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Parallel control structure scheme for load frequency controller design using direct synthesis approach

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ABSTRACT

This paper presents load frequency controller design for a single area as well as the multi-area thermal power system using direct synthesis approach with parallel control structure (PCS) scheme. The set-point and load frequency controller has been designed for frequency regulation and maintains tie-line power within a pre-specified limit for LFC power system. The proposed controller has been implemented for single-area, two-area, and four-area thermal power system for frequency regulation. The proposed method shows impressive simulation results compared with existed control method. The robustness of the proposed method has been examined with the help maximum sensitivity and parametric variation in the nominal power system.

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1. INTRODUCTION

In power system, the frequency and tie-line power exchange deviate from its nominal value due to change in load and other abnormality. In load frequency control (LFC) retain the system frequency and tie-line power exchange between two areas at its nominal (pre-defined) value [1]. Many researchers have studied different design techniques for LFC in an interconnected power to maintain its frequency and tie-line power exchange at its pre-specified value i.e. available in the literature [2, 3].

A lot of research has been done in the LFC system for improvement in frequency deviation as well as tie-line power exchange between others area. Various controller design technique has been implemented for LFC system such as fractional order Proportional-Integral-Derivative (FOPID) [4], Proportional-integral-derivative-acceleration (PIDA) [5, 6], Model predictive control (MPC) [7, 8], Fuzzy logic controller (FLC) [9, 10], internal model control (IMC) [11-14], cascade control [15, 16], sliding mode control (SMC) [17, 18], direct synthesis (DS) approach [19-21], variable structure control [22], active-disturbance-rejection-control (ADRC) [23-24], H∞ control [25], two degree of freedom (2DoF) control [26, 27], coefficient diagram method [28] etc.

Debbarma and Dutta [4] have proposed FOPID controller for LFC power system using flower pollination algorithm to obtain an optimum value of controller gain and the authors also utilize Electric vehicles as a source in frequency regulation of power system. Raju *et al.* [5] presents PID plus double derivative (PID+DD) controller based on ant-lion optimization technique for frequency regulation in multi-area thermal power system and provide improved performance in terms of settling time (t_s), peak value. The authors also applied random step load at a different time in the three-area thermal power system and show better robustness of double derivative controller. Guha *et al.* [6] proposed double derivative PID controller with the application of multiverse optimization technique for frequency regulation in multi-area hydro-thermal power system and also consider generation rate constraint (GRC) and governor dead band (GDB) as non-linearity in the system model. Model predictive control is the modern technique for LFC in the power system. Linear matrix inequality (LMI) scheme is used to obtain MPC controller gain for LFC in three areas thermal power system by Shiroei *et al*. [7]. Ersdal *et al*. [8] has used MPC for frequency regulation in the Nordic power system using Kalman filter estimation technique. Sakia *et al*. [9] have proposed fuzzy logic plus integral double derivative (FIDD) controller for LFC in the three-area power system based on bacterial foraging algorithm. Fuzzy logic along with adaptive MPC technique has been proposed by Kayalvizhi and Kumar [10] for LFC in micro-grid.

Tan [11-13] presents a PID controller via 2DoF-IMC for frequency regulation problem in single-area as well as a multi-area power system. The authors proposed Anti-GRC strategy to minimize the problem associated with the application of generation rate constraint in LFC [11]. Saxena and Hote [14] proposed a robust PID controller via internal model control (IMC) technique for LFC problem in a single area as well as the multi-area power system. Das *et al*. [15] have proposed cascade PD-PID controller for LFC in three-area thermal power system along with GRC using bat-algorithm and its response is superior to PI, PD, PID controller. Das *et al*. [16] proposed cascade PI-PD controller optimized using a flower-pollination algorithm and its performance are improved compared to classical PI, PD, PID controller. It shows that cascade control performance is better than the classical control technique. Sliding mode controller (SMC) has been designed by Vrdoljak *et al*. [17] for LFC in the power system based on state estimation approach and its controller also work in a non-minimum phase system. However, the sliding mode controller requires knowledge of full state feedback using state estimation technique. Mi *et al*. [18] proposed SMC to regulate frequency deviation and tie-line power exchange for the multi-area power system. The authors used Lyapunov stability to confirm the frequency is zero. Chen and Seborg [19] presents PID controller design using DS approach for first and second order system with time delay and its simulation results reveal the better disturbance rejection. Padhan and Majhi [20] present a new PID tuning method for LFC power system and its controller gains are obtained by Laurent series expansion of controller transfer function. Anwar and Pan [21] presents a PID controller for LFC in single as well as multi-area thermal power system using DS method in the frequency domain.

The variable control structure is used to design the Proportional-integral (PI) controller for LFC in the multi-area power system by Ray *et al*. [22]. Fu and Tan [23] present the ADRC technique for LFC in multi-area power system along with the communication delays. The ADRC controller gain is obtained using the IMC approach. Linear active disturbance rejection controller (LADRC) design has been proposed by Tang *et al*. [24] based on the hybrid particle swarm optimization approach for LFC in wind power plant. Peng *et al*. [25] proposed $H\infty$ controller for LFC in the networked-based multi-area power system. Debbarma *et al*. [26] proposed 2DoF-proportional-integral with double derivative (2DoF-PIDD) controller for frequency regulation in the three-area thermal power system and controller parameter is obtained using the firefly algorithm (FA) technique. 2DoF-PID controller has been designed based on teaching learning-based optimization technique to regulate frequency deviation and tie-line power exchange for multi-area power system by Sahu *et al*. [27]. Load frequency controller has been designed by Bernard *et al*. [28] based on Coefficient diagram method (CDM) for two-area as well as three area power system.

The parallel control structure (PCS) is also named as 2DoF control structure has been discussed by Karungaran and Wenjian [29]. Figure 1 shows the generalized form of the PCS which has the ability to tune the controller to get the desired set-point response and load-disturbance response independently. The modified PCS scheme has been used to design a PID controller for an unstable process system with small time delay using DS approach by Ajmeri and Ali [30].

The above literature motivates to design a controller for LFC problem using PCS scheme. The nomenclature used in this paper is elaborated in Appendix A. In this paper, the PCS scheme has been used to design PID load frequency controller for a multi-area thermal power system using DS approach. The major contribution of this paper is as summarized below:

a. The new control structure to design a PID controller for LFC in the thermal power system.
b. The set-point controller and load frequency controller has been designed via pole-placement using direct synthesis approach.
c. Robustness of the controller has been analysed using uncertainty in the system parameter and random load has been applied to the system.
d. The proposed PID controller performance has been compared with existing PID design methods for a single area as well as the multi-area LFC system.

The whole paper is described in five chapters as follows: In chapter 1 described the introduction of the paper. The problem formulation of the multi-area thermal power system is elaborated in chapter 2. Controller design methodology for LFC using DS approach has been discussed in chapter 3. In chapter 4 discussed the simulation results of the different case studied of the power system and at last conclusion of the paper is described in chapter 5.

2. PROBLEM FORMULATION

The parallel control structure (PCS) as shown in Figure 1, which has the nominal model of the plant (M_n) and actual model of the plant (M_a) is considered to design set-point controller (K_{c1}) and load-disturbance controller (K_{c2}) for load frequency control. The controller K_{c1} is used to regulate the set-point response of the system while K_{c2} is used to regulate load-disturbance of the system. The closed-loop response

(Δf) of the PCS is given by $$\Delta f = r\left(\frac{M_a K_{c1}}{1+M_n K_{c1}}\right)\left(\frac{1+M_n K_{c2}}{1+M_a K_{c2}}\right)+\left(\frac{M_a}{1+M_a K_{c2}}\right)d \quad (1)$$

Where r, d, Δf are the reference input, load disturbance and process output (change in frequency deviation) of the system. Under nominal condition ($M_a=M_n$), Δf may be represented as follows:

$$\Delta f = r\left(\frac{M_n K_{c1}}{1+M_n K_{c1}}\right)+\left(\frac{M_n}{1+M_n K_{c2}}\right)d \quad (2)$$

2.1. Single area power system

The PID controller $K_{ci}(s)$ has been used to maintain the load frequency control of the thermal power system, which may be written as

$$K_{ci}(s) = K_{pi} + \frac{K_{ii}}{s} + K_{di}s \text{ (i=1,2)} \quad (3)$$

Where K_{pi}, K_{ii}, K_{di} are the proportional, integral, derivative constants of ith controller, respectively. The linearized model of the single-area thermal power system as shown in Figure 2, which is used to design the controller parameter. The transfer function of the power system model from u to Δf as shown in Figure 1 is

Written as $$M_n = \frac{\Delta f}{u} = \frac{T_g T_t T_p}{1+T_g T_t T_p / R} \quad (4)$$

Where T_g, T_t, T_p are the transfer function of the governor, turbine & generator and load respectively. R is the speed regulation of the governor.

2.2. Multi-area power system

The controller design technique of single-area power system is extended to a multi-area power system. The change in frequency, as well as tie-line power exchange between areas, also varies from its pre-specified value due to load demand fluctuates in a multi-area power system. Area control error (ACE) is the combination of the small change in frequency deviation and tie-line power exchange and that ACE is minimized by using a controller gain parameter. The schematic block diagram of a multi-area power system is shown in Figure 3. The ACE of the i^{th} area may be represented as

$$ACE_i = \Delta p_{tie,i} + \beta_i \Delta f_i \quad (5)$$

Where β_i is the frequency bias factor. The tie-line power exchange ($\Delta p_{tie,i}$) between area i^{th} and other area is given by

$$\Delta p_{tiei} = \sum_{\substack{j=1 \\ j\neq i}}^{N} \Delta p_{tieij} = \frac{1}{s}\left[\sum_{\substack{j=1 \\ j\neq i}}^{N} t_{ij}\Delta f_i - \sum_{\substack{j=1 \\ j\neq i}}^{N} t_{ij}\Delta f_j\right] \quad (6)$$

Where t_{ij} is the synchronizing power coefficient of the multi-area power system. The transfer function model of the multi-area power system can be represented as

$$M_{ni} = \beta_i \frac{T_{gi} T_{ti} T_{pi}}{1+T_{gi} T_{ti} T_{pi} / R_i} \quad (7)$$

The load frequency control in a multi-area power system is as same as single area power system where the tuning of each single area system is independently with consideration in the modified plant model as given in (7).

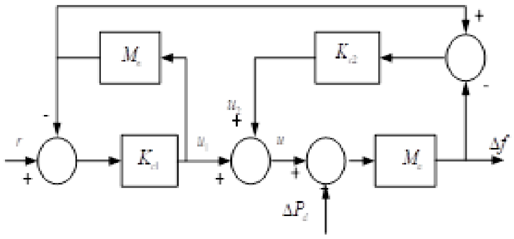

Figure 1. The schematic block diagram of the parallel control structure

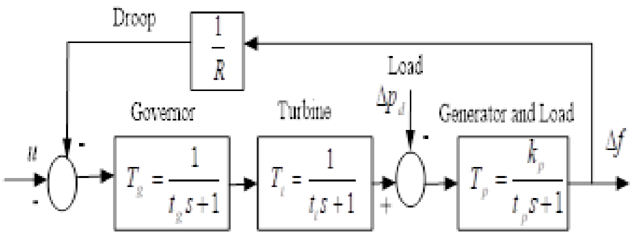

Figure 2. Single-area thermal power system

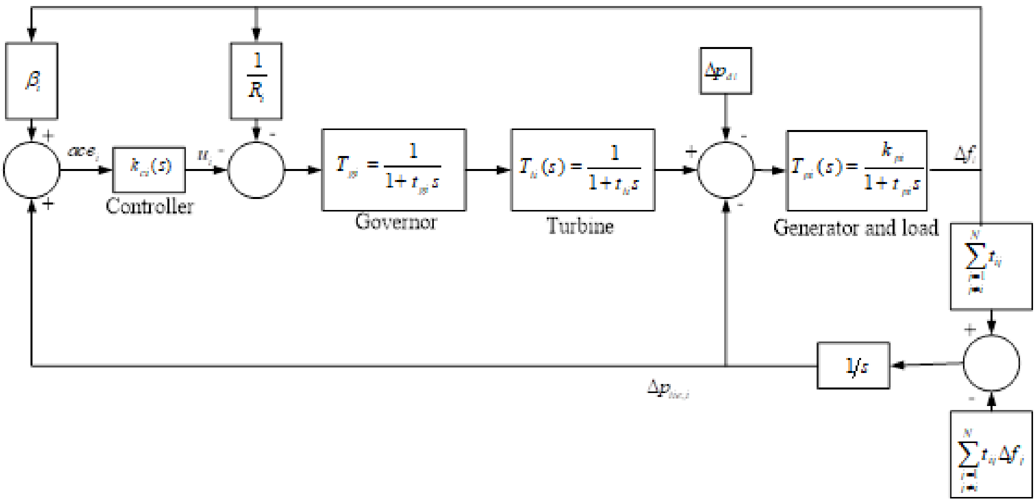

Figure 3. Schematic block diagram of the control area i

3. CONTROLLER DESIGN METHODOLOGY

In this paper, the parallel control structure (PCS) has been used to design PID controller using direct synthesis (DS) approach. The Parallel control structure (PCS) has also known as two degrees of freedom control structure [30] because the set-point controller and load disturbance controller are tuned independently of each other. Figure 1 shows a basic block diagram of the parallel control structure (PCS). In DS approach, a desired transfer function of the system is considered for the closed loop transfer function of the system. By approximating the desired transfer function with closed-loop transfer function of the system, a mathematical expression of the controller is obtained in terms of the desired transfer function and the closed-loop transfer function of the system. In PCS decouples the regulatory (load-disturbance rejection) problem from servomechanism (set-point tracking) problem.

3.1. Set-point tracking controller (K_{c1})

The desired set-point closed-loop transfer function Psp(s) (from r to Δf) of the power system is considered as given by

$$P_{sp}(s) = \frac{1}{(Ts+1)^n}, \tag{8}$$

where T is the time constant of the desired set-point reference model, n is the order of the desired set-point reference model.

From (2), the closed loop set-point transfer function ($P_{r,f}$) from (Δf to r) may be written as

$$P_{r,f} = \frac{K_{c1}M_n}{1+K_{c1}M_n} \tag{9}$$

The closed-loop characteristic equation from (9) may be written as

$$1+K_{c1}M_n = 0 \tag{10}$$

In the direct synthesis (DS) technique, the controller has been designed by equating the closed loop set-point transfer function model with that of the desired set-point reference model, which may be written as

$$P_{r,f}(s) = P_{sp}(s) \tag{11}$$

The following aspects have been assumed to obtain such desired performance matching of LFC system using DS approach:

a. To obtain the desired transient response, the pole of the desired set-point reference model at $s=-1/T$ may be assumed as the pole of the closed-loop system which results in the following equation.

$$1+K_{c1}M_n = 0 \text{ for } s=-1/T \tag{12}$$

$$\text{Or, } K_{c1}(s) = -\frac{1}{T_g(s)T_t(s)T_p(s)} - \frac{1}{R} \tag{13}$$

Using (3), (13) may be written as

$$K_{p1} - TK_{i1} - \frac{K_{d1}}{T} = \left[-\frac{1}{T_g(s)T_t(s)T_p(s)} - \frac{1}{R}\right]\Bigg|_{s=-1/T} = Z \tag{14}$$

b. To obtain better steady state performance of the power system by matching the frequency response of the two systems at very small frequency point (say $\omega = 0.001$ rad/s) which results in the following expression.

$$P_{r,f}(j\omega) \cong P_{SP}(j\omega) \tag{15}$$

The (15) may be written as

$$\frac{K_{c1}(j\omega)M_n(j\omega)}{1+K_{c1}(j\omega)M_n(j\omega)} \cong P_{SP}(j\omega) \tag{16}$$

$$K_{c1} \cong \frac{P_{SP}(j\omega)}{M_n(1-P_{SP}(j\omega))} \tag{17}$$

The expression of PID controller parameter for LFC may be obtained by using (3) and (17) as given by

$$K_{p1} + \frac{K_{i1}}{j\omega} + K_{d1}j\omega \cong \left(\frac{P_{SP}(j\omega)}{1-P_{SP}(j\omega)}\right)\frac{1}{T_p(j\omega)T_g(j\omega)T_t(j\omega)} - \frac{1}{R} \tag{18}$$

Assuming $X \cong \left(\frac{P_{SP}(j\omega)}{1-P_{SP}(j\omega)}\right)\frac{1}{T_p(j\omega)T_g(j\omega)T_t(j\omega)} - \frac{1}{R}$, the (18) may be written as

$$K_{p1} + j(K_{d1}\omega - \frac{k_{i1}}{\omega}) = \text{Re}[X] + j\,\text{Im}[X] \tag{19}$$

By separating real and imaginary parts of (19), we get the following two equations as given by.

$$K_{p1} = \text{Re}[X] \tag{20}$$

$$K_{d1}\omega + k_i(\frac{-1}{\omega}) = \text{Im}[X] \tag{21}$$

The (14), (20) and (21) may be arranged in matrix form as given by

$$\begin{bmatrix} 1 & -T & -1/T \\ 1 & 0 & 0 \\ 0 & \frac{-1}{\omega} & \omega \end{bmatrix} \begin{bmatrix} K_{p1} \\ K_{i1} \\ K_{d1} \end{bmatrix} = \begin{bmatrix} Z \\ \text{Re}[X] \\ \text{Im}[X] \end{bmatrix} \tag{22}$$

By solving the. (22), the PID controller gain for set-point response will be obtained.

3.2. Load-disturbance controller (K_{c2})

The desired load-disturbance closed-loop transfer function $P_{LD}(s)$ (from ΔP_d to Δf) of the power system is considered as given by

$$P_{LD}(s) = \frac{Ks}{(Ts+1)^n}, \tag{23}$$

where T is the time constant of the desired load-disturbance reference model, n is the order of the desired load-disturbance reference model and the constant gain $K = 1/K_{i2}$. To ensure the frequency deviation of the system at steady state is zero due to one zero at the origin is placed in the desired load-disturbance reference model as in (23).

From (2), the closed loop load-disturbance transfer function ($P_{d,f}$) from (Δf to d) may be written as

$$P_{d,f} = \frac{M_n}{1 + K_{c2}M_n} \tag{24}$$

The closed-loop characteristic equation from (24) may be written as

$$1 + K_{c2}M_n = 0 \tag{25}$$

In the direct synthesis (DS) technique, the controller has been designed by equating the closed loop load-disturbance transfer function model with that of the desired load-disturbance reference model, which may be written as

$$P_{d,f}(s) = P_{LD}(s) \tag{26}$$

The following aspects have been assumed to obtain such desired performance matching of LFC system using DS approach:

a. To obtain the desired transient response, the pole of the desired load-disturbance reference model at $s = -1/T$ may be assumed as the pole of the closed-loop system which results in the following equation.

$$1 + K_{c2}M_n = 0 \text{ for } s = -1/T \tag{27}$$

$$\text{Or, } K_{c2}(s) = -\frac{1}{T_g(s)T_t(s)T_p(s)} - \frac{1}{R} \tag{28}$$

Using (3), (28) may be written as

$$K_{p2} - TK_{i2} - \frac{K_{d2}}{T} = \left[-\frac{1}{T_g(s)T_t(s)T_p(s)} - \frac{1}{R} \right]\Bigg|_{s=-1/T} = Z \qquad (29)$$

b. To obtain better steady state performance of the power system by matching the frequency response of the two systems at very small frequency point (say $\omega = 0.001$ rad/s) which results in the following expression.

$$P_{d,f}(j\omega) \cong P_{LD}(j\omega) \qquad (30)$$

The (30) may be written as

$$\frac{M_n(j\omega)}{1 + K_{c2}(j\omega)M_n(j\omega)} \cong P_{LD}(j\omega) \qquad (31)$$

$$K_{c2} \cong \frac{1}{P_{LD}(j\omega)} - \frac{1}{M_n(j\omega)} \qquad (32)$$

Or, $K_{c2} \cong \frac{1}{P_{LD}(j\omega)} - \frac{1}{T_p(j\omega)T_g(j\omega)T_t(j\omega)} - \frac{1}{R}$ (33)

The expression of PID controller parameter for LFC may be obtained by using (3) and (33) as given by

$$K_{p2} + \frac{K_{i2}}{j\omega} + K_{d2}j\omega \cong \left(\frac{K_{i2}}{P_{ld}(j\omega)} \right) - \frac{1}{T_p(j\omega)T_g(j\omega)T_t(j\omega)} - \frac{1}{R} \qquad (34)$$

Assuming $W = \frac{1}{P_{ld}(j\omega)} = \frac{(1+Ts)^n}{s}$ and $Y \cong \frac{1}{T_p(j\omega)T_g(j\omega)T_t(j\omega)} + \frac{1}{R}$, the (34) may be written as

$$K_{p2} + j(K_{d2}\omega - \frac{k_{i2}}{\omega}) = (K_{i2}\,\mathrm{Re}[W] - \mathrm{Re}[Y]) + j(K_{i2}\,\mathrm{Im}[W] - \mathrm{Im}[Y]) \qquad (35)$$

By separating real and imaginary parts of (35), we get the following two equations as given by.

$$K_{p2} - K_{i2}\,\mathrm{Re}[W] = -\mathrm{Re}[Y] \qquad (36)$$

$$K_{d2}\omega + k_{i2}(\frac{-1}{\omega} - \mathrm{Im}[W]) = -\mathrm{Im}[Y] \qquad (37)$$

The (29), (36) and (37) may be arranged in matrix form as given by

$$\begin{bmatrix} 1 & -T & -1/T \\ 1 & -\mathrm{Re}[W] & 0 \\ 0 & \frac{-1}{\omega} - \mathrm{Im}[W] & \omega \end{bmatrix} \begin{bmatrix} K_{p2} \\ K_{i2} \\ K_{d2} \end{bmatrix} = \begin{bmatrix} Z \\ -\mathrm{Re}[Y] \\ -\mathrm{Im}[Y] \end{bmatrix} \qquad (38)$$

By solving the (38), the PID controller gain for load-disturbance will be obtained.

4. SIMULATION RESULTS AND DISCUSSIONS:

In this part, simulation results of a single area, two area and four-area thermal power system has been considered and show the major advantages of the proposed PID controller design method.

Case study 1: A single-area LFC power system with non-reheated thermal turbine (NRTT) [21] is considered with the following parameters $k_p = 120$, $t_p = 20$, $t_t = 0.3$, $t_g = 0.08$, R=2.4. The desired set-point and load disturbance transfer function model is considered with T=0.18, n=3. The proposed set-point PID controller is obtained as $K_{c1}(s)$ =0.1728+0.7870/s+0.1418s and load- disturbance PID controller is obtained as $K_{c2}(s)$ =3.4001+7.0835/s+0.5187s. The load demand ΔP_d=0.01 p.u. at t=0 sec is applied in LFC power system to verify the performance of the proposed controller. The frequency regulation of the proposed PID controller is as shown in Figure 4 and its comparative performance of the proposed method is compared with that of prevalent designed techniques such as Anwar and Pan [21], Padhan and Majhi [20], Tan [11]. The detailed analysis of case study 1 is given in Table 1. The simulation results of case study 1 reveal that the frequency deviation (Δf), the integral of absolute error (IAE), and settling time (t_s) are minimum value compared to Anwar and Pan [21], Padhan and Majhi [20], Tan [11]. The percentage improvement of peak value w.r.t Tan is as shown in Table 1 measured with the given formula as

$$\%\ \text{improvement} = \frac{\text{peak value (reported)} - \text{peak value (proposed)}}{\text{peak value (reported)}} \times 100 \tag{39}$$

To analyses, the robustness of the proposed PID controller, -50% parameter variation in k_p and t_p of nominal plant model and frequency deviation of the perturbed plant is shown in Figure 5. The maximum sensitivity is defined as $M_s = \max_{0\le\omega\le\infty} \left|1/\left[1+K_{c2}(j\omega)M_n(j\omega)\right]\right|$. The lowest value of M_s indicates the robustness of the system.

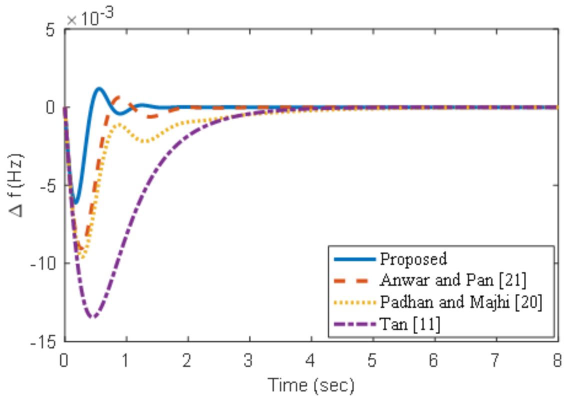

Figure 4. Frequency deviation response for case study 1 with nominal plant

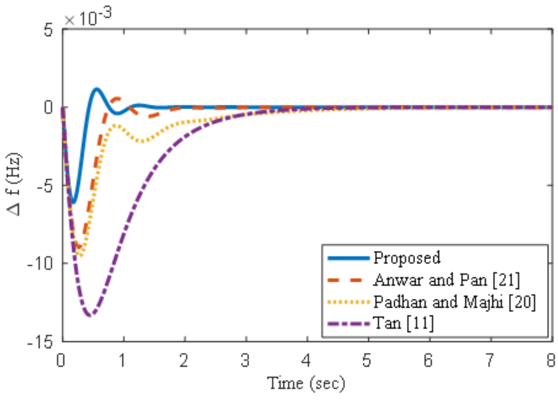

Figure 5. Frequency deviation response for case study 1 with *-50%* variations in k_p and t_p

Table 1. Comparative performance of case study 1

Method	K_{p2}	k_{i2}	K_{d2}	M_s	Nominal plant: Peak value ($x10^{-3}$)	Nominal plant: % Improvement in term of Peak value w.r.t Tan	Nominal plant: t_s (sec)	Nominal plant: IAE ($x10^{-3}$)	Perturbed plant: Peak value ($x10^{-3}$)	Perturbed plant: t_s (sec)	Perturbed plant: IAE ($x10^{-3}$)
Proposed PID	3.40	7.08	0.51	1.92	6.12	54.32	1.02	1.94	6.12	1.02	1.93
Anwar & Pan [21]	1.52	2.50	0.27	1.74	9.02	32.68	1.74	4.20	8.97	1.73	4.20
Padhan & Majhi [20]	1.49	1.30	0.235	1.77	9.6	28.35	4.07	7.68	9.52	4.09	7.68
Tan [11]	0.40	0.63	0.183	1.24	13.4	-	3.51	15.8	13.3	3.58	15.8

Case study 2: A single-area thermal power system with Re-heated turbine (RTD) [21] has been considered with the following parameters as given by

$k_p = 120$, $t_p = 20$, $t_t = 0.3$, $t_g = 0.08$, R=2.4, $t_r = 4.2$ and c = 0.35

The desired set-point and load disturbance transfer function model is considered with T=0.15, n=3. The proposed set-point PID controller is obtained as $K_{c1}(s)$ = 0.2864+0.9444/s+0.3211s and load- disturbance PID controller is obtained as $K_{c2}(s)$ = 8.139+19.03/s+1.0921s. The load demand ΔP_d=0.01 p.u.MW at t=0 sec is applied in LFC power system to assure the performance of the proposed controller. The frequency regulation of the proposed PID controller is as shown in Figure 6 and its comparative performance of the proposed method is compared with that of prevalent designed techniques such as Anwar and Pan [21], Padhan and Majhi [20] and Tan [11]. The detailed analysis of case study 2 is given in Table 2. The simulation results of case study 2 reveal the frequency deviation (Δf), the integral of absolute error (IAE), and settling time (t_s) are much better than that of Anwar and Pan [21], Padhan and Majhi [20] and Tan [11]. The percentage improvement of peak value w.r.t Tan [11] is as shown in Table 2.

To analyses, the robustness of the proposed PID controller, -50% parameter variation in k_p and t_p of nominal plant model and frequency deviation of the perturbed plant is shown in Figure 7. In case study 2 the maximum sensitivity M_s is 2.37, which is lower than that of Anwar and Pan [21] Padhan and Majhi [20] and Tan [11].

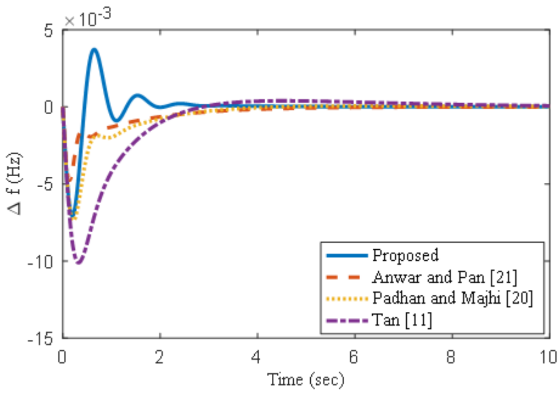

Figure 6. Frequency deviation response for case study 2 with nominal plant

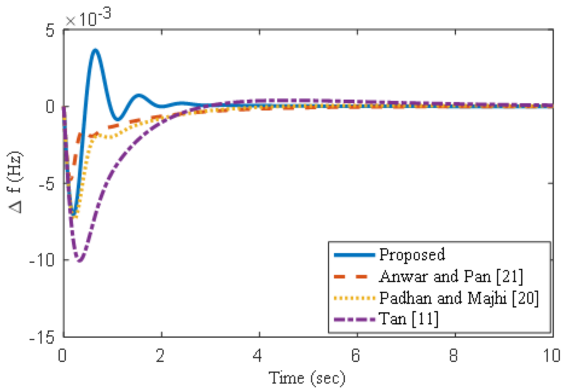

Figure 7. Frequency deviation response for case study 2 with *-50%* variations in k_p and τ_p

Table 2. Comparative performance of case study 2

Method	K_{p2}	k_{i2}	K_{d2}	M_s	Nominal plant				Perturbed plant		
					Peak value ($x10^{-3}$)	%Improvement in term of Peak value w.r.t [20]	t_s (sec)	IAE ($x10^{-3}$)	Peak value ($x10^{-3}$)	t_s (sec)	IAE ($x10^{-3}$)
Proposed PID	8.13	19.03	1.09	2.39	7.06	29.4	1.8	3.82	7.03	1.8	3.77
Anwar & Pan [21]	10.60	2.50	2.57	1.76	4.75	52.5	3.64	4.0	4.73	3.65	4.0
Padhan & Majhi [20]	6.16	1.93	1.16	1.61	7.38	26.2	3.23	5.80	7.34	3.24	5.80
Tan [11]	2.79	1.27	0.787	1.32	10.0	-	7.4	11.4	10.0	7.4	11.4

Case study 3: A two area power system with NRT has been reported from [21] with the following system parameter as $k_{p1} = k_{p2} = 120$, $t_{p1} = t_{p2} = 20$, $t_{t1} = t_{t2} = 0.3$, $t_{g1} = t_{g2} = 0.08$, R_1=R_2=2.4, β_1=β_2=0.425.

The desired set-point and load disturbance transfer function model is considered with T=0.18, n=3. The proposed set-point PID controller is obtained as $K_{c1}(s)$ =-0.4065+1.8517/s+0.3336s and load-disturbance PID controller is obtained as $K_{c2}(s)$ =8+16.65/s+1.22s. The load demand ΔP_d=0.01 p.u. at t=0 sec is applied in LFC power system to verify the performance of the proposed controller. The frequency regulation of the proposed PID controller is as shown in Figures 8, 9, 10 and the simulation results of the proposed design method are compared with that of Anwar and Pan [21], Tan [11]. The detailed analysis of case study 3 is described in Table 3. The simulation results of case study 4 reveal that the percent overshoot (%OS) in frequency deviation (Δf), the integral of absolute error (IAE), and settling time (t_s) are better than that of Anwar and Pan [21], Tan [11] in each area. The percent overshoot (%OS) in tie-line power, settling time (t_s), IAE is improved than that of Anwar and Pan [21] and Tan [11]. In case study 3 the maximum sensitivity M_s is 2.37, which is higher than that of Anwar and Pan [21] and Tan [11].

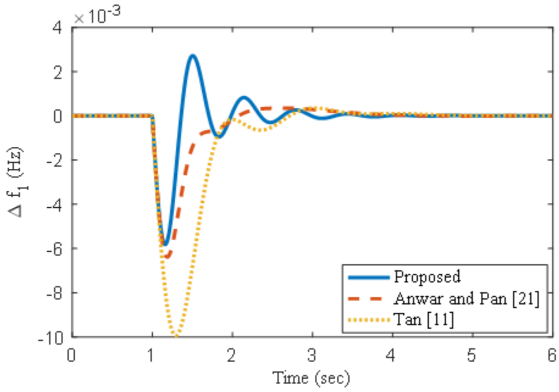

Figure 8. Frequency regulation of area 1 for case study 3

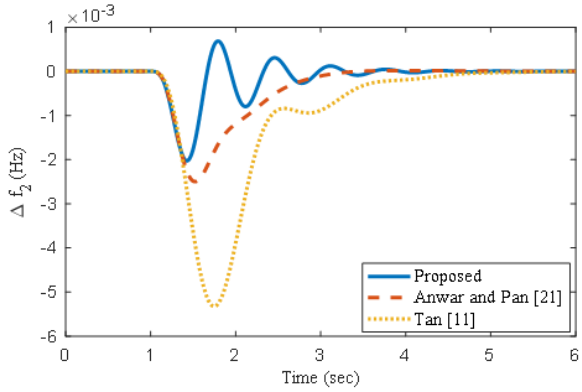

Figure 9. Frequency regulation of area 2 for case study 3

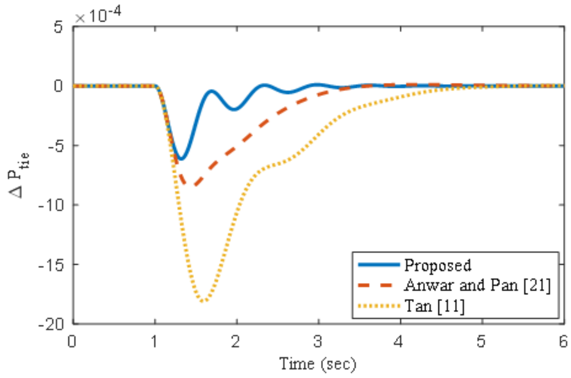

Figure 10. Tie-line power exchange between area 1&2 for case 3

Table 3. Comparative performance of case study 3

Method	K_{p2}	K_{i2}	K_{d2}	M_s	Area 1 Δf_1 %OS (x10^{-3})	Area 1 Δf_1 t_s (sec)	Area 1 Δf_1 IAE (x10^{-3})	Area 2 Δf_2 %OS (x10^{-3})	Area 2 Δf_2 t_s	Area 2 Δf_2 IAE (x10^{-3})	Tie-line power ΔP_{tie} % OS (x10^{-4})	Tie-line power ΔP_{tie} t_s (sec)	Tie-line power ΔP_{tie} IAE (x10^{-3})
Proposed PID	8	16.65	1.22	2.37	5.82	2.86	1.10	2.02	2.86	0.35	0.63	1.54	0.30
Anwar and Pan [21]	3.55	5.95	1.22	1.75	6.38	3.2	1.80	2.50	2.82	0.17	8.50	2.57	0.87
Tan [11]	1.569	2.3966	0.525	1.43	9.92	3.32	4.18	5.32	3.9	0.65	18.06	3.42	2.09

Case study 4: A four area LFC power system with NRTT as shown in Figure 11 has been considered from [13] with the following system parameter

Area No. 1: $k_{p1} = 120$, $t_{p1} = 20$, $t_{t1} = 0.3$, $t_{g1} = 0.08$, R_1=2.4, Area No. 2: $k_{p2} = 112.5$, $t_{p2} = 25$, $t_{t2} = 0.33$, $t_{g2} = 0.072$, R_2=2.7, Area No. 3: $k_{p3} = 125$, $t_{p3} = 20$, $t_{t3} = 0.35$, $t_{g3} = 0.07$, R_3=2.5 Area No. 4: $k_{p4} = 115$, $t_{p4} = 15$, $t_{t4} = 0.375$, $t_{g4} = 0.085$, R_4=2.0

The synchronizing constants are $t_{12} = t_{13} = t_{14} = t_{21} = t_{23} = t_{32} = t_{41} = 0.545$ and the frequency bias constants are $\beta_1 = \beta_2 = \beta_3 = \beta_4 = 0.425$.

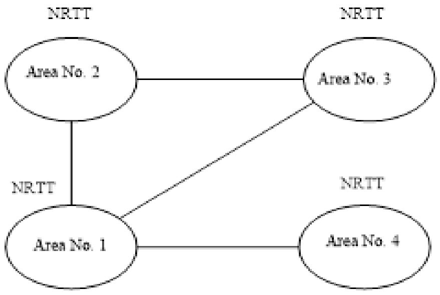

Figure 11. Four-area non-reheat thermal turbine (NRTT) system

A four-area interconnected thermal power system is studied to demonstrate the advantage of the proposed controller. The area no.1, 2, 3 are interconnected to each other, while the area no. 4 is connected with area 1 only and each area in power is non-reheated thermal turbine (NRTT). The desired set-point and load disturbance transfer function model for each area are considered with T=0.30, n=3. The proposed set-point PID controller for each area is obtained as

$$K_{c11}(s) = 0.0470 + \frac{0.4722}{s} + 0.096s\,,\; K_{c12}(s) = 0.1245 + \frac{0.4214}{s} + 0.1272s\,,$$
$$K_{c13}(s) = 0.0455 + \frac{0.4533}{s} + 0.1130s\,,\;\; K_{c14}(s) = -0.0202 + \frac{0.5652}{s} + 0.1160s$$

The load- disturbance PID controller for each area is obtained as

$$K_{c21}(s) = 1.2483 + \frac{1.8599}{s} + 0.3322s\,,\;\; K_{c22}(s) = 2.0189 + \frac{2.6646}{s} + 0.4937s$$
$$K_{c23}(s) = 1.403 + \frac{2.0122}{s} + 0.3799s\,,\;\; K_{c24}(s) = 1.0386 + \frac{1.7192}{s} + 0.3298s$$

The simulation results of the proposed controller are observed by applying load demand ΔP_d=0.01 p.u.MW at t=1 sec in an area no. 1, 2 and load demand ΔP_d=0.01 p.u.MW at t=20 sec in an area no. 3, 4 simultaneously. The change in frequency deviation is shown in Figure 12 while tie-line power between interconnected-area is shown in Figure 13. The simulation result of the proposed controller as shown in Figure 12 and Figure 13 is compared with Tan [13] and observed that the proposed method is better than Tan [13] in terms of frequency deviation and settling time.

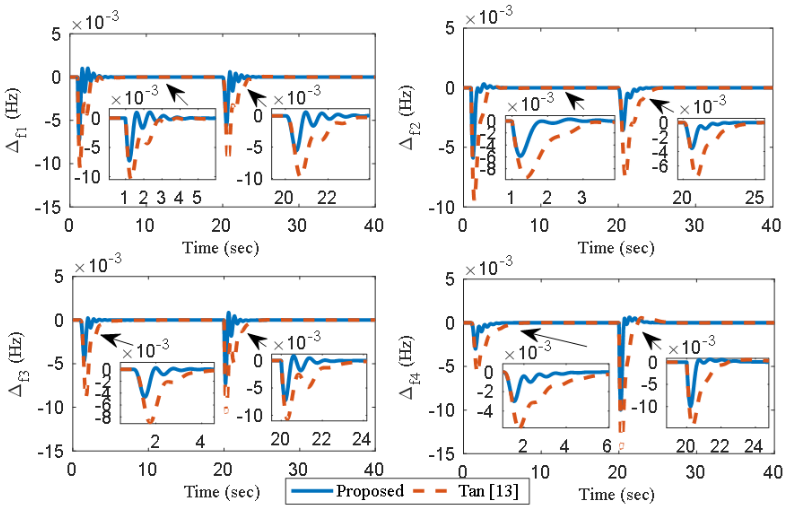

Figure 12. Frequency regulation of four area power system in case study 4

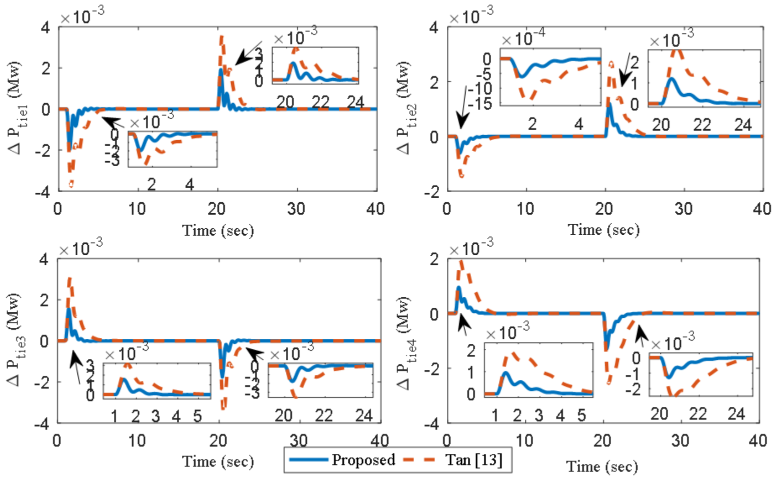

Figure 13. Tie-line power exchange of four-area power system in case 4

4.1. Random loading pattern (RLP)

To assure robustness of the proposed PID controller method, different step change in load applied at particular interval of time in case study 1. The simulation results as shown in Figure 14 for case study 1 by applying random step change in load. The simulation results reveal the percent overshoot and settling time is improved even that high magnitude of step load apply in LFC power system. Thus, the proposed design technique is effective in LFC power system

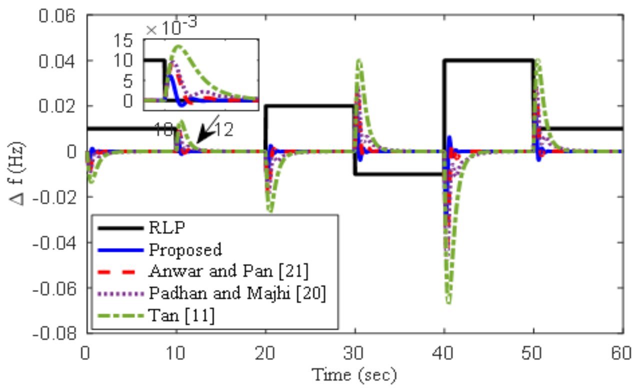

Figure 14. Frequency regulation of case study 1 with RLP

5. CONCLUSION

In this article, the PCS scheme has been used to design the set-point and load-frequency controller for a single-area and the multi-area power system using the DS approach. The proposed technique has been considered for single-area reheat as well as non-reheated thermal turbine power system, two-area non-reheated system, four-area non-reheated system. Proposed technique show better simulation response in terms of percent overshoot, settling time, and IAE for the nominal system as well as the perturbed system. Robustness of the proposed method has been analyzed with system parameter variation and the random load applied at a particular time in the LFC power system. The main advantages of the proposed technique are to improved percent overshoot and settling time compared to standard reported literature.

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