Robust CDA-PIDA Control Scheme for Load Frequency Control of Interconnected Power Systems

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Abstract: This paper proposes a robust CDA-PIDA control scheme for load frequency control problem. The proportional integral derivative acceleration (PIDA) controller is a variant of PID and it is used to cope with large overshoot and settling time in higher order systems. The tuning of PIDA controller is based on coefficient diagram algorithm (CDA). The CDA is based on algebraic design approach and it is demonstrated sufficient condition for stability. In this paper, CDA-PIDA control scheme is designed for two area interconnected power system. The overall closed loop system stability is guaranteed in case of two area power system because each area CDA-PIDA controller is designed independently. The robustness of the proposed control scheme is demonstrated in presence of parametric uncertainty, load disturbances and physical constraint. The robustness and eminence of CDA-PIDA control scheme is proved through comparison between the CDA-PIDA and recently published control schemes.

Keywords: PIDA Controller, Coefficient Diagram Algorithm (CDA), Load Frequency Control (LFC) problem, Two Area Interconnected Power System, CDA-PIDA, Robustness.

1. INTRODUCTION

In recent years, the increase in sudden load and a varying structure of a power system, it becomes a major issue to operate and control the power system (Mohanty *et al.*, 2017). The idea of multi area modeling of interconnected power systems through tie line has been proposed by (Elgerd *et al.*, 1970). In case of emergencies such as random load disturbance and capacity outage, the interconnecting units exchange power using tie line, and enhance the power system stability and reliability (Chen *et al.*, 2017). Due to sudden load disturbance or capacity outage, the generated active power becomes lesser than demand, frequency of generating units and tie line power of interconnecting units tends to decrease and increase (Sahu *et al.*, 2016). The abnormal variation in frequency i.e., frequency instability even causes of power system blackout. The frequency deviation and tie line power deviation maintain zero or minimum using load frequency controller (LFC). The LFC regulate the steam turbine governing valve system to control the flow of steam to the turbine shaft to control the movement of rotating mass generator and load, i.e. regulate the power generation. The main objectives of LFC for power system are (a) frequency deviation and tie line power deviation must approach to zero, (b) load disturbance rejection, and (c) handling the parametric uncertainty and physical constraints (Saxena and Hote, 2013, 2017).

To achieve objectives of LFC, various control strategies have been presented in the literature such as classical control (Concordia *et al.*, 1957), adaptive control (Vrdoljak *et al.,* 2010; Mohamed e*t al.*, 2011), optimal control (Elgerd et al., 1970), and robust control (Singh *et at.*, 2013). A detailed literature review of LFC problem may be found in (Pappachen *et al.*, 2017). For smoother control of frequency, this paper prefers the secondary control, which can surely maintain zero area control error (ACE). The majority of literature work is focused on tuning and design of proportional integral derivative (PID) controllers and its variants due to their simple design, easy maintenance, and understanding the operation.

The PIDA controller is a variant of PID and it is used to cope with large overshoot and settling time of system (Jung *et al.*, 1996). The tuning of PIDA controller is a critical issue for robustness of control scheme (Jung *et al.*, 1996). In literature, various tuning schemes have been proposed for PID such as internal model control (IMC) (Saxena and Hote, 2013, 2017), direct synthesis (DS) approach (Anwar and Pan, 2015), Laurent series expansion approach (Padhan and Majhi, 2013) etc. Furthermore, the tuning of both PID and PIDA is based on evolutionary optimization techniques, such as Bacterial foraging optimization (BFO), particle swarm optimization (PSO), Teacher learning based optimization (TLBO), Genetic algorithm (GA), Lion optimizer algorithm (LOA), Multi-verse optimization (MVO) and Moth flame Optimization (MFO) (Saikia *et al.*, 2011; Sahu *et al.*, 2016; Guha *et al.,* 2017; Mohanty *et al.*, 2017) etc. The limitation of these algorithms are that they require the pre-determination of some input control specification. An optimization algorithm is provided acceptable response for some define objective functions and conditions, but not for all conditions. Recently, (Guha *et al.,* 2017) applied PID+DD (plus double derivative) control scheme for LFC problem. In this study, authors have considered physical constraints and $\pm 25\%$ parametric uncertainty to show the performance of proposed controller for LFC problem. Therefore, to explore the adequacy of PID+DD controller for complex power system, further investigation is also required.

The coefficient diagram method (CDM) is an algebraic design approach (Manabe, 1998). The CDM is provided the guarantee for system stability. It is based on Lipatov's stability theorem (Manabe, 1998). This theorem provides robust values of the stability indices and stability limits for CDM design. (Bernard *et al.*, 2014) and (Mohamed *et al.*, 2016) have been proposed a polynomial controller based on CDM approach for LFC problem. In these studies, authors have considered a polynomial controller (PolyC). The order of PolyC is not pre-specified for systems i.e., this type of controllers don't provides robustness. Also, authors have considered only upper bound parametric uncertainty (Bernard *et al.*, 2014; Mohamed *et al.*, 2016). In CDM, the values of stability indices and stability limits are acquired based on trial-error method. Keep in mind this problem of CDM, this paper proposes a coefficient diagram algorithm (CDA), which provides the values of stability indices and stability limits using optimization method and it does apply for tuning of PIDA controller for LFC problem. According to the best our knowledge, no literature is found regarding CDA-PIDA control scheme for LFC problem. This paper introduces a novel control scheme CDA-PIDA for LFC control. The major contribution of authors in the paper are as follows:

1. Proposes an algorithm based on CDM.

2. Demonstrates tuning of PIDA controller based on CDA for LFC problem.

3. To design the two area interconnected power system with non-reheat turbine.

4. To study the effect of parametric uncertainty, physical constraints and load disturbance on the system configuration for the sake of robustness of the controller.

5. To exhibit the efficacy and adequacy of the proposed control scheme over other prevalent published control scheme, a widespread comparative study is based on time domain specification such as settling time.

2. THE SYSTEM MODEL

The mathematical modeling of single area non-reheat turbine based power system is described in (Anwar *et al.*, 2015; Tan, 2009). The plant for LFC system consists of governor, turbine, rotating mass generating unit and load. The linearized model around the operating point of plant is depicted in Fig. 1. The transfer function of plant for non-reheated turbine with droop characteristics can be written as

$$G(s) = \frac{G_g(s)G_t(s)G_p(s)}{1 + G_g(s)G_t(s)G_p(s)/R} \quad (1)$$

where, Governor with dynamic $G_g(s) = 1/(sT_g + 1)$, Turbine with dynamic $G_t(s) = 1/(sT_t + 1)$, rotating mass generating unit and load with dynamic $G_p(s) = K_p/(sT_p + 1)$ and R is governor speed regulation due to action of governor (Hz/p.u.MW), ΔP_d is a step change load disturbance (p.u.MW), K_p is generator and load plant gain, T_p is generator and load plant time constant (sec.), T_T is time constant of turbine in seconds, T_g is time constant of governor in seconds, Δf is frequency deviation, u is control input.

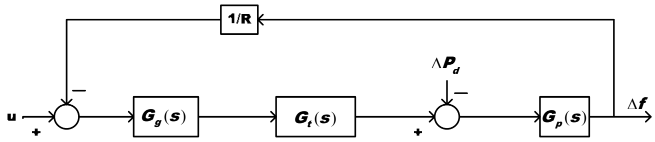


Fig. 1. Block diagram of single area power system.

3. CONTROL DESIGN STRATEGY

In general, control engineers prefer classical and modern control theory for controller design in load frequency control problem. In this paper, a coefficient diagram algorithm (CDA) is used to tune the parameters of PIDA controller. The CDA is based on algebraic control design approach. It is also a graphical approach. The analysis of stability in this CDA is based on Lipatov's stability theorem (Manabe, 1998).

3.1 Proposed Coefficient Diagram Algorithm (CDA)

Coefficient diagram (CD) has been proposed in (Manabe, 1998). The CD provides the stability, optimal time domain specification and robustness features of system in the single coefficient diagram. The mathematical formulation of CDA is given as follows:

The target characteristics polynomial $P_{target}(s)$ is written as

$$P_{target}(s) = D_c(s)D(s) + N(s)N_c(s) \quad (2)$$

where, $N(s)$ and $D(s)$ are the numerator and denominator polynomial of the system transfer function. $N_c(s)$ and $D_c(s)$ is a numerator and denominator polynomial of the controller transfer function respectively and these are designed to satisfy the desired transient response.

The desired characteristics polynomial (*P(s)*) is given as

$$P(s) = \left(\sum_{i=0}^{n} a_i s^i\right), \; a_i > 0 \quad (3)$$

where, a_i is the coefficients of *P(s)*.

The stability indices (γ_i) and stability limits (γ_i^*) parameters are defined to check stability and robustness of system are given as follows (Manabe, 1998)

$$\gamma_i = \frac{a_i^2}{a_{i+1}a_{i-1}}, \qquad i \in [1, n-1], \qquad \gamma_0 = \gamma_n = \infty \quad (4)$$

$$\gamma_i^* = \frac{1}{\gamma_{i-1}} + \frac{1}{\gamma_{i+1}}, \quad i \in [1, n-1] \tag{5}$$

The time constant (τ) is defined to check speed of closed loop system response, which is as follows (Manabe, 1998)

$$\tau = \frac{a_1}{a_0} \tag{6}$$

According to Manabe's standard form (Manabe, 1998), *P(s)* is given by:

$$P(s) = a_0 \left[\left\{ \sum_{i=2}^{n} \left(\prod_{j=1}^{i-1} \frac{1}{\gamma_{i-j}^{j}} \right) (\tau s)^i \right\} + \tau s + 1 \right] \tag{7}$$

$$P(s) = P_{target}(s) \tag{8}$$

3.2 Stability Criterion

The sufficient conditions for stability in sense of Lipatov's theorems (Lapatov and Sokolov, 1979) are written as

$$a_i > 1.12 \left[\frac{a_{i-1}}{a_{i+1}} a_{i+2} + \frac{a_{i+1}}{a_{i-1}} a_{i-2} \right] \tag{9}$$

$$\text{for some } i, \qquad \gamma_i > 1.1236\,\gamma_i^*, \qquad i \in [2,\ n-2] \tag{10}$$

The necessary conditions for instability in sense of Lipatov's theorems (Lapatov and Sokolov, 1979) are written as

$$a_{i+1} a_i \ge a_{i+2} a_{i-1} \tag{11}$$

$$\gamma_i \times \gamma_{i-1} \le 1, \quad \text{for all } i,\ i \in [2, n-1] \tag{12}$$

The flowchart for coefficient diagram algorithm is shown in Fig. 2.

Note 1: In the CDA, the values of stability indices and stability limits obtain using FMINCON optimization method (Gill *et al.,* 1981) with Lipatov's stability conditions constraints, which are also satisfied Lipatov's stability theorems. In MATLAB, fmincon function is inbuilt.

Note 2: The objective function used here is defined as Minimize $J = (error.*error)$

Subject to:

$\gamma_i > 1.1236\gamma_i$, $\quad i \in [2, n \quad 2]$

$\gamma_i \times \gamma_{i-1} \le 1,\ i \in [2, n-1]$

where, *error=y -1; y* = step response output vector.

3.3 PIDA controller

The general mathematical form of PIDA controller can be written as

$$C(s) = \frac{N_c(s)}{D_c(s)} = k_p + \frac{k_i}{s} + k_d s + k_a s^2 = \frac{k_a s^3 + k_d s^2 + k_p s + k_i}{s} \tag{13}$$

The PIDA controller can be helpful in improving the steady state accuracy and robustness of the higher order plant (Dorf *et al.*, 1996). The structure of PIDA controller is shown in Fig. 3.

Note 3: In (13), K_a is an acceleration coefficient which improves phase margin, increases the damping factor and allows the proportional gain to be large.

3.4 Proposed CDA-PIDA control scheme for LFC Problem

The block diagram of power system with CDA-PIDA is shown in Fig. 4.

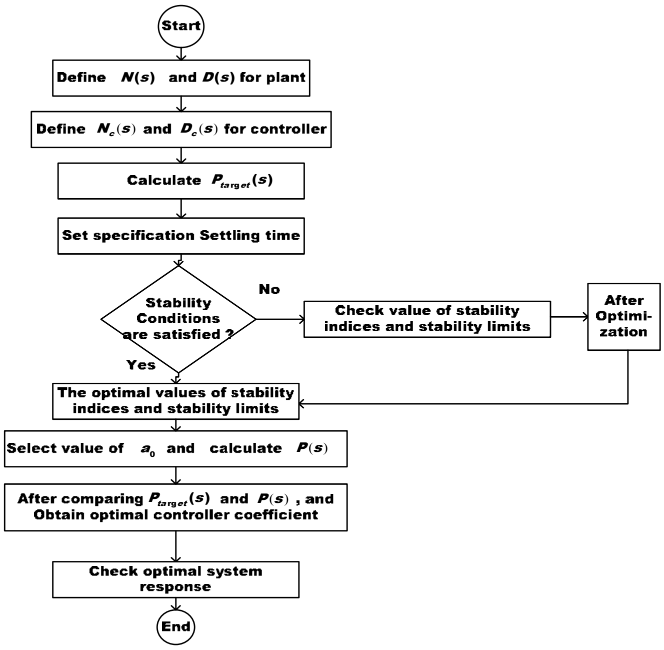


Fig. 2. Simplified flowchart for Coefficient Diagram Algorithm

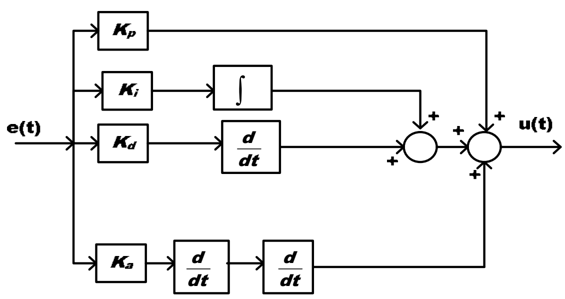


Fig. 3. The structure of PIDA Controller

The *N(s)* and *D(s)* is calculated from (1) after taking parameters values from appendix A. The $N_c(s)$ and $D_c(s)$ is considered from (13). Assume, settling time as $T_s = 2\sec$.

$$N(s) = 250$$

$$D(s) = s^3 + 15.88 s^2 + 42.46 s + 106.2$$

$$N_c(s) = k_a s^3 + k_d s^2 + k_p s + k_i$$

$$D_c(s) = s$$

Further, $P_{target}(s)$ is calculated using (2) as follows

$$P_{target}(s) = s^4 + (15.88 + 250k_a)s^3 + (42.46 + 250k_d)s^2 + (106.2 + 250k_p)s + 250k_i \quad (14)$$

The stability indices (γ_i) is calculated through CDA, so we obtain

$$\gamma_i = [2.5,\ 5,\ 2], \quad i \in [1,3],\ \gamma_0 = \gamma_4 = \infty$$

And the stability limits γ_i^* is measured by using CDA, we acquire:

$$\gamma_i^* = [0.2002,\ 0.8997,\ 0.2],\ i \in [1,3]$$

And choosing $a_0 = 1$ in (7), we obtain

$$P(s) = s^4 + 28.8687s^3 + 416.7024s^2 + 1203s + 1389.1 \quad (15)$$

After comparing (14) and (15), we obtain

$k_p = 4.387$, $k_i = 5.557$, $k_d = 1.497$ $k_a = 0.05195$

The CDA-PIDA controller is same for area 1 and 2 because the system transfer function for area 1 and 2 is same from (1) i.e., no need of controller tuning for area 1 and 2 separately.

4. SYSTEM UNDER STUDY

The two area interconnected power system is shown in Fig. 4. The tie line is used to interconnecting the individual areas to improve system stability, security and reliability. The area frequency and tie line power vary with load demand change. The tie line power deviation may be expressed as

$$\Delta P_{tieline} = \frac{T_{12}}{s} \quad (16)$$

where, T_{12} is a tie-line synchronizing parameter between area 1 and 2 (p.u. MW/rad.).

The system under study configuration parameters are given in appendix A for Fig. 4.

The values of physical constraints such as generation rate constraints (GRC) is 0.1 p.u./min. or 0.001667 p.u./sec. and governor dead-band (GDB) is 0.036 Hz/p.u. MW (Corcordia *et al.*, 1957; Tan, 2009).

The following cases are studied for evolution of performance of CDA-PIDA control scheme for LFC:

Case 1: The controller is evaluated in presence of nominal parameters of two area power system with 1% and 2% load disturbance at t=1sec and t=10 sec respectively for area 1 and area 2.

Case 2: The controller is evaluated in presence of +/- 50% changes in the parameter values of two area power system with 1% and 2% load disturbance at t=1sec and t=10 sec respectively for area 1 and area 2.

Case 3: The controller is evaluated in presence of physical constraints such as GRC and GDB for case 1 and 2.

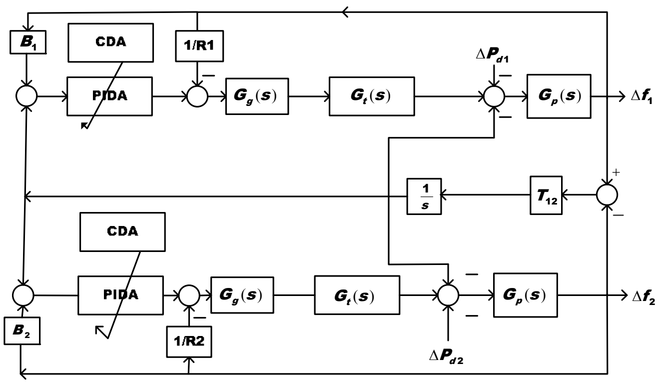


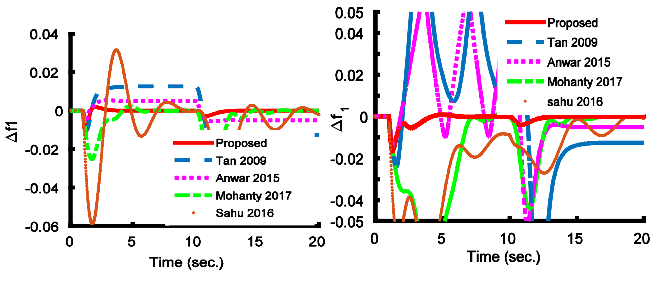
Fig. 4. The two area power system configuration with CDA-PIDA.

5. RESULTS AND DISCUSSIONS

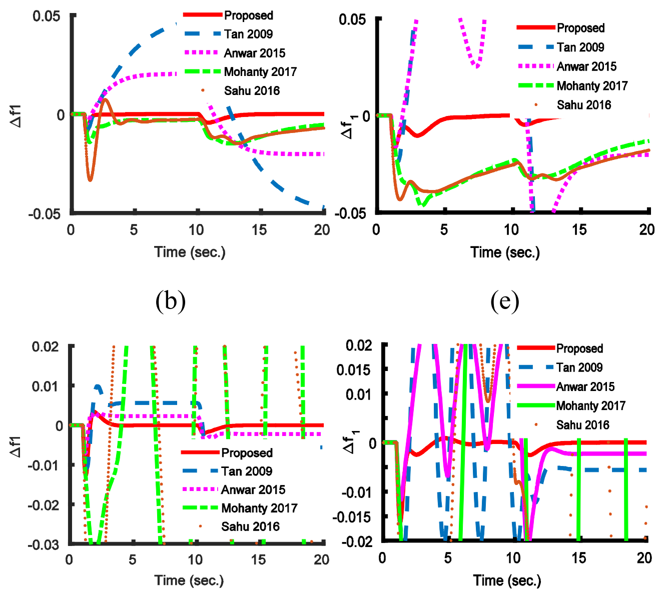
The controller parameters have been depicted in Table 1. The simulation results are shown in Fig. 5-7. From the results, the proposed controller reduces the frequency deviation and tie line power deviation to zero, within 1-3 seconds in case 1 compare to other control schemes as shown in Fig. 5-7 (a). Further, the effect of parametric uncertainty is considered, in case 2. The frequency deviation and tie line power deviation have been reached zero within 2-3 seconds compare to other control schemes as depicted in Fig. 5-7 (b-c). Furthermore, the effect of GRC and GDB is considered, in case 3. The frequency deviation and tie line power deviation have been maintained zero within 2-3 seconds compare to other control schemes as demonstrated in Fig. 5-7 (d-f).

Table 1. Controller parameters

Controller	k_p	k_i	k_d	k_a or k_{dd}
Tan (2009)	1.5692	2.3966	0.5259	-
Anwar (2015)	3.55	5.95	1.22	-
Sahu (2016)	0.0260	0.2997	-	0.1819
Mohanty (2017)	-0.3735	0.3645	-	-
Proposed PIDA-CDA	4.3871	5.5565	1.4970	0.0520



(a) (d)



(b) (e)

(c) (f)

Fig. 5 (a-f). Frequency deviation in area 1 for (a,d) nominal , (b,e) lower bound, and (c,f) upper bound system parameters, for (a-c) without and (d-f) with, GRC and GDB respectively.

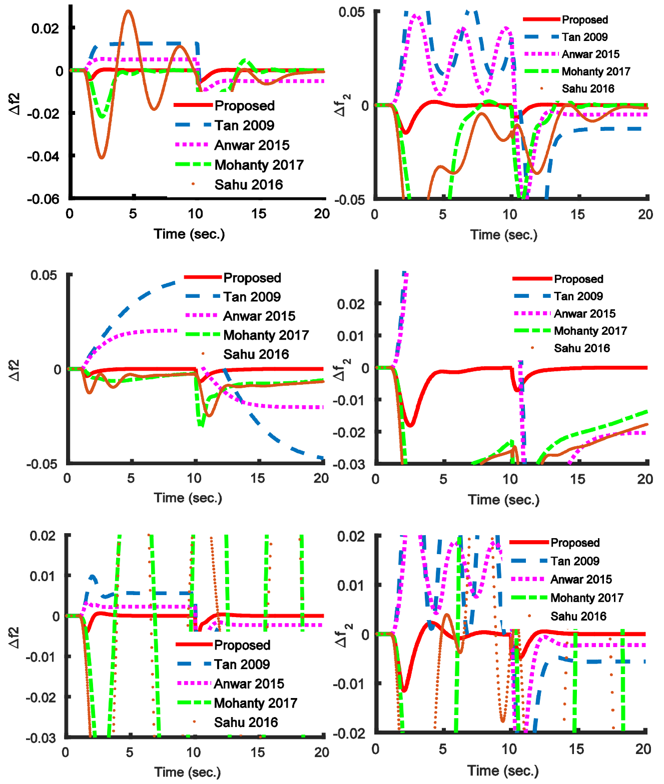


Fig. 6 (a-f). Frequency deviation in area 2 for (a,d) nominal , (b,e) lower bound, and (c,f) upper bound system parameters, for (a-c) without and (d-f) with, GRC and GDB respectively.

The effectiveness of PIDA-CDA control scheme is also evaluated by observing the settling time in case of nominal values of system parameters as shown in Table 2. The settling time of PIDA-CDA is lesser as compared to other control scheme. The CDA-PIDA control scheme is better compared to TLBO-PIDD control scheme (Sahu *et al.*, 2016) for LFC.

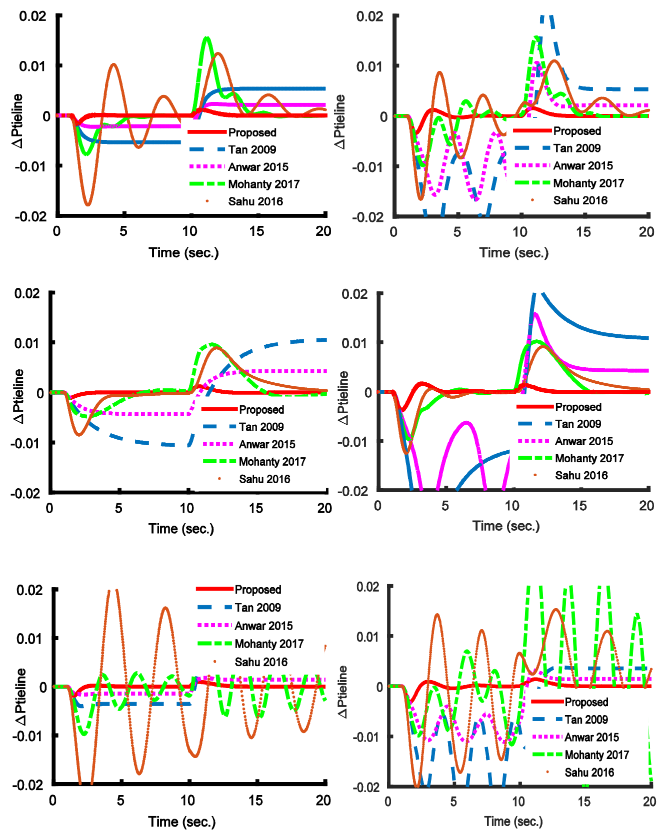


Fig. 7 (a-f). Tie line power deviation for (a,d) nominal , (b,e) lower bound, and (c,f) upper bound system parameters, for (a-c) without and (d-f) with, GRC and GDB respectively.

Remark: The CDA-PIDA control scheme is fulfilled the objectives of LFC in the presence of parametric uncertainty, physical constraints and load disturbance, where other control schemes are failed.

Table 2. Areas' frequency deviation (Δf_1, Δf_2) and tie-line power deviation ($\Delta P_{tieline}$) for nominal values (case 1) in terms of settling time

Controller	Δf_1	Δf_2	$\Delta P_{tieline}$
IMC-PID (Tan (2009))	3.00	3.00	3.00
DS-PID (Anwar (2015))	2.50	2.00	2.10
TLBO-PID (Sahu (2016))	NA	NA	NA
MFO-PI (Mohanty (2017))	6.00	5.00	4.00
Proposed CDA-PIDA	1.90	1.85	2.00

NA=The settling time is not attained steady state as shown in Fig. 5-7(a).

6. CONCLUSIONS

This paper is presented the robust CDA-PIDA controller for load frequency control problem. The performance of CDA-PIDA control scheme is evaluated under ± 50% parametric uncertainty, load disturbance and physical constraints such as GRC and GDB. The CDA-PIDA controller is robust and better over other IMC-PID, DS-PID, TLBO-PIDD and MFO-

PI control schemes for load frequency control of interconnected power systems. The proposed controller will be extended for multi-area interconnected power system.

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Appendix A. SYSTEM PARAMETERS

Nominal values of system parameters (Tan, 2009; Anwar *et al.,* 2015; Sahu *et al.,* 2016; Mohanty *et al.*, 2017) are given as follows:
Frequency bias $B_i = 0.425$, $R_i = 2.4$, $T_{pi} = 20$, $T_{gi} = 0.08$, $T_{12} = 0.545$, $T_{ti} = 0.3$, $K_{pi} = 120$, $i = 1,2$.