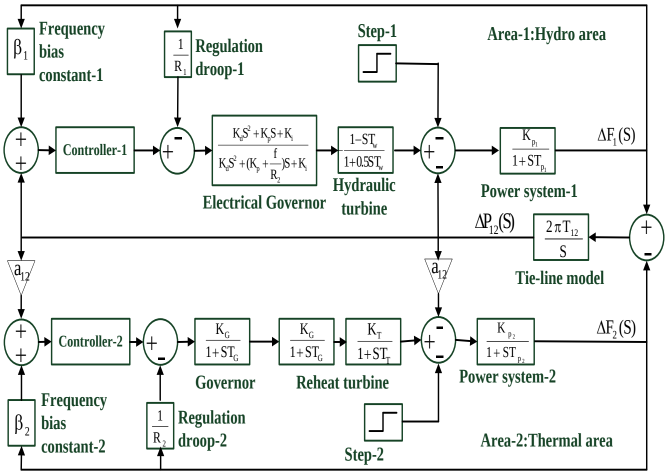


Fig.4 MATLAB/SIMULINK model of two area hydro-thermal interconnected system

As the number of interconnecting areas increases the complexity of the system will increases, so it is difficult to control the system with conventional controllers for the corresponding changes in the load demand. The power system researchers are going to adopt more and more optimization techniques to control the valve input to the turbine as fast as possible.

VI. RESULT AND ANALYSIS

The results of single and two area interconnected hydro-thermal power systems are clearly analyzed in the following: Here the time taken to reach steady state value is in the order of seconds, because in thermal and hydro power systems consists mechanical equipments which has more time constants when compared with the electrical devices.

The conventional integral controller gains for the hydro area and thermal area are found to be K_{I1}=-1.2 and K_{I2}=-0.5 respectively. Using conventional PI controller, optimum gains K_{P1}=-0.01, K_{I1}=-0.6 for hydro area and K_{P2}=-0.1, K_{I2}=-0.5 for thermal area. The optimum value of integral controller gains for the hydro area and thermal area are K_{I1}=-0.84 and K_{I2}=-0.98 respectively, using ISE technique.

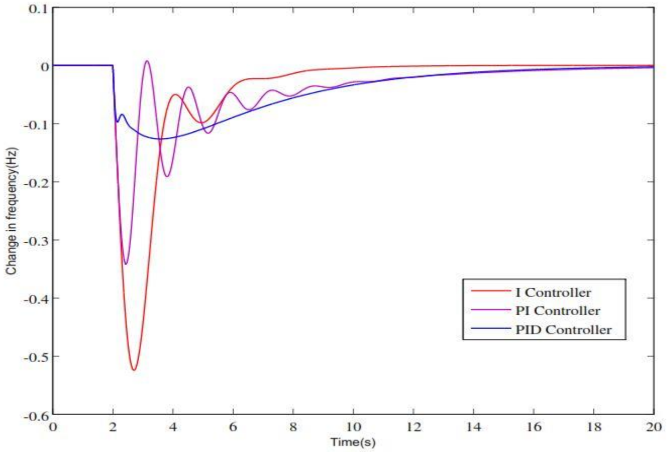
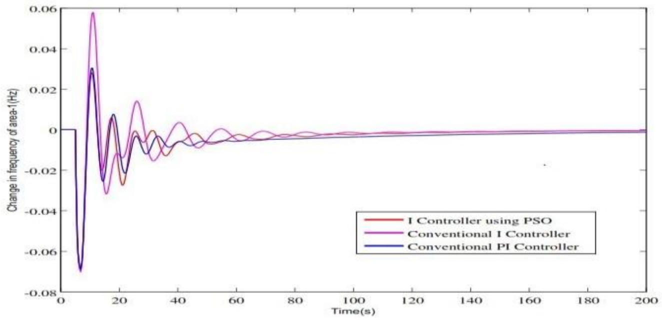


Fig.5 Comparison of I, PI and PID controller response of single area non-reheat thermal area

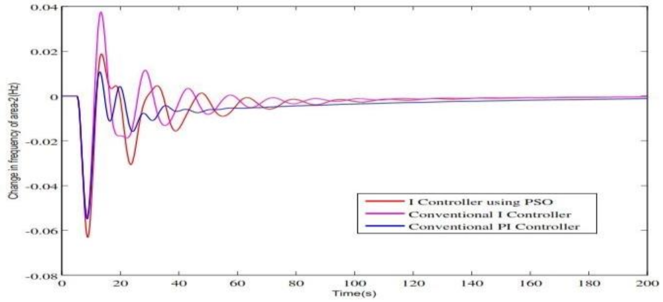
The steady state error and time response specifications such as peak overshoot, peak time and settling time are improved and are clearly shown in Fig.5. The comparison among these parameters in quantitatively has shown in table.1 with I, PI and PID controllers. By investigating these controllers the peak overshoot is reduces from 0.52 to 0.09. Here the Settling time (the time taken by the response to reach steady state value), was considered for 2% tolerance band, is less for integral controller then for PI controller and more for PID controller. The variation in the delay, rise and peak times of these controllers are quite similar.

The responses of Δf_1, Δf_2 and $\Delta P_{tie-line}$ for Step change in demand of 1% is applied at t=5s in hydro area shown in fig.6(a)-(c) and fig.7(a)-(c) shows the responses of Δf_1, Δf_2 and $\Delta P_{tie-line}$ for same Step load perturbation in thermal area. Examining these responses, it is clearly seen that the incremental changes in tie-line power is settling around 40s with PSO optimized I controller and around 90s for both I and PI controller when 1% SLP in hydro area. And better system performance in terms of minimum settling times in frequency and tie-line power deviations has achieved with PSO optimized I controller compared to conventional I and PI controllers.

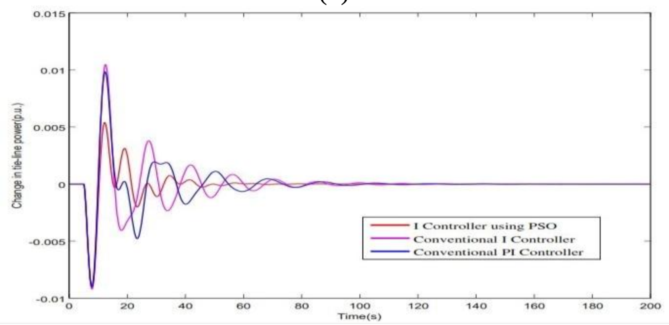
The peak overshoot and settling time are less in PSO optimized I controller and more in the conventional I controller for changes in the load in both hydro and thermal areas.



(a)



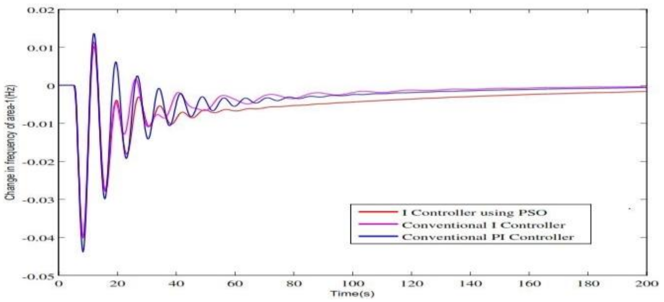
(b)



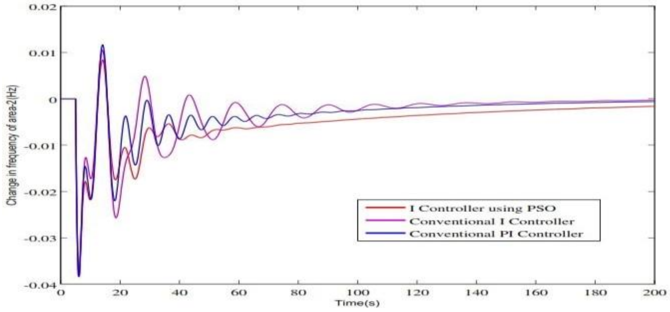
(c)

Fig.6 Comparison of integral, PI and I controller using PSO responses with 1% SLP in hydro area, (a) Δf_1 , (b) Δf_2 and (c) $\Delta P_{tie-lie}$

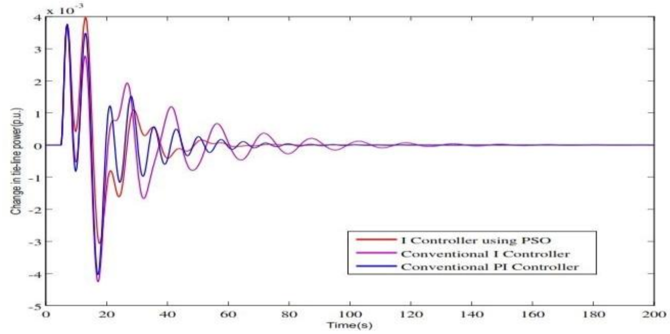
Hence, it can be concluded that the optimized control strategy, PSO optimized I controller, provides a better control under wide variations in the loading condition of the system.



(a)



(b)



(c)

Fig.7 Comparison of integral, PI and I controller using PSO responses with 1% SLP in thermal area, (a) Δf_1 , (b) Δf_2 and (c) $\Delta P_{tie-lie}$

Table.1 Comparison of time response specifications of frequency for single area ALFC

S.no.	Parameters	Change in frequency (I)	Change in frequency (PI)	Change in frequency (PID)
1	Peak overshoot	52%	32.5 %	9%
2	Settling time	10 S	18 S	19 S
3	Delay time	2.2 S	2.2 S	2.2 S
4	Rise time	2.4 S	2.3 S	2.25 S
5	Peak time	2.8 S	2.5 S	2.3 S

CONCLUSION

In electricity power industry, there is an ongoing need for efficient and effective LFC techniques to counter the ever-increasing complexity of large-scale power systems and robustness against parameter uncertainties as well as plant/model mismatch and external load change. In this paper, a single area thermal power system is considered at the first instance with conventional controllers, out of these the PID controller provides superior results compared to I and PI controllers. And a widely used two-area hydro thermal system problems with I, PI and PSO optimized I controller are presented. Among these, with PSO has got the best dynamic response of frequency and tie-line powers. Future work may be carried out by including the study of the effect of changes in loading and system parameters with these controllers in the interconnected multi (Hydro-thermal-PV) area Automatic Load Frequency controls.

APPENDIX

Nominal parameters of Interconnected Hydro-thermal system investigated:

$$f = 60\text{Hz} \quad R_1 = R_2 = 2.4\text{Hz}/\text{p.u.MW}$$

$$T_g = 0.08\text{s} \quad P_{\text{tie-line,max}} = 200\,\text{MW}$$

$$T_r = 10\text{s} \quad K_r = 0.5 \quad T_t = 0.3\text{s}$$

$$K_d = 4.0 \quad K_p = 1.0 \quad K_i = 5.0$$

$$P_{r1} = P_{r2} = 2000\,\text{MW} \quad T_w = 1.0\text{s}$$

$$\beta_1 = \beta_2 = 8.33 * 10^{-3}\,\text{p.u.MW}/\text{Hz}$$

$$a_{12} = -1 \quad T_{12} = 0.086\,\text{p.u.MW}/\text{rad}$$

$$K_{p1} = K_{p2} = 120\,\text{Hz}/\text{p.u.MW}$$

$$T_{p1} = T_{p2} = 20\text{s}$$

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