Wind Energy Infiltrated Multi-Area Power System: Optimized 2-DOF-FOPID Controller for LFC

Indrajit Koley*‡, Asim Datta**, Goutam Kumar Panda***

*Department of Electrical Engineering, Siliguri Institute of Technology, Siliguri-734009, India

** Department of Electrical Engineering, Mizoram University, Aizawl, Mizoram-736004, India

*** Department of Electrical Engineering, Jalpaiguri Government Engineering College, Jalpaiguri-735102, India

(indrajit.koley@gmail.com, asimdatta2012@gmail.com, gpandaee@gmail.com)

‡ Corresponding Author; Indrajit Koley, Siliguri Institute of Technology, P.O-Sukna, Salbari, Siliguri-734009, W.B, India, Tel: +919832726002, indrajit.koley@gmail.com

Received: 13.03.2020 Accepted:11.04.2020

Abstract- The major concern for deviation of frequency in renewable energy penetrated power generating system is the intermittent nature of the inputs in addition to variable load demand. This paper investigates load frequency control (LFC) of a thermal-wind-thermal based hybrid power generating unit. A two-degree-of-freedom (2-DOF) fractional-order-proportional–integral–derivative (FOPID) controller is implemented to control the frequency of the proposed system. Cuckoo search algorithm (CSA) is applied to optimize the gains parameters of the proposed controller. The results obtained from the proposed CSA tuned 2-DOF-FOPID controller are compared with the traditionally well-known conventional controllers. MATLAB simulation shows that, compared to the conventional widely applied PI and PID controllers, the presented controller reveals superior response in terms of lesser transient time, less overshoot, wide robustness to limit the frequency deviation (FD) within the acceptable range considering integral square error (ISE) as an objective function.

Keywords Cuckoo search algorithm (CSA), hybrid power system, load frequency control (LFC), robust 2-DOF FOPID controller, wind energy infiltration

1. Introduction

Incorporation of renewable energy sources (RES) with the thermal power generating system has become an appropriate choice with the increased demand as per the present scenario of energy sector. But the main concern in generation of power from the RES is the fluting nature of inputs which rules the output power and frequency of the system [1]. Solar and wind are the most prominent renewable energy sources due to their wide-spread availability. Compared to solar energy, the wind is more prospective in mega range generation due to high power intensity and probable day-night generation [2]. Recent trend in the power systems is to interconnect mega-power coastal wind-farms with conventional thermal based power system for a prospective power balance. In wind farms the rotor of the induction generator rotates due to the speed of the wind which is not steady throughout and the system frequency is highly affected by the variable wind generation [3]. That is why it is vastly required to regulate the power generation for limiting the frequency deviation (FD). When wind energy-based area is interconnected with the conventional thermal based area(s), load frequency control (LFC) in such hybrid system seems to be a very challenging task. Many researches have been carried out in recent past for LFC in single and multi-area electrical power systems [4].

The key objective of LFC is to control the deviation of output frequency of entire power system and tie line power within a patience range during the variation in both power generation and demand of load [1]. To overcome the limitations of open loop control system and to design closed loop control system, conventional controllers such as integral (I), proportional-integral (PI), proportional–integral-derivative (PID), are widely used in LFC [5]. PI control is required for non-integrating measures in designing of system for automatic generation and control (AGC) in power systems. Authors in [6] designed a dual mode bat inspired algorithm tuned PI control system for LFC in multi-area generating system. However, there are many disadvantages of PI controllers like greater maximum deviation, unsuitable for slow moving process variables, higher response time and period of oscillation. Hybrid fuzzified integral control [7] and PI with artificial intelligent [8] have also been explored. But the dynamic responses of PI controllers are always with additional oscillations and settling time. Whereas the PID controller can be applied for regulating both the slow and fast process variables with moderate peak overshoot and constancy. A genetic-fuzzy tuned LFC system was proposed for a multi-area thermal generating unit [9]. A unified PID tuning [10] and an optimal multiple input-multiple output (MIMO) [11] PID controllers were presented. Fuzzy based particle swarm optimization (PSO) [12] and PID controller optimized by cuckoo search method [13] were presented. Two-degree-of-freedom (2-DOF) PI [14] and 2-DOF PID [15] controllers were applied for LFC in power systems. The conventional single-DOF PI, PID, and integral order (IO) controllers are not capable enough for tracking of set point and disturbance elimination of the power system. A radical improvement is obtained in the area of designing of control system with the introduction of fractional order (FO) calculus [16]. The order of regular integrator and differentiator parameters are replaced by non-integer values with this method. Controllers with fractional mathematics provide better performance. With improved computation, fractional order (FO) controllers perform for complex processes [17]. Differential evolution (DE) [15], genetic algorithms (GA) [4], etc., have also been applied for optimal setting of controller gains in 2-DOF PID based load frequency controllers. IO [18] and internal model control (IMC) [19] based 2-DOF [20] control strategies gave superior performance in LFC [18]. A 2-DOF controller has high dynamic response in tracking of set-point variables and regulation over 1-DOF controller. Implementation of teaching learning-based optimization (TLBO) with parallel 2-DOF PID controller for LFC in two-area thermal power system is presented [20]. Recent researchers on LFC with FO based controllers [21] have found advantages such as robustness, better dynamic response, etc. in thermal based multi-area power system. Though FO based controllers have many advantages, remarkably, rare initiative has been taken to design FO based robust LFC controller for application under renewable energy penetrated challenging environments.

Very few literatures in the recent past have studied and evaluated the performance of FO controllers in LFC in power systems which need further investigations. The present work investigates a robust 2-DOF FOPID controller in a multi-area LFC problem which has not been explored properly before under intermittent renewable energy penetrated environment. This paper presents the dominance and benefit of FO controller along with 2-DOF concept in AGC in a renewable energy penetrated multi-area power system. Step load perturbation (SLP) is applied in this LFC study with full accuracy.

2. Challenges in Wind Energy Penetrated Power System

In recent days, renewable energy sources (RESs) have been emerged into a great attention [22]. Due to the favorable economic policy and climate consideration, the infiltration of RES in power systems is being rapidly augmented throughout the world. Among the RES, the wind energy is the most fortunate one in large-scale and day-night generation [2]. Nevertheless, the rapidly increased incorporation of wind power generating units has conveyed a severe contest in real-time power system frequency regulation. Maximum power tracking for a wind turbine generator (WTG) is a dynamic operation causing for indeterminate contribution. There may be a zero-spinning reserve for exploitation in the frequency auxiliary amenities during the functioning of the WTGs in maximum power tracking mode. The augmented integration of wind power generation and the necessities to follow grid codes essentially call for advanced AGC technologies for present and future interconnected power systems [3]. New and innovative AGC technologies may be helpful for avoiding unnecessary shut-down/re-starting and turbine over speeding to improve the wind plant life [23]. Investigations show that the effects on the system frequency due to the wind energy integration is substantial, which become more at higher level of penetration [24]. That is why, recently, instrumentation of progressive AGC strategies to achieve a skillful frequency regulation in renewable energy penetrated multi-area power systems has been emphasized by the power system research community [25].

3. System Description

The investigated multi-area power system includes three-area thermal-wind-thermal generating systems with the capacity of 2000MW, 600 MW and 2000 MW. The thermal-wind-thermal system indicates interconnection of two steam power plants with one wind turbine plant. The projected power system is depicted with transfer function models in Fig. 1. The speed regulation factor (SRF_i) of the speed governor is taken as 2.4 Hz/p.u MW. The frequency bias (FB_i) value is taken same as the frequency response characteristics [23], $b_i=D_i + 1/SRF_i$, where $D_i = \dfrac{\Delta P_{Di}}{\Delta f}$. Per unit values of individual area parameters are assumed on their relevant area bases. Therefore, for modeling the multi-area systems the parameters are considered as $a_{12}= \frac{P_{r1}}{P_{r2}}$, $a_{23}= \frac{P_{r2}}{P_{r3}}$. Where a_{12} and a_{13} are the area size ratios and P_{ri} is the

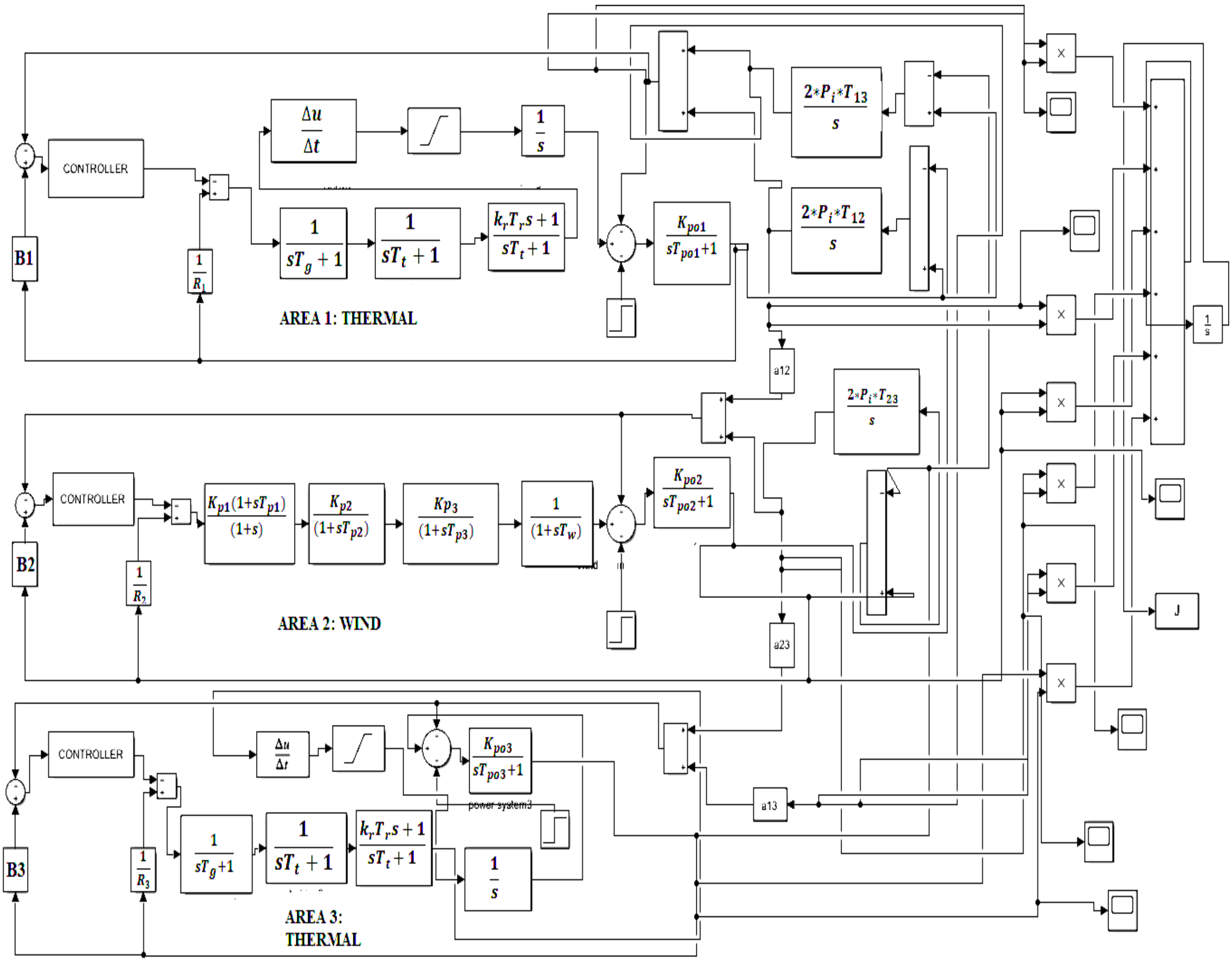


Fig. 1. Multi-area power system with transfer function model.

capacity of rated power of individual area *i*. The system is also studied with the conventional single order classical controllers, PI and PID. SLP of 0.1 p.u is applied to study the dynamic response of the used controllers in each area. A CSA tuned optimized 2-DOF FOPID controller is used for making the deviation of output frequency of the entire system constant under the application of step load. All the generating areas are modeled in Matlab/SIMULINK environment on basids of the transfer functions. A cost function (*J*) is expressed in Eq. (1) in terms of integral squared error of bus frequency and tie bus power. Optimization is performed for the minimization of *J* given as [5]:

$$J = ISE = \int_0^T \{(\Delta f_i)^2 + (\Delta P_{tie\ i-j})^2\} dt \qquad (1)$$

The steps for the entire simulation is shown is Fig.2.

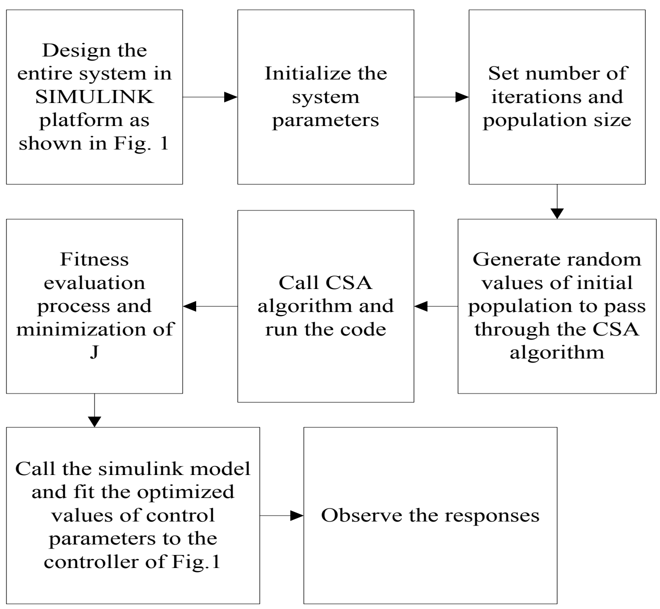


Fig. 2. Simulation steps.

3.1. Modeling of Thermal System

The thermal power generation system comprises of steam turbine, governor, re-heater and speed regulation gain. The transfer function (TF) model of different units are interconnected, as shown in the thermal areas of Fig. 1. [5][26]:

The governor system is represented as:

$$G_g(s) = \frac{1}{1+sT_g} \tag{2}$$

The representation of steam turbine system with TF as:

$$G_t(s) = \frac{1}{1+sT_t} \tag{3}$$

The transfer functions for the re-heat system:

$$G_r(s) = \frac{1+sK_rT_r}{1+sT_r} \tag{4}$$

where, T_g is the time constant (TC) of the speed governor, T_t is the TC of the turbine, T_r is the TC of the re-heating system, K_r is the gain of the unit of high-pressure stage.

3.2. Modeling of Wind Generation System

The wind generation system comprises of actuator, pitch control, data fit pitch response and wind turbine. The power delivered from wind turbine is dependent upon various parameters like speed of wind (V_w), pitch angle (β), blade radius (r), air density (ρ), and power co-efficient (C_P (λ, β)). The power generated from wind turbine is given as follows [27]:

$$P_m = \frac{1}{2}\pi\rho C_p(\lambda,\beta)R^2V_w^3 \tag{5}$$

$$\lambda = \frac{\omega R}{V_w} \tag{6}$$

where, ω = speed of wind, λ = speed ratio

The power coefficient is expressed as :

$$C_p(\lambda,\beta) = \sum_{i=0}^{4}\sum_{j=0}^{4}\alpha_{ij}\beta^i\lambda^j \tag{7}$$

where α_{ij} = coefficient of C_p .

The TF model of pitch actuator:

$$G_x(s) = \frac{K_{p1}K_{p2}(1+sT_{p1})}{(1+s)(1+sT_{p2})} \tag{8}$$

The TF model of data fit system:

$$G_d(s) = \frac{K_{p3}}{1+sT_{p3}} \tag{9}$$

The TF of the wind turbine is represented by:

$$G_w(s) = \frac{1}{1+sT_w} \tag{10}$$

where T_x= TC for pitch actuator, T_d= TC for data fit system, and T_w= TC for wind turbine [28].

4. Optimization of Controller Parameters

In the recent past, numerous optimization techniques or algorithms have been applied in designing load frequency controllers to solve the problem related to regulation of power system frequency [3]. To design of an advanced robust controller with accurately optimized analogous parameters for optimal performance are the challenges in LFC. Different heuristic and metaheuristic optimization techniques or algorithms like PSO [29], Antlion optimize [22], bacterial foraging optimization (BFO) [30], Grasshopper Optimization Algorithm (GOA) [31], Firefly algorithm (FA), artificial bee colony (ABC) [4], etc. were practiced by researchers for designing of the load frequency controllers. PSO based on metaheuristic algorithm that mathematically models behaviors of swarms is presented in [12]. Antlion optimize is used to optimize problems iteratively simulating the interaction of ants and antlions in environment [32]. BFO is a nature-inspired optimization technique that emulates the *foraging* strategy of E. coli [30]. GOA is one that imitates the comportment of grasshopper swarms in environment [31]. The Firefly algorithm (FA) is a also a metaheuristic optimization motivated by the blinking property of fireflies. ABC optimization algorithm mathematically models and mimics the intelligent foraging nature of honey bee swarm [4]. Recently, Cuckoo search algorithm (CSA) has been applied by researchers in solving optimization problems [33]. Yildiz [34] has applied CSA for the deciding of optimal machining parameters in milling processes, and also derived an advanced conclusion. Research illustrates that CSA is a very efficient and could perform much better than some other well-known metaheuristic algorithms [5]. Few recent researches address intelligent optimization practices like genetic algorithm (GA) [25], Fuzzy logic [9], etc., for the LFC issue in the interconnected power systems. Outcome of CSA is comparatively better than metaheuristic algorithms in respect of convergence, precision and robustness [33]. But still, it is noticed that very few reports are available on the intelligent frequency control design for wind generation penetrated power systems.

Seeing the recent scenario and the necessity for integrating of renewable energy to the already existing conventional electrical power system, an attempt is made to use CSA tuned proposed controller. The responses are compared with other optimization techniques like FA and GA.

5.1. Cuckoo Search Algorithm (CSA)

CSA is nature-inspired meta-heuristic optimization tool introduced in 2009 by Deb and Yang [35]. CSA is stimulated by nature dependent on brood reproductive way of cuckoo birds to enhance their population. It is influenced by the upbringing strategy of the species of some cuckoos in connection with Lévy flight behavior of some birds. Lévy flights are arbitrary walks in random directions whose step lengths are derived from the Lévy distribution. Several researches have presented that the flight behavior of many species have demonstrated the typical behavior of Lévy flights [36]. The bird is popular due to their reproduction strategy and sound. The Cuckoo birds use to lay their eggs in some other bird's nest. Some species like, brood-parasitic tapera, are often very particular in the imitation in color and pattern of the eggs of a few selected swarm species. In this way, Cuckoos have evolved to increases their reproductively. Rules for CSA are [37]:

a. Randomly a nest is chosen to lay eggs.
b. High quality of eggs with the best nest is passed to the subsequent generation.
c. For a particular number of nests, a swarm cuckoo could find an extraneous egg with a probability P_a = [0,1]. In the situation, the swarm cuckoo could either heave the egg away or build a new nest somewhere else.

The last rule can be roughly applied with the probability fraction P_a of the$n$ host nests with new random nests (solutions). Flowchart of CSA is shown in Fig. 3.

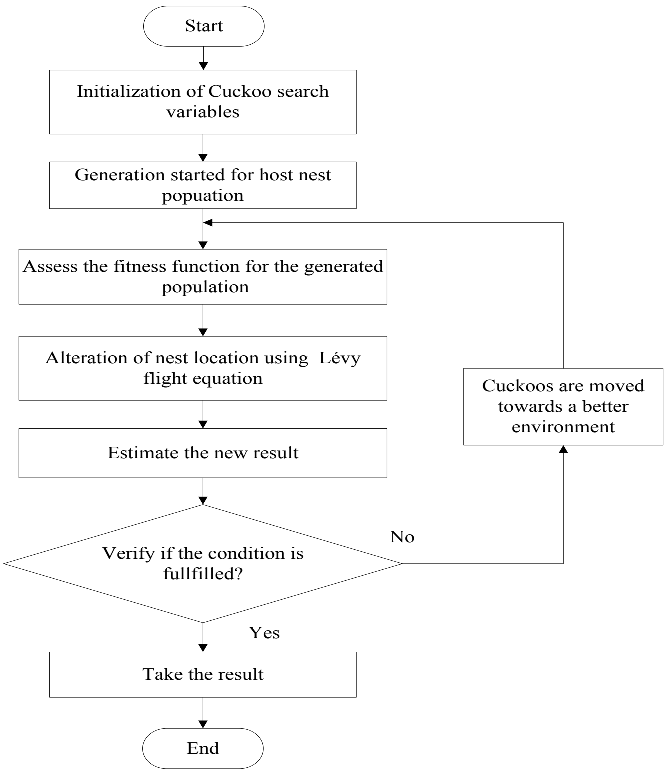


Fig. 3. Flowchart of CSA [13].

6. 2-DOF-FOPID Controller

In a closed-loop control system, the degree of freedom determines the command input response and the independent disturbance rejection characteristics. The transfer functions that can be attuned in dependently govern the DOF of a closed-loop control system. Smoothly set-point variable tracking and disturbance suppression are the key considerations to select 2-DOF-FOPID controller by the control engineers. 2-DOF-FOPID controller gives difference with the single DOF FOPID controller by giving output signal after comparing with the reference signal with the measured signal [12]. The controller's output is the summation of proportional, derivative and integral actions of the corresponding difference signals and the actions are decided on the weight of the gain parameters. The used controller improves the stability, gives fast response compared to conventional PI and PID controllers. For PID the derivative operator boosts turbulences radically that sources instability for the system. Therefore, a filter is generally included in the FO derivative term in order to lessen the harmful effect of the high-frequency restrained signal. The concept and advantages of 2-DOF controllers over conventional controllers are described in [15].

The transfer functions of 2-DOF-FOPID controller are presented as [38]:

$$C(s) = K_p + \frac{K_I}{S^{\lambda}} + \frac{K_D S^{\mu}}{1 + \frac{K_D s^{\mu}}{K_P N}} \quad (11)$$

$$F(s) = K_p \beta + \frac{K_I}{S^{\lambda}} + \frac{K_D S^{\mu}}{1 + \frac{K_D s^{\mu}}{K_P N}} \delta \quad (12)$$

Where, N is the coefficient of derivative filter and β, δ are the parameters of set-point weight.

The fractional derivative can be expressed by the commonly applied Riemann–Liouville (R–L) expression as [38]:

$$_x D^x f(t) = \frac{1}{\tau(n-x)} \frac{d^n}{dt^n} \int_a^t (t-\tau)^{n-x-1} f(\tau) d\tau \quad (13)$$

Where n is an integer number, the range of integer x is $n-1 \le x < 1$, and τ(.) is called as Euler's gamma function.

The fractional integral function is expressed as:

$$_x D^{-x}{}_t f(t) = \frac{1}{\tau(x)} \int_a^t (t-\tau)^{x-1} f(\tau) d\tau \quad (14)$$

where $_x D^{-x}{}_t$ = fractional operator.

The fractional derivative expression of Riemann–Liouville definition can be transformed in Laplace domain as [39]:

$$L\{{}_aD^{\alpha}{}_t f(t)\} = s^j F(s) - \sum_{k=0}^{n-1} s^{j-k-1}{}_{\alpha} f(t) \quad (15)$$

The extra tuning parameters: the non-integer order integer (λ) and the differentiator (μ) enables the additional advantage of tuning of system dynamics.2-DOF control scheme in Laplace domain is shown in Fig. 4.

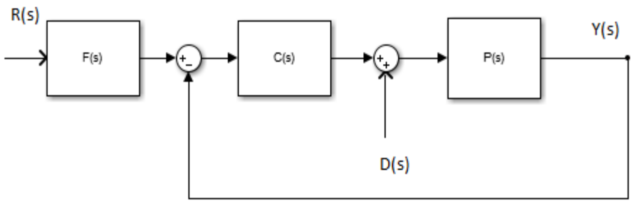


Fig. 4. 2-DOF control scheme [38].

F(s) is the pre filter of the reference signal, C(s) is the single degree of freedom controller, D(s) is the load disturbance, R(s) is the reference signal and Y(s)is the feedback from the measured system output

7. Simulation Results and Comparative Study

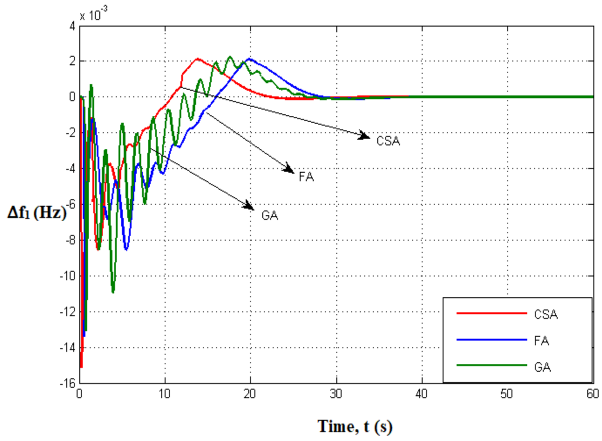
A simulation-based study is done on a thermal-thermal-wind based multi-area hybrid power system to investigate the response of the applied 2-DOF-FOPID controller. Matlab/SIMULINK platform is applied to model the entire system. The gains of the proposed controller are optimized with CSA technique. Figure 5 shows the comparative study of the responses obtained from CSA tuned 2-DOF-FOPID controller with FA and GA tuned 2-DOF-FOPID controller. Responses reveal that the settling time and overall responses of the system with CSA tuned 2-DOF-FOPID controller is much better as compared to FA and GA tuned controller. Furthermore, the responses of the system obtained from 2-DOF-FOPID controller are compared with the traditional PI and PID controllers considering 0.1 p.u load disturbance for each area; it is found that the proposed controller shows superior outcomes. The optimized values of the gains of 2-DOF-FOPID controller with CSA are represented in Table 1. Table 2 represents the settling time, peak overshoot and peak undershoot of the FD of the all the individual areas with CSA, GA and FA tuned 2-DOF-FOPID controller. It is clearly observed from the responses that the CSA tuned 2-DOF-FOPID controller is superior compared to GA and FA technique.

Table 1. Optimized values of the gains of 2-DOF-FOPID controller for three areas with CSA

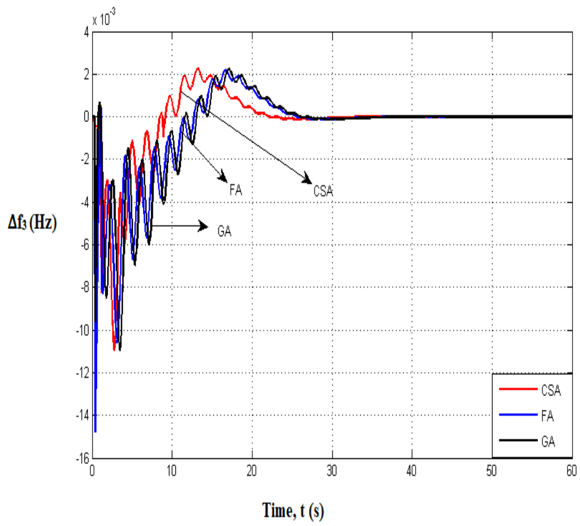
Algorithm	**Area**	**2-DOF-FOPID Controller Parameters**				
		K_{Pi}	K_{Ii}	K_{Di}	λ_i	μ_i
CSA	Area 1	-0.002	-0.2401	-0.4366	0.9091	0.9509
	Area 2	0.0027	0.2705	-0.2621	0.9582	0.7522
	Area 3	-0.0054	-0.2826	0.0691	0.9155	0.1385

Table 2. Data of Settling time, peak overshot, and peak undershoot for CSA, FA and GA optimized system

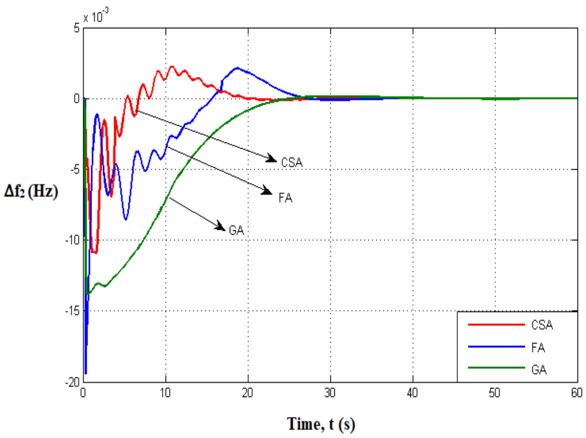
Algorithm	**CSA**			**FA**			**GA**		
Parameter (Hz)	**Settling time (s)**	**Peak overshoot (s)**	**Peak undershoot (s)**	**Settling time (s)**	**Peak overshoot (s)**	**Peak undershoot (s)**	**Settling time (s)**	**Peak overshoot (s)**	**Peak undershoot (-) (s)**
Δf_1	21.9	0.020	0.015	27.1	0.020	0.013	30.1	0.021	0.010
Δf_2	25.1	0.0027	0.010	27.7	0.002	0.019	31.7	-0.0007	-0.013
Δf_3	20.9	0.002	0.009	25.3	0.002	0.014	25.9	0.002	0.0109
ΔP_{1-2}	22.5	0.002	0.014	29.3	0.002	0.020	31.1	0.002	0.026
ΔP_{1-3}	19.1	0.002	0.010	25.1	0.002	0.019	27.4	0.002	0.022
ΔP_{2-3}	21.4	0.002	0.009	26.1	0.002	0.021	27.0	0.0021	0.010



(a)



(c)



(b)

Fig. 5. Comparative study of responses of (a) Δf_1 (b) Δf_2 (c) Δf_3 with CSA, FA and GA.

Table 3 represents the Eigen values of the two connected thermal and wind areas. From the results it is observed that the real part of the Eigen values is having negative sign which confirms stability of the system.

Table 3. Eigen values of area 1 and area 2 with 0.1 p.u load disturbance in area 1

CSA	FA	GA
-9.87640+0.00000i	-9.86391+0.00000i	-9.847986+0.00000i
-13.48657+0.00000i	-15.69874+0.00000i	-15.678945+0.00000i
-0.0874985+3.8469i	-0.63896+5.5679i	-0.76869+5.36948i
-0.0874985+3.8469i	-0.63896+5.5679i	-0.76869+5.36948i
-0.748656+1.1256i	-0.8647+2.28779i	-0.87965+1.7569i
-0.748656+1.1256i	-0.8647+2.28779i	-0.87965+1.7569i
-0.68796+1.05987i	-0.789466+1.98766i	-0.745896+1.06985i
-0.59875+1.002676i	-0.698236+1.03645i	-0.691278+1.0226i
-1.56812+0.0000i	-0.68945+0.0000i	-0.81135+0.0000i
-0.76488+0.0000i	-0.21653+0.0000i	-0.197889+0.0000i
-0.26789+0.0000i	-0.3652+0.0000i	-0.3596+0.0000i

The optimal gains of each controller are determined and dynamic responses subsequent to the optimal gains are investigated. The critical parameters of all the dynamic responses such as the settling time, peak overshoots and peak undershoot under 0.1 p.u disturbance of load in area 1 are observed and presented in Table 4. Figure 6 presents the dynamic responses of FD and deviation of tie line power of each area under 0.1 p.u load disturbance. From Fig. 5 it is observed that the responses obtained from the 2-DOF-FOPID controllers are better considering the settling time, peak deviations and magnitude of oscillations.

Table 4. Data of Settling time, peak overshot, and peak undershoot for 0.1 p.u load change in area 1

Parameter	Settling time (s)			Peak overshoot			Peak undershoot (–)		
	PI	PID	2-DOF-FOPID	PI	PID	2-DOF-FOPID	PI	PID	2-DOF-FOPID
Δf_1	30.6	27.5	21.5	0.0035	0.003	0.002	0.034	0.026	0.009
Δf_2	27.6	26.5	15.4	0.005	0.004	0.001	0.034	0.027	0.011
Δf_3	25.5	23.4	16.6	0.004	0.0038	0.001	0.035	0.03	0.022
$\Delta P_{1\text{-}2}$	28.4	25.2	16.8	0.006	0.04	0.003	0.020	0.26	0.02
$\Delta P_{1\text{-}3}$	29.3	26.4	17.1	0.002	0.0021	0.0018	0.0217	0.014	0.010
$\Delta P_{2\text{-}3}$	27.1	20.4	12.3	0.002	0.002	0.003	0.021	0.011	0.009

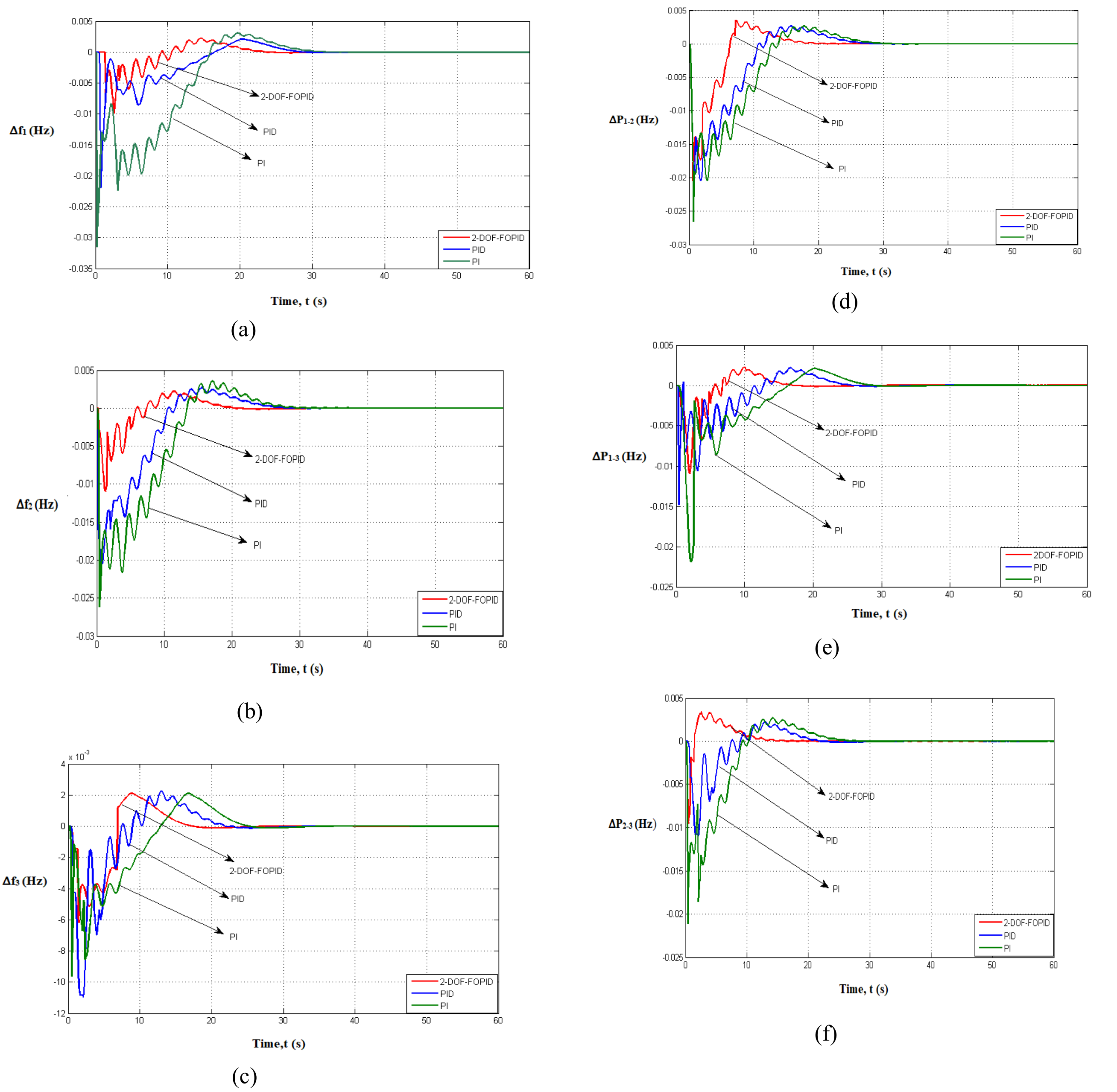


Fig. 6. Comparative study of time responses of (a) Δf_1 (b) Δf_2 (c) Δf_3 (d) $\Delta P_{1\text{-}2}$ (e) $\Delta P_{1\text{-}3}$ (f) $\Delta P_{2\text{-}3}$ with different controllers for 0.1 p.u load disturbance in area 1

Table 5 presents the data of settling time, peak overshoot and peak undershoot of the responses obtained from the multiarea power system with PI, PID and 2-DOF-FOPID controllers for 0.1 p.u load disturbance in wind area. Figure 6 shows the responses of the three connected areas with PI, PID and 2-DOF-FOPID controllers. Comparative study from Fig. 7 as well as the analysis of Table 5 show that, the proposed 2-DOF-FOPID controller presents faster settling time and acceptable transient response as compared to PID and PI controllers.

Table 5. Data of Settling time, peak overshot, and peak undershoot for 0.1 p.u load change in area 2

Parameter	Settling time (s)			Peak overshoot			Peak undershoot (–)		
	PI	PID	2-DOF-FOPID	PI	PID	2-DOF-FOPID	PI	PID	2-DOF-FOPID
Δf_1	27.8	23.2	14.8	0.002	0.002	0.0001	0.02	0.009	0.013
Δf_2	26.6	23.5	15.8	0.0022	0.002	0.002	0.013	0.009	0.01
Δf_3	30.9	28.5	23.0	-0.009	0.003	0.002	0.035	0.03	0.01

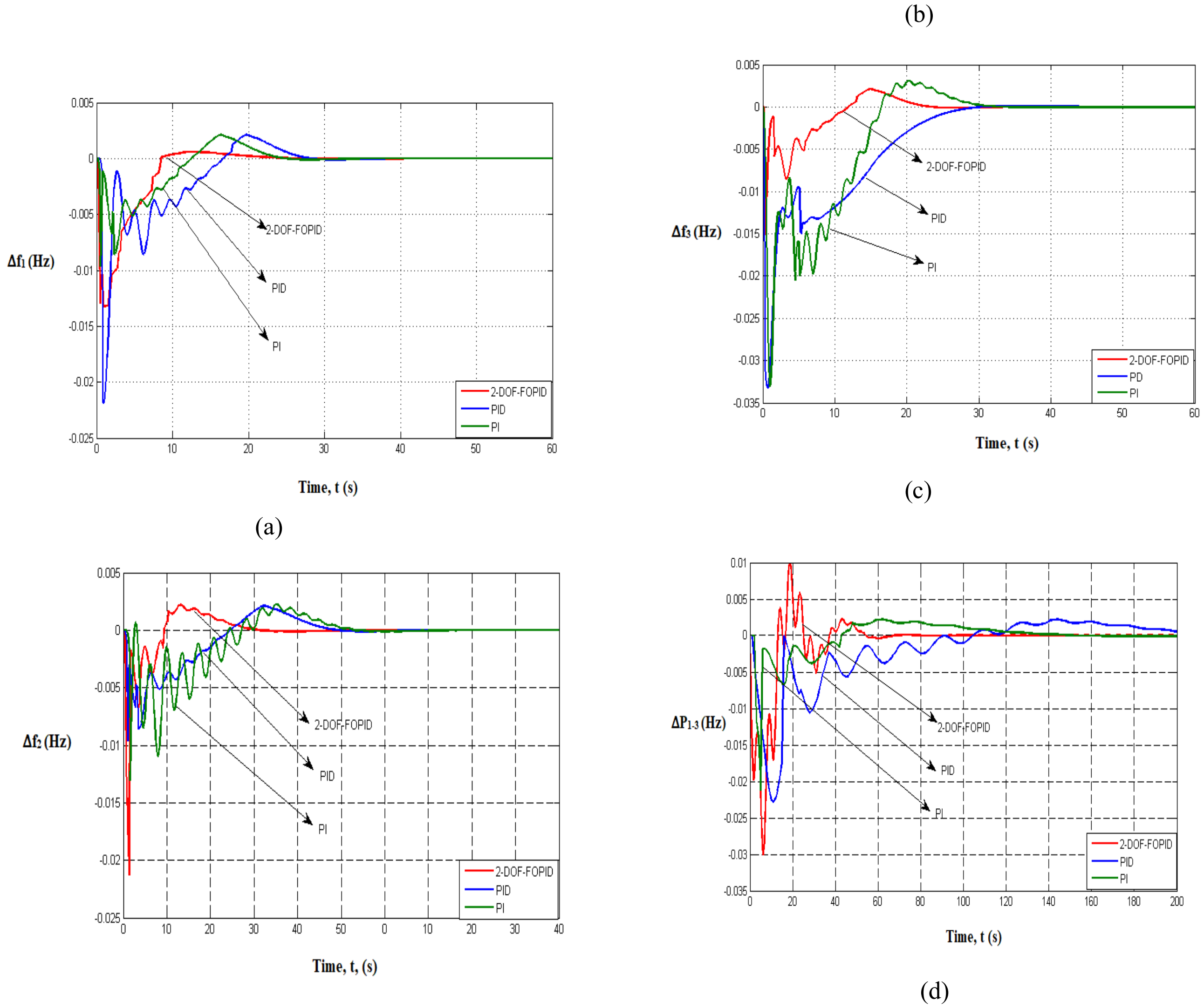
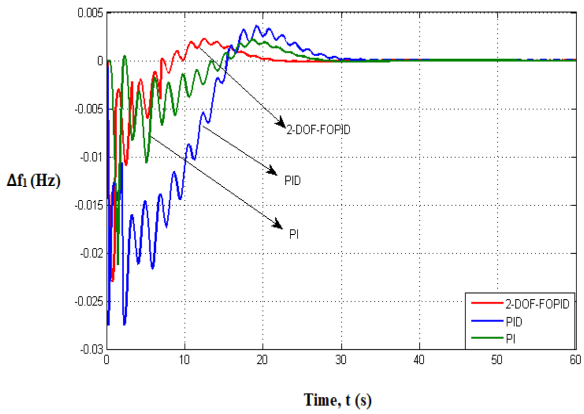


Fig. 7. Comparative study of time responses of (a) Δf_1 (b) Δf_2 (c) Δf_3 (d)Δ P_{1-3} with different controllers for 0.1 p.u load disturbance in area 2.

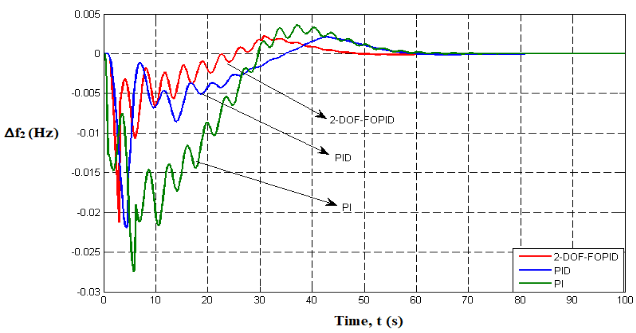
Table 6. Data of Settling time, peak overshot, and peak undershoot for 0.1 p.u load change in area 3

Parameter	Settling time (s)			Peak overshoot			Peak undershoot (–)		
	PI	PID	2-DOF-FOPID	PI	PID	2-DOF-FOPID	PI	PID	2-DOF-FOPID
Δf_1	30.8	27.5	20.1	0.002	0.003	0.0001	0.027	0.027	0.020
Δf_2	31.8	28.8	22.2	0.0032	0.003	0.002	0.02	0.02	0.02
Δf_3	31.1	30.9	22.4	0.004	0.0004	0.002	0.022	0.02	0.02

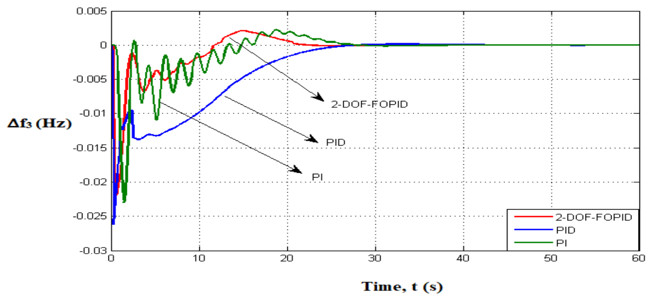
Comparison is also done with 0.1 p.u load perturbation in area 3 and the data of settling time, peak overshoot and peak undershoot are noted in Table 6. From the responses obtained from Figs. 6, 7 and 8, it is obvious that CSA tuned 2-DOF-FOPID controller provides superior outcomes in terms of lesser settling time and good transient responses as compared to conventional PI and PID controllers as mentioned in abstract. Whereas Fig. 5 demonstrates the superiority of CSA for faster dynamic response as compared to GA and FA.



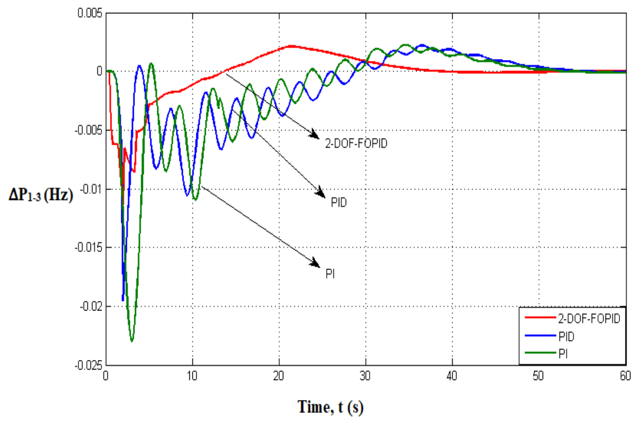
(a)



(b)



(d)



(e)

Fig. 8. Comparative study of time responses of (a) Δf_1 (b) Δf_2 (c) Δf_3 (d)Δ $P_{1\text{-}3}$ with different controllers for 0.1 p.u load disturbance in area 3.

Further the robustness of the system is investigated with +50% and -50% loadings and the data of settling times, peak overshoot and peak undershoots are noted as shown in Table 7. Figure 8 presents the responses of 2-DOF-FOPID controllers with +50% and -50% loading compared to nominal. From the responses of Fig. 8 and analysis of Table 7 it is found that the proposed controller gives robust performance for wide range of load variations.

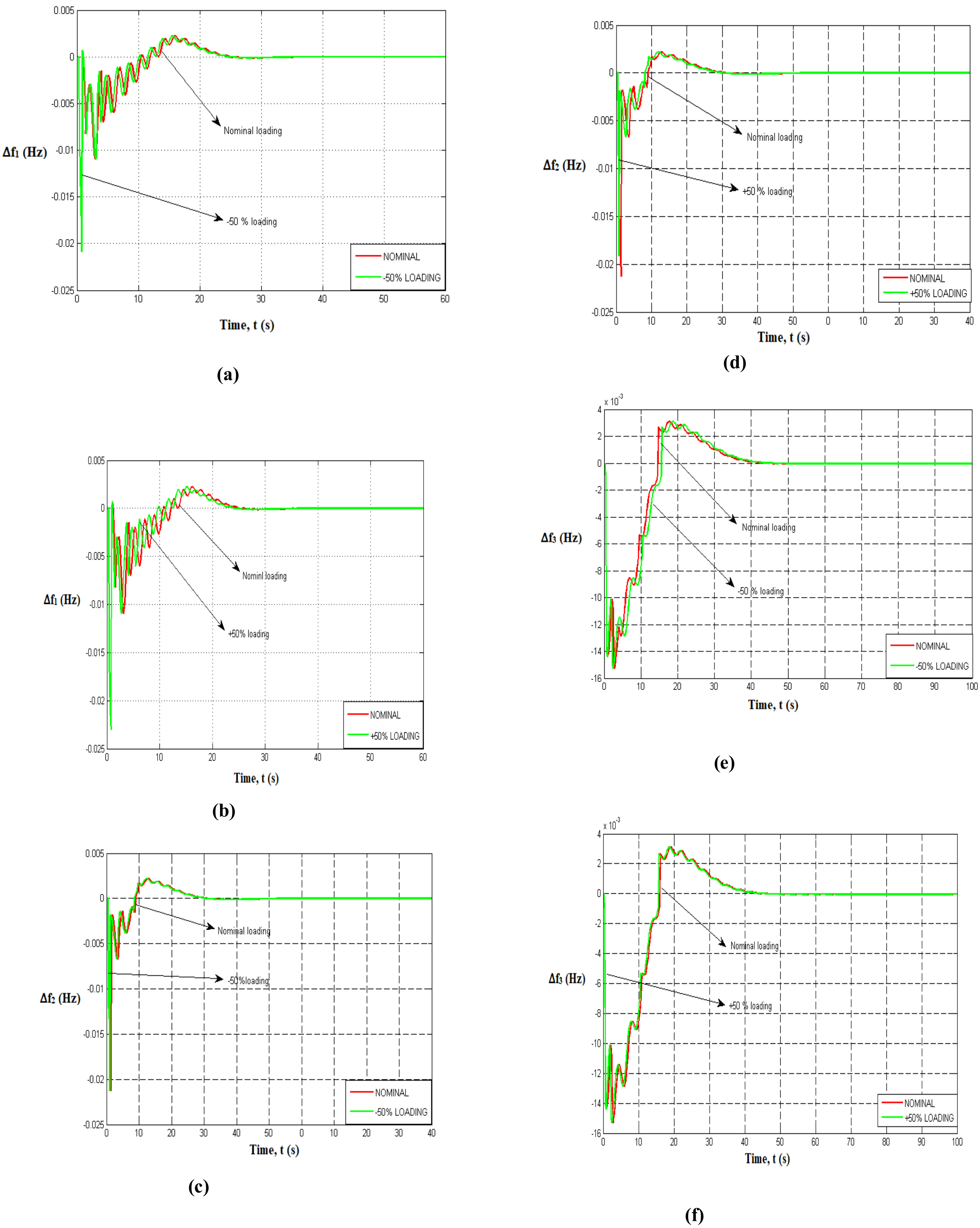


Fig. 9. Sensitivity analysis of time responses of (a) Δf_1 (b) Δf_2 (c) Δf_3 (d) ΔP_{1-2} (e) ΔP_{1-3} (f) ΔP_{2-3} with 2-DOF-FOPID controller for nominal loading, with +50% loading and -50%loading.

Table 7. Sensitivity analysis at different loading on the area 1

Area 1 loading	Deviations	Maximum overshoot (Hz/p.u)	Maximum Undershoot (Hz/p.u)	Settling time (second)
+50% loading	Δf_1	0.002	-0.024	23.9
	Δf_2	0.0019	-0.021	14.6
	Δf_3	0.003	-0.015	19.6
-50% loading	Δf_1	0.0022	-0.022	23.5
	Δf_2	0.002	-0.019	14.9
	Δf_3	0.0029	-0.014	19.8

8. Conclusion

LFC in a wind energy penetrated unequal multi-area thermal-thermal-wind system is investigated by using CSA optimized robust 2-DOF-FOPID controller. From the comparative study with conventional PID and PI controller, it is found that the CSA tuned 2-DOF-FOPID controller provides much better output in terms of dynamic response, peak deviation of frequencies, tie-line power, and time error. The outputs of GA and FA are also compared with CSA and it also found that the CSA tuned system gives better curve. The proposed 2-DOF-FOPID is also found to perform well with the higher order of step load perturbation. Finally, it can be concluded that CSA optimized 2-DOF-FOPID control scheme is more robust and faster for LFC in complex wind energy penetrated multi-area power system.

Appendix:

The nominal system parameters are f = 50 Hz, T_g=0.08 s, T_t= 0.03 s, T_r= 10 s, K_r= 0.5 s, K_{poi}= 120 Hz/p.u, T_{poi}= 20 s, T_{ij}= 0.086 MW/rad, K_{p1} =1.25, T_{p1} =0.6 s, T_w =4 s, H_i= 5 s, D_i= 8.33*10^{-3} p.u, B_i= 0.425 p.u MW/Hz, R_i=2.4 p.u /MW. T_w = 0.8 s, K_w =1.

References

[1] A. Datta, R. Sarker, I. Hazarika, "An Efficient Technique using Modified pq Theory for Controlling Power Flow in a Single-Stage Single-Phase Grid-Connected PV System",IEEE Transactions on Industrial Informatics, vol.15, pp.4635 – 4645, August.2019.

[2] E.Bekiroglu, M.D.Yaza, "Analysis of Grid Connected Wind Power System", 2019 8th International Conference on Renewable Energy Research and Applications (ICRERA), Brasov ,3-6 November 2019.

[3] G. Xu, F. Liu, J.Hu and T.Bi, "Coordination of wind turbines and synchronous generators for system frequency control", Renewable Energy, vol. 129, pp. 225-236, December 2018.

[4] R. Shankar, S.R. Pradhan, K. Chatterjee and R. Mandal "A comprehensive state of the art literature survey on LFC mechanism for power system", Renewable and Sustainable Energy Reviews, vol. 76, pp. 1185–1207, September 2017.

[5] P. Dash, L.C. Saikia, N. Sinha, "Comparison of performances of several FACTS devices using Cuckoo search algorithm optimized 2DOF controllers in multi-area AGC", Electrical Power and Energy Systems, vol. 65 , pp. 316–324, February 2015.

[6] M.R. Sathya, M.T. Ansari, "Load frequency control using Bat inspired algorithm based dual mode gain scheduling of PI controllers for interconnected power system", International Journal of Electrical Power & Energy Systems, vol. 64,pp. 365-374, January 2015.

[7] K.A. Ellithy, "Comparative Study of Decentralized Load Frequency Controllers: Conventional", Optimal and Fuzzy logic, Series on Energy and Power Systems , pp. 368-391, January 2004.

[8] K. Jagatheesan, B. Anand , N. Dey, and A. S. Ashour, "Artificial intelligence in performance analysis of load frequency control in thermal-wind-hydro power systems", International Journal of Advanced Computer Science and Applications, DOI:10.14569/IJACSA.2015.060727,vol.6,July 2015.

[9] A. Nayak, M.K. Maharana, "Performance Assessment of Fuzzy Logic Controller for Load Frequency Control in multi source multi area system", International Journal of Renewable Energy Research, Vol. 9, No. 4, pp. 1957-1605, December 2019.

[10] W.Tan, "Unified tuning of PID load frequency controller for power systems via IMC", IEEE transactions on power system, Vol. 25, No. 1, pp. 341-350, February 2010.

[11] A. Yazdizade, M.H. Ramezani, E. Hamedrahmat," Decentralized load frequency control using a new robust optimal MISO PID controller", International Journal of Electrical Power and Energy Systems, Vol. 35, No. 1, pp. 57–65, February 2012.

[12] H. Shayeghi, A. Jalili, H. Shayanfar, "A, Multi-stage fuzzy load frequency control using PSO", Energy Conversion and Management, Vol. 49, No. 10, pp. 2570-2580. October. 2008.

[13] L. C. Saikia, S. K. Das, P. Dash and M. Raju, "Multi Area AGC with AC/DC link and BES and Cuckoo Search optimized PID controller", Proceedings of the 2015 Third International Conference on Computer, Communication, Control and Information Technology (C3IT), Hoogly, 7-8 Febryary 2015.

[14] J. Sancheza, A.Visioli and S. Dormido, "A two-degree-of-freedom PI controller based on events", Journal of Process Control, DOI: 10.1016/j.jprocont.2010.12.001, Vol. 21, No. 4, pp. 639-651, April 2011.

[15] R. K. Sahu, S. Panda and U. K. Rout, "DE optimized parallel 2-DOF PID controller for load frequency control of power system with governor dead-band nonlinearity", International Journal of Electrical Power & Energy Systems, vol.49, pp. 19–33, July 2013.

[16] N. Pachauri, V. Singh, A. Rani, "Two degree of freedom PID based inferential control of continuous bioreactor for ethanol production", ISA Transactions, vol. 68, pp. 235-250, May 2017.

[17] M. Jain, A. Rani, N. Pachauri, V. Singh and Alok P. Mittal, "Design of fractional order 2-DOF PI controller for real-time control of heat flow experiment", Engineering Science and Technology, an International Journal, Vol.22, No. 1, pp. 215-228, February 2019.

[18] R. Vilanova, V.M. Alfaro and O. Arrieta, "Simple robust autotuning rules for 2-DoF PI controllers", ISA Transactions, Vol.51, No. 1, pp. 30–41, January 2012.

[19] A.J. Veronica, N.S. Kumar, "Load Frequency Controller Design for Microgrid Using Internal Model Control Approach", International Journal of Renewable Energy Research, Vol. 7, No. 2, pp. 778-786, June 2017.

[20] R. K. Sahu, S. Panda, U. K. Rout and D. K. Sahoo, "Teaching learning based optimization algorithm for automatic generation control of power system using 2-DOF PID controller", International Journal of Electrical Power and Energy Systems, vol. 77, pp. 287–301, May 2016

[21] S. Saxena, "Load frequency control strategy via fractional-order controller and reduced-order modeling", International Journal of Electrical Power and Energy Systems, vol. 104, pp. 603–614, January 2019.

[22] S.S.Dash,"Tutorial 1: Opportunities and challenges of integrating renewable energy sources in smart", 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), San Diego , Nov. 5-8 November 2017.

[23] S. M. Muyeen , "Wind Energy Conversion Systems", Green Energy and Technology,2012.

[24] H. U. Banna, A. Luna, S.Ying, H.Ghorbani and P. Rodriguez., "Impacts of wind energy in-feed on power system small signal stability", 2014 International Conference on Renewable Energy Research and Application (ICRERA), DOI: 10.1109/ICRERA.2014.7016459, 19-22 October 2014.

[25] O.Kiymaz, T.Yavuz, "Wind power electrical systems integration and technical and economic analysis of hybrid wind power plants." 2016 IEEE International Conference on Renewable Energy Research and Applications(ICRERA).DOI:10.1109/icrera.2016.7884529 , 20-23 November 2016.

[26] A. Saha, L.C. Saikia, "Renewable energy source -based multiarea AGC system with integration of EV utilizing cascade controller considering time delay", International Transactions on Electrical Energy System, vol. 29, pp. 1-22, July 2018 .

[27] A. Abazari, H. Monsef, B. Wu, "Coordination strategies of distributed energy resources including FESS, DEG, FC and WTG in load frequency control (LFC) scheme of hybrid isolated micro-grid", International Journal of Electrical Power & Energy Systems, vol. 109, pp. 535-547, July 2019.

[28] T. Mahto, V. Mukherjee, "Frequency stabilization of a hybrid two- area power system by a novel quasi-op positional harmony search algorithm", IET Generation Transmission and Distribution, Vol. 9, No. 15, pp. 2167-2179, November 2015.

[29] I.Atteya, H. A. Ashour, N. Fahmi and D. Strickla, "Distribution network reconfiguration in smart grid system using modified particle swarm optimization." 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), Birmingham, pp. 305-313, 20-23 November 2016

[30] S. Panda, S. S.Chandra , S.Mahapatra,"A hybrid BFOA–MOL approach for FACTS-based damping controller design using modified local input signal", International Journal of Electrical Power Energy System, vol. 67, pp. 238 –251, May 2015.

[31] M.S.Nosratabadi, M.Bornapour, M.A. "Gharaei, Grasshopper optimization algorithm for optimal load frequency control considering Predictive Functional Modified PID controller in restructured multi-resource multi-area power system with Redox Flow Battery units", Control Engineering Practice , vol. 89, pp. 204–227, August 2019.

[32] S. Mirjalili, "The ant lion optimizer", Advances in Engineering Software, vol.83, pp. 80-98, May 2015.

[33] M. Gheisarnejad, "An effective hybrid harmony search and cuckoo optimization algorithm based

fuzzy PID controller for load frequency control", Applied Soft Computing, vol. 65, pp. 121–138, April 2018.

[34] A.R. Yildiz, "Cuckoo search algorithm for the selection of optimal machining parameters in milling operations", International Journal of Advanced Manufacturing Technology, vol. 64, pp. 55–61, March 2012.

[35] X. S. Yang, S. Deb, "Cuckoo search via Le ´ vy flights.Nature & Biologically Inspired Computing", 2009 World Congress on Nature & Biologically Inspired Computing (NaBIC), pp. 210–214, 9-11 December 2009.

[36] C.T. Brown, L.S. Liebovitch, R. Glendon,"Le´ vy flights in dobeju/hoansi foraging patterns", Human Ecology, vol. 35, pp. 129–138, December 2006.

[37] M. Mareli ,B. Twala, "An adaptive Cuckoo search algorithm for optimization", Applied Computing and Informatics, Vol. 14, No.2 pp. 107-115, July 2017.

[38] S. Debbarma, L.C.Saikia, N. Sinha, "Automatic generation control using two degree of freedom fractional order PID controller", International Journal of Electrical Power and Energy Systems, vol. 58, pp. 120-129, June 2014.

[39] S. Debbarma ,L. C. Saikia, "Effect of fractional-order controller on automatic generation control of a multi-area thermal system", International Conference on Sustainable Energy and Intelligent Systems (SEISCON 2011), Chennai, 20-22 July 2011.