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A novel hybrid many optimizing liaisons gravitational search algorithm approach for AGC of power systems

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ABSTRACT

A hybrid Many Optimizing Liaisons Gravitational Search Algorithm (hMOL-GSA)-based fuzzy PID controller is proposed in this work for Automatic Generation Control problem. MOL is a simplified version of particle swarm optimization which ignores the particle best position consequently simplifying the algorithm. The proposed method is employed to tune the fuzzy PID parameters. The outcomes are equated with some newly proposed methods like Artificial Bee Colony (ABC)-based PID for the identical test systems to validate the supremacy of GSA and proposed hMOL-GSA techniques. Further, the design task has been carried out in a three-area test system and the outcomes are equated with newly proposed Firefly Algorithm (FA) optimized PID and Teaching Learning-Based Optimization (TLBO) tuned PID controller for the identical system. Better system response has been observed with proposed hMOL-GSA method. Finally, sensitivity study is being carried out and robustness of the proposed method is established.

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optimizing liaisons

1. Introduction

Automatic generation control (AGC) is a vital problem for the satisfactory operation of power systems. The key role of AGC is to regulate the frequency and tie-line power changes. In order to improve reliability and to supply sufficient electrical power to the end-user with increasing load demand, the isolated power systems are interconnected. In an interconnected power system, each area supports one another in emergencies by supplying power to the needy area through tie lines. AGC alters the generator output power for the equivalent load variation by making the Area Control Error (ACE) to zero [1–3]. Several researchers have proposed various control/optimization strategies during normal operation and small disturbances, choosing different objective functions in AGC. There is always scope to propose and implement new optimization technique to real world problem as each meta-heuristic algorithm has its own merits and demerits and implementing new high-performance algorithm is a challenging problem for engineers.

In the literature, numerous control schemes have been suggested for AGC of power systems to realize improved performance. In [4–7], a critical literature review related to AGC problem and distinct control methods including various intelligent/soft computing techniques, which are pertaining to the problem of AGC. Various power system modelling, control strategies, control techniques and soft computing techniques

are presented for AGC problems. Now days in the area of AGC, new optimization approach has been extensively exercised to find the parameters of different controller. In [8], various AGC-based conventional controllers in an interconnected power system have been studied. An optimal control approach for AGC has been presented in [9]. In [10], the authors have studied the PID controller gains tuned by Imperialist Competitive Algorithm (ICA). Various novel technique/control approaches such as Firefly Algorithm (FA) optimized PI controller [11,12], Flower Pollination Algorithm (FPA) tuned PID controller [13], Grey Wolf Optimization (GWO) tuned classical controller with PI and PID structure [14], Differential Evolution (DE) tuned 2-DOF PID [15], TLBO tuned 2-DOF PID [16], ICA-based fuzzy-PI [17], hybrid FA and Pattern Search (hFA-PS) optimized PI and PID [18], A hybrid gravitational search algorithm (GSA) and PS tuned PI/PID controller [19], hybrid Stochastic Fractal Search and Local Unimodal Sampling (hSFS-LUS) optimized multistage PDF plus (1 + PI) [20] have been recently suggested for various types of power systems for frequency control.

It is evident from the literature review that, there is scope to work on AGC by investigating new control structures and optimization technique. There has been continuing investigation for improving AGC system response by different control strategies and soft computing method. The system performance become

inferior and even it may become unstable, if inappropriate controller parameters are selected. Hence, it is required to tune the controller to get desired achievements with the suitable selection of parameters, which ensure that the obtained system would be stable and would meet the desired objectives. For better performance of any meta-heuristic technique, it is necessary to keep an equilibrium among exploitation and exploration throughout the process. Global optimization technique GSA if used alone may provide an optimal/near optimal solution. The idea is to take advantages of many optimizing liaisons (MOL) and GSA, i.e. the exploitation capability of MOL and exploration capacity of GSA in proposed hybrid MOL-GSA technique to get improved results. Keeping these points in view, there is an inspiration for MOL and GSA hybridization.

The original contributions of the current study are:

- A maiden approach is proposed for the AGC problem with hybrid MOL-GSA technique.
- The scaling factors (input/output) of fuzzy PID are tuned employing hybrid MOL-GSA method.
- The advantage of hybrid MOL-GSA technique over recently published optimization technique such as ABC technique is illustrated by evaluating the results for an identical test system.
- The method is also employed in a three dissimilar area system and comparative dynamic performance of proposed approach with few newly reported methods such as TLBO- and

FA-based controllers for the same system has been presented.

- To illustrate the efficacy of the suggested method, variation in nominal values of system parameters, operating load condition are carried out for sensitivity analysis.

This reminder of this work is planned as follows. Modelling of system under study, fuzzy PID structure are provided in Section 2. An outline of MOL, GSA and hybrid MOL-GSA methods has been described in Section 3. Simulation outcomes are provided in Section 4. Lastly, in Section 5 conclusions are summarized.

2. Proposed method

2.1. System under study

Firstly, 2-area reheat system as presented in Figure 1 is taken [21]. The parameters of the system are provided in the appendix. Regulation parameter R is shown in Figure 1. B denotes the frequency bias parameter in p.u.MW/Hz. The control outputs are represented as u_1 and u_2 for areas 1 and 2, respectively. T_H and T_T represent time constants of hydraulic and turbine in second, respectively. T_r and K_r indicate time constant of reheat steam turbine and re-heat gain, respectively. K_P represents the power system gain in Hz/p.u.MW. T_P represents time constant of power system in sec. ΔF_1 and ΔF_2 are the frequency variations of area-1 and area-2, respectively. ΔP_D is the load.

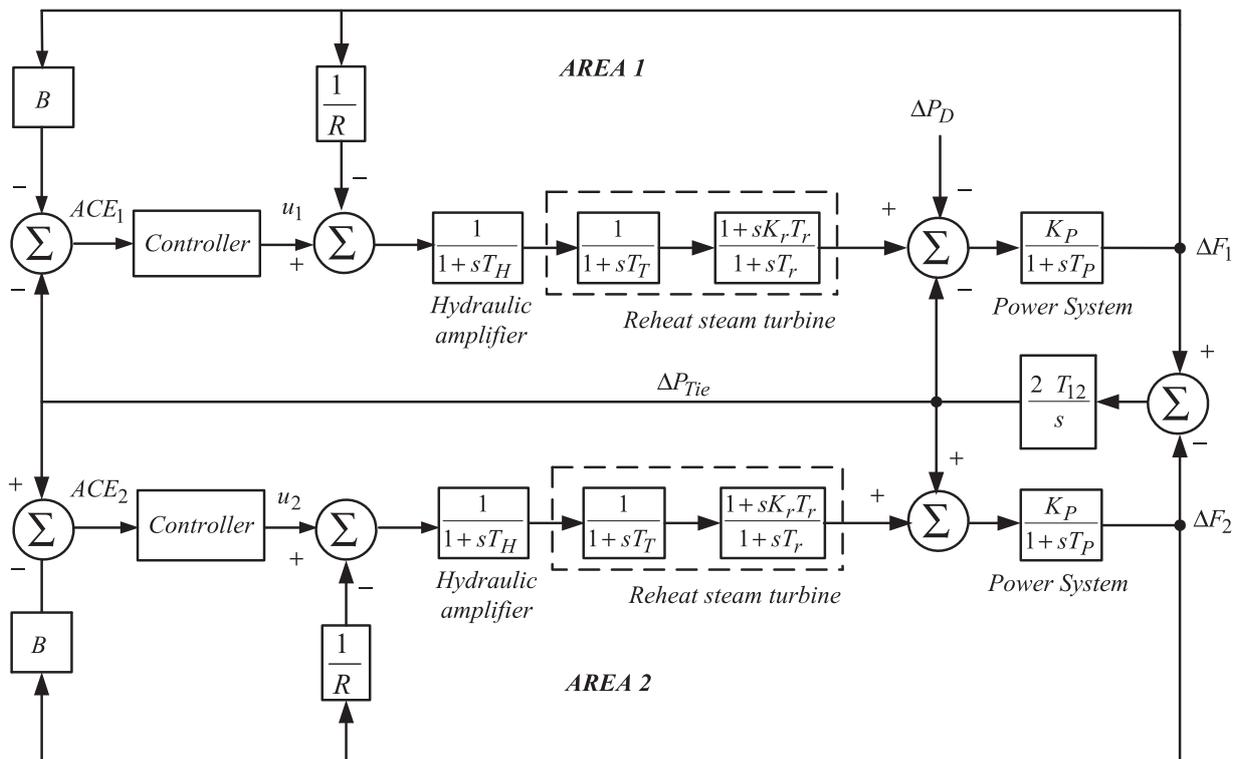


Figure 1. Two-area transfer function model.

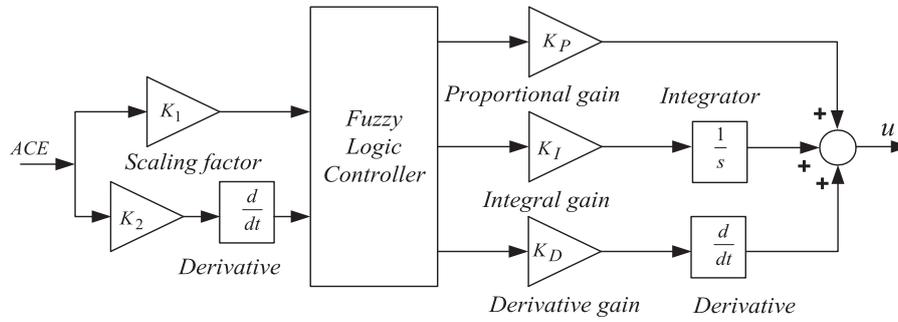


Figure 2. Fuzzy PID structure.

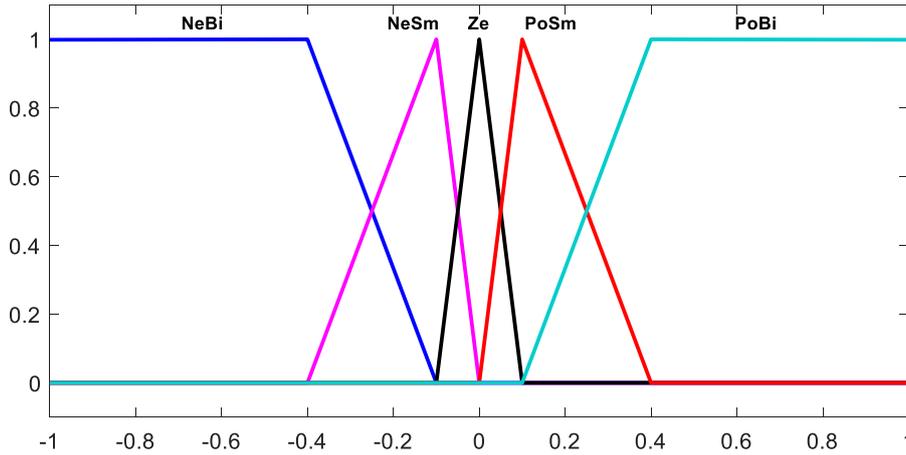


Figure 3. Membership functions for fuzzy inputs and outputs.

2.2. Controller structure

The PID controller is well known and most accepted feedback controllers in industrial applications because of its usefulness, simple design, cost-effective and effectiveness for linear plants. The controller with only proportional action has the ability to reduce rise time, but steady-state error cannot be removed. By using integral action this steady-state error can be eradicated but the transient response of the system becomes poorer. This transient response can be improved by using derivative action and it also reduces overshoot and stability of the system. But, the conventional PID controllers may be ineffectual because of its linear structure, particularly, for complex systems associated with delay time and uncertainties. Alternatively, the fuzzy logic controller (FLC) can handle nonlinearity and uncertainties and can be designed to get the desired system performance. Fuzzy PID structure has been proposed in literature to get overall improved performance [22,23]. Therefore, fuzzy PID are chosen in this study for AGC. The configuration of fuzzy PID structure is displayed in Figure 2 which is a mixture of fuzzy PD and PID structures from [24], with input scaling parameters (K_1 and K_2) of FLC and gains of PID (K_P , K_I , K_D). The controllers take individual ACEs ($e_1(t)$ and $e_2(t)$) as inputs as expressed by:

$$e_1(t) = B_1 \Delta F_1 + \Delta P_{Tie12}, \quad (1)$$

Table 1. Rule base for fuzzy inputs and outputs.

e	Δe				
	NeBi	NeSm	Ze	PoSm	PoBi
NeBi	NeBi	NeBi	NeSm	NeSm	Ze
NeSm	NeBi	NeSm	NeSm	Ze	PoSm
Ze	NeSm	NeSm	Ze	PoSm	PoSm
PoSm	NeSm	Ze	PoSm	PoSm	PoBi
PoBi	Ze	PoSm	PoSm	PoBi	PoBi

$$e_2(t) = B_2 \Delta F_2 + \Delta P_{Tie21} \quad (2)$$

u_1 and u_2 are controller outputs, which decides the reference real power settings of each units. The membership functions for fuzzy inputs and outputs are presented in Figure 3 and the rule base is described in Table 1. The input MFs for e and Δe are chosen in the range $[-1, 1]$. Triangular MFs are chosen as they are the most popular, easy to implement and economical. Mamdani fuzzy interface is chosen for the present study. In Table 1, the fuzzy linguistic variables are NeBi (Negative Big), NeSm (Negative Small), Ze (Zero), PoSm (Positive Small), PoBi (Positive Big). The scaling parameters (K_1, K_2, K_3, K_4) and PID parameters ($K_{P1}, K_{P2}, K_{I1}, K_{I2}, K_{D1}$ and K_{D2}) are optimized to minimize the objective function by applying proposed algorithm.

During the configuration of a controller, the fitness criterion is described first depending on the requirements and limitations. The function is normally dependent on performance criteria which accounts for the

whole closed loop performance. In AGC problem, the parameters to be considered for objective function calculations are deviations in frequency and tie-line power. In [10,19], the authors have reported that ITAE is superior than other options. So, in the current study ITAE criteria is chosen to tune the parameters and expressed by:

$$J = \text{ITAE} = \int_0^{t_{\text{sim}}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{\text{tie}}|) \cdot t \cdot dt, \quad (3)$$

where, ΔF_1 and ΔF_2 are the variation in frequencies in each area, ΔP_{tie} is deviation in tie-line power, and t_{sim} is the simulation time.

3. Outline of MOL, GSA and hybrid MOL-GSA

3.1. Many optimizing liaison

The shortened form of Particle Swarm Optimization (PSO) was suggested in [25] which is derived from original PSO [26] by neglecting particle's best position and called it MOL. As the algorithm is shortened, it is easy to select MOL parameters compared to PSO. The idea of PSO is established on the collective conduct of bird herding. In PSO, particles fly from place to place to determine better solutions. In this progress, all the particles look for food in their search path depending on their individual best and best obtained throughout the process. Arithmetically PSO can be described as.

$$v_j^{k+1} = wv_j^k + \kappa_P \times \mathfrak{R}_P(pbest_j - x_j^k) + \kappa_G \times \mathfrak{R}_G \times (gbest - x_j^k), \quad (4)$$

where v_j^k and x_j^k characterizes the velocity and position of j th particle in generation k , respectively. In Equation (4) $pbest_j$ and $gbest$ are the best location of particle j and the best location of swarm. κ_P and κ_G are cognitive and social factors. \mathfrak{R}_P and \mathfrak{R}_G are the arbitrary quantities created in the range [0, 1]. The inertia weight 'w' preserve an equilibrium among global and local search processes and helps PSO to find an optimum solution. The inertia weight 'w' is calculated by:

$$w = w_{\text{max}} - \left(\frac{w_{\text{max}} - w_{\text{min}}}{k_{\text{max}}} \right) k, \quad (5)$$

here w_{max} and w_{min} are the upper and lower limits, respectively. The next location acquired by the particle is found by mixing a velocity part in the equation. Restrictions are forced on the distance covered by the particle in a sole step. This exploration method of altering particle position lasts till the algorithm stops.

In PSO, positions of particles are updated depending on $gbest$ and $pbest$ while in MOL, they are updated based on $gbest$ only. Therefore, in MOL algorithm, $pbest$ is removed and velocity expression reduces to Eq. (6).

$$v_j^{k+1} = wv_j^k + \kappa_G \times \mathfrak{R}_G \times (gbest - x_j^k). \quad (6)$$

3.2. Gravitational search algorithm

GSA was suggested in [27] which is inspired by Newton's Law of Gravity. It says that each mass in the universe attracts other masses with force. The force depends on weight of masses and the distance among them. The body with more mass will be subjected to greater gravitational force. The positions of masses represent the candidate solutions. GSA can be described as follows:

In the search space, N masses are chosen whose positions are randomly selected.

The gravitational force acting between mass m and n at any time t is given by:

$$F_{nm}^d(t) = G(t) = \frac{M_{pn}(t) \times M_{am}(t)}{R_{nm}(t) + \Psi} (x_n^d(t) - x_m^d(t)), \quad (7)$$

where M_{am} and M_{pn} represent the active and passive masses of bodies m and n , $G(t)$ is constant which depends on time (iteration). $R_{nm}(t)$ is the Euclidian space between bodies m and n . Ψ is a fixed parameter.

$G(t)$ is determines by

$$G(t) = G_0 \times (\exp^{-\alpha(Iter/Iter_{\text{max}})}) \quad (8)$$

G_0 is the gravitational constant at the starting, α is the reducing constant, $Iter_{\text{max}}$ and $Iter$ are maximum iteration and current iterations and d is the dimension of the problem.

The aggregate force acting on mass n is

$$F_n^d(t) = \sum_{m=1, m \neq n}^N \rho(F_{nm}^d(t)), \quad (9)$$

where ρ is an random value chosen in the interval [0, 1]

Acceleration of a body n with mass M_i at time t , is given by:

$$A_n^d(t) = \frac{F_n^d(t)}{M_i(t)}. \quad (10)$$

Velocity of mass is expressed as

$$v_n^d(t+1) = \mathfrak{R}_n \times (v_n^d(t) + A_n^d(t)) \quad (11)$$

\mathfrak{R}_n is an arbitrary value created in range 0–1. The position of mass n can be formulated as:

$$x_n^d(t+1) = x_n^d(t) + v_n^d(t+1). \quad (12)$$

3.3. Hybrid MOLGSA

In [28] it is described that two technique may be merged to develop a different technique in low level or high level using co-evolutionary or relay approaches. In [29], PSO has been hybridized with GSA by combining the strength of both PSO and GSA. In the present work,

hybrid MOLGSA is suggested where the capability of social thinking of MOL is united with global exploration ability of GSA. Velocity in hybrid MOL-GSA is formulated as.

$$v_n(t+1) = w \times v_n(t) + k_1 \times rand \times a_n(t) + k_2 \times rand \times (gbest - x_n(t)), \quad (13)$$

where, $v_n(t)$ = velocity of particle, k_1 and w are weighting factor and weighting function, $rand$ is a random value selected from 0 to 1, $a_n(t)$ = acceleration of particle. Subscript n represents particle and t represents the current iteration.

The position of the particle is updated by.

$$x_n(t+1) = x_n(t) + v_n(t+1). \quad (14)$$

In the formulation of hybrid MOL-GSA, particles are initialized randomly. Then Equations (7)–(10) are used to find Gravitational force, G_0 , aggregate force and α . To get the optimal value, velocity and position of particles is updated in successive iterations using Equations (13) and (14). The process continues till the stopping conditions is meet.

4. Results

4.1. Application of GSA and hybrid MOL-GSA technique

The model is designed and simulated using MATLAB in SIMULINK environment for the studied system. In GSA, the following values used are: maximum iteration $T = 100$; population size $NP = 20$; gravitational constants $G_0 = 100$ and $\alpha = 20$ [19]. Since ITAE has been chosen as an objective function, ITAE value for the given test case is calculated and used in the algorithm. Initially, dissimilar PID, fuzzy PI and fuzzy PID controllers are taken for every area. PID parameters are

selected in the interval $[-2 \ 2]$. Scaling coefficients and PID parameters are selected in the interval $[0 \ 2]$ and $[-2 \ 2]$, respectively. The system is simulated by applying a 1% SLP in area-1. The objective criterion is computed in the .m file by execution of computer program and then utilized in the optimization process. To find the best GSA parameter, repeated experiments with GSA were performed. Fifty trial execution of the optimization process was conducted and the resulting perfect outcome over the 50 executions is selected as the controller coefficients. The finest results found in the 50 independent runs are given in Table 2.

4.2. Analysis of results

The dynamic performance is evaluated using settling time, under shoot and ITAE values as presented in Table 3. The same with Artificial Bee Colony (ABC) optimized PID [21] is also given in Table 3. It is obvious, for identical test system, controller and objective function, improved dynamic performance is achieved with GSA tuned PID (ITAE = 0.0514) than ABC tuned PID (ITAE = 0.0691). The ITAE is decreased by 74.38% with GSA-based PID compared to ABC-based PID [21]. In addition, the settling times for ΔF_1 , ΔF_2 and ΔP_{Tie} are decreased by 71.35%, 68.59% and 58.9% for GSA-based PID, respectively, than the corresponding values provided in [21]. Further, the decrease in peak undershoot for ΔF_1 , ΔF_2 and ΔP_{Tie} with GSA tuned PID compared to the ABC-based PID [21]. Hence, it can be concluded that GSA technique outperform ABC technique.

To enhance the dynamic performance, changes in controller structure are introduced. Fuzzy PI/ fuzzy PID controller are considered and parameters are optimized using GSA employing same ITAE objective function. The results are given in Table 3. It is obvious from Table 3 that, lesser ITAE value is

Table 2. Tuned parameters.

Controller gains		GSA:PID	GSA:Fuzzy-PI	GSA:Fuzzy-PID	hGSA-MOL:Fuzzy-PID
Area 1	K_1	–	1.2147	1.7178	1.7178
	K_2	–	1.0861	0.8927	0.3927
	K_{P1}	1.7656	1.3598	0.7812	1.7812
	K_{I1}	0.1762	1.7168	1.4073	1.9073
	K_{D1}	1.4004	–	0.2813	0.2813
Area 2	K_3	–	0.3246	0.7668	1.7668
	K_4	–	0.0113	1.1907	1.1907
	K_{P2}	0.3404	0.2733	0.8009	0.3009
	K_{I2}	1.6661	0.3997	0.2362	1.2362
	K_{D2}	1.4561	–	0.1237	0.1237

Table 3. Performance comparison for two-area test system.

Parameters	Settling time (s)			Under shoot $\times 10^{-3}$			ITAE
	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	
ABC:PID [21]	12.36	12.80	8.42	–5.1	–3.2	–1.0	0.0691
GSA: PID	8.82	8.78	4.96	–4.9	–2.9	–0.9	0.0514
GSA: Fuzzy PI	8.32	8.08	4.14	–4.6	–1.9	–0.6	0.0170
GSA: Fuzzy PID	7.04	7.20	2.65	–1.8	–1.1	–0.4	0.0143
hGSA-MOL: Fuzzy PID	4.13	2.61	2.37	–1.2	–0.6	–0.2	0.0082

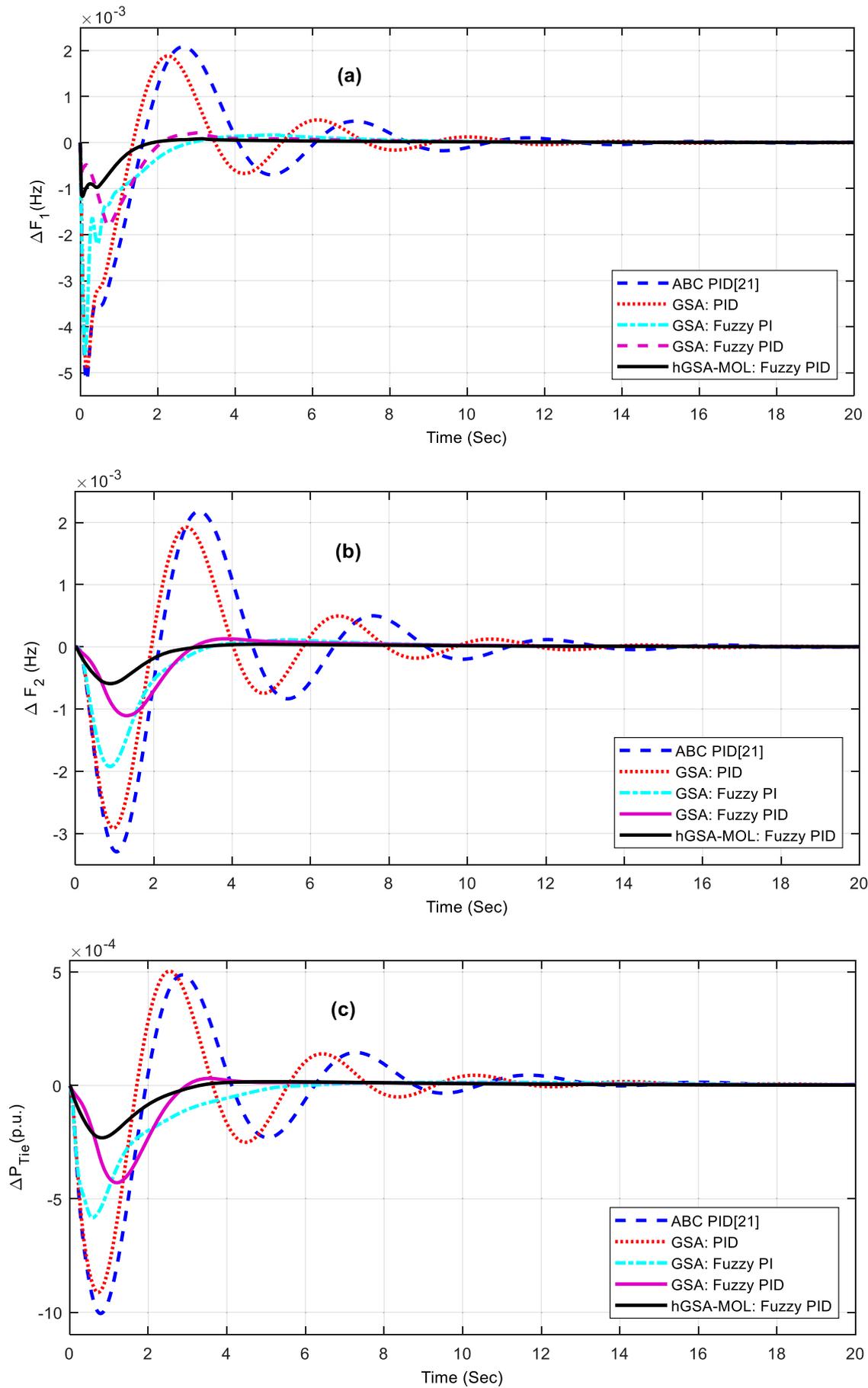


Figure 4. Dynamic responses at 1% change in area-1 (a) ΔF_1 (b) ΔF_2 (c) ΔP_{Tie} .

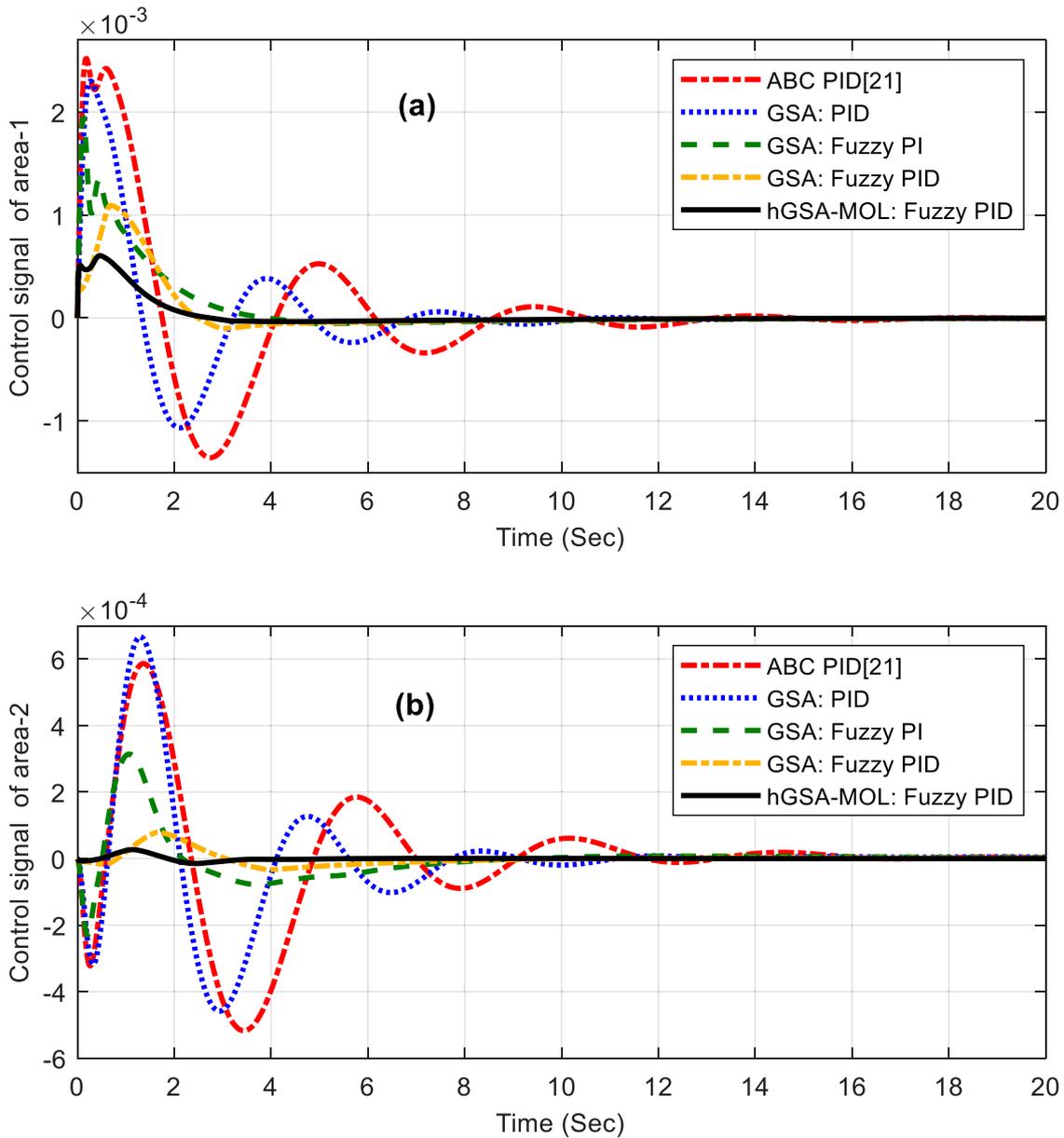


Figure 5. Comparison of control signals due to each strategy (a) Area-1 (b) Area-2.

Table 4. Sensitivity analysis for two-area test system.

Parameter variation	% Change	Settling time (s)			Under shoot $\times 10^{-3}$			ITAE
		ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	
Nominal	0	4.13	2.61	2.37	-1.2	-0.6	-0.2	0.0082
Loading condition	+25	4.14	2.61	2.37	-1.2	-0.6	-0.2	0.0082
	-25	4.14	2.62	2.37	-1.2	-0.6	-0.2	0.0082
T_H	+25	4.06	2.59	2.35	-1.4	-0.6	-0.2	0.0081
	-25	4.20	2.66	2.42	-1.2	-0.6	-0.2	0.0083
T_T	+25	4.03	2.53	2.32	-1.6	-0.6	-0.2	0.0080
	-25	4.29	2.74	2.49	-1.2	-0.6	-0.2	0.0085
T_R	+25	3.92	2.71	2.43	-1.2	-0.6	-0.2	0.0099
	-25	4.26	2.51	2.30	-1.2	-0.6	-0.2	0.0064
T_{12}	+25	3.85	2.50	2.29	-1.2	-0.6	-0.2	0.0081
	-25	4.51	2.82	2.52	-1.2	-0.5	-0.2	0.0084
R	+25	4.19	2.58	2.37	-1.2	-0.6	-0.2	0.0082
	-25	4.03	2.68	2.39	-1.2	-0.6	-0.2	0.0082

acquired with GSA-based fuzzy PID (ITAE = 0.0143) than GSA-based fuzzy PI (ITAE = 0.0170), GSA-based PID (ITAE = 0.0514) and ABC-based PID (ITAE = 0.0691). In the last step, proposed hMOL-GSA technique is applied and out comes are given

in Table 3. It is observed from Table 3 that lowest ITAE value is attained with hMOL-GSA-based fuzzy PID (ITAE = 0.0082) than others. Therefore, superior dynamic responses in term of settling times and peak undershoot in system response are realized

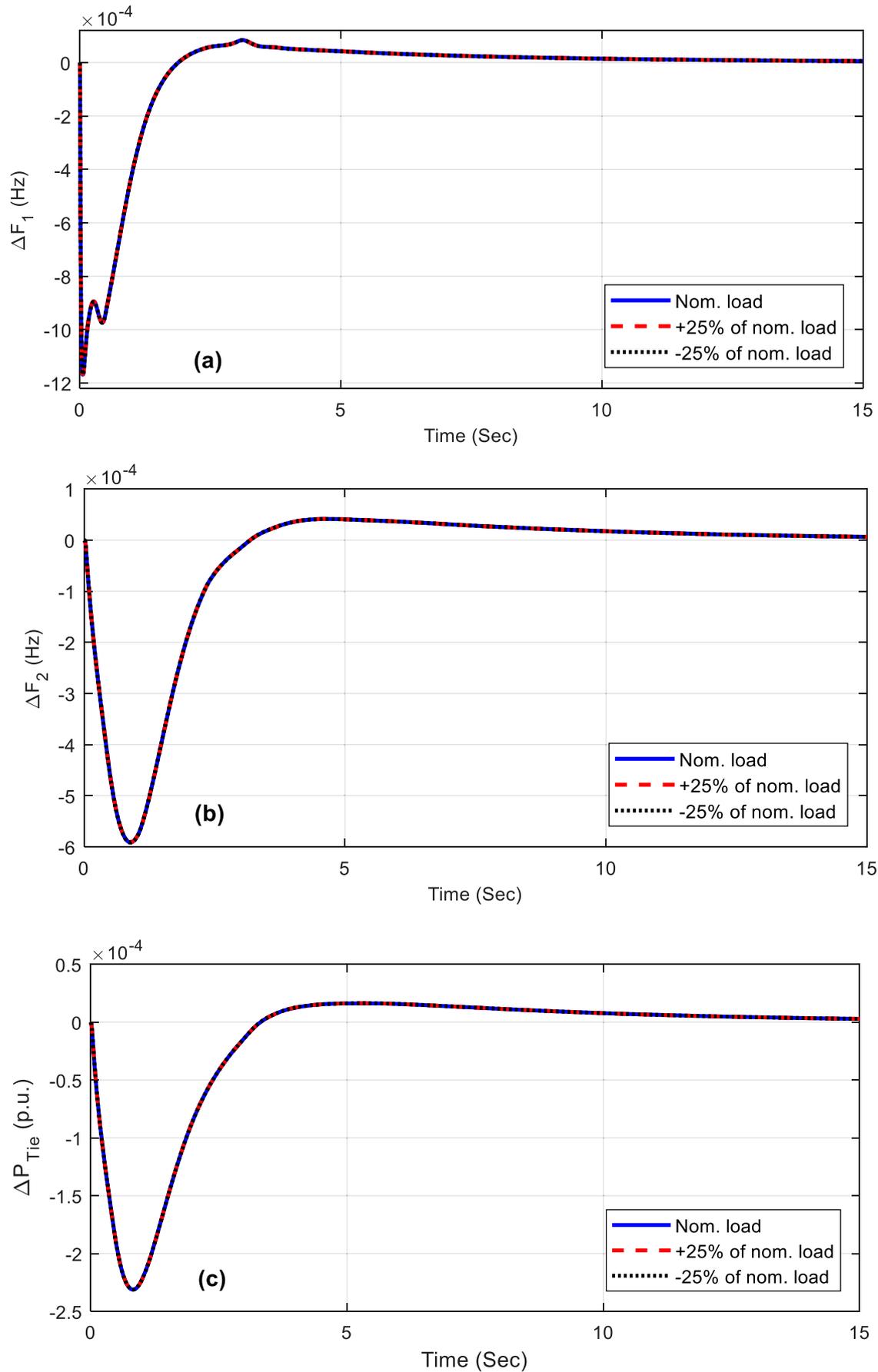


Figure 6. Dynamic responses at 1% change in area-1 in different loading (a) ΔF_1 (b) ΔF_2 (c) ΔP_{Tie} .

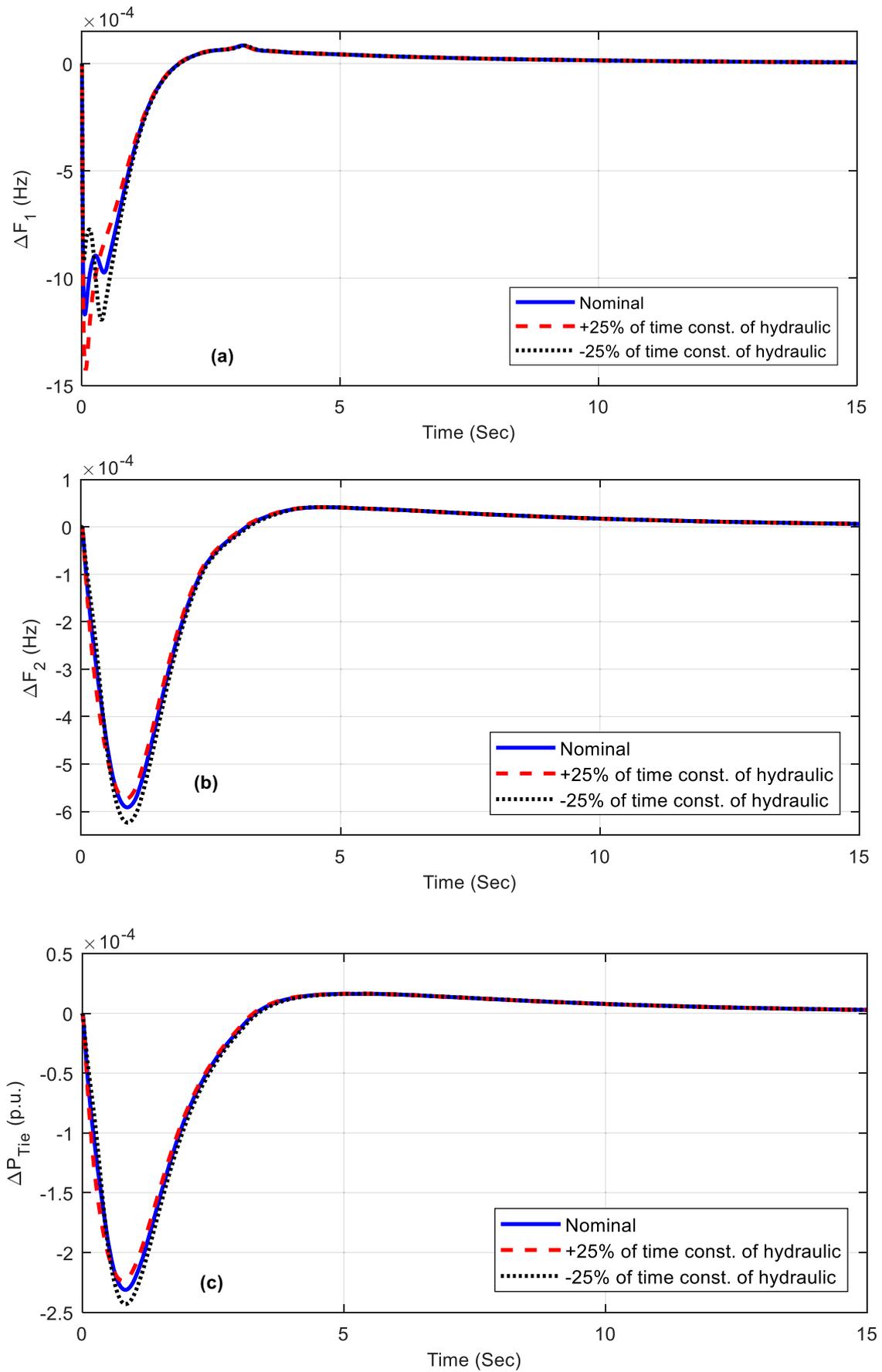


Figure 7. Dynamic responses at 1% change in area-1 for different time constant of hydraulic (a) ΔF_1 (b) ΔF_2 (c) ΔP_{Tie} .

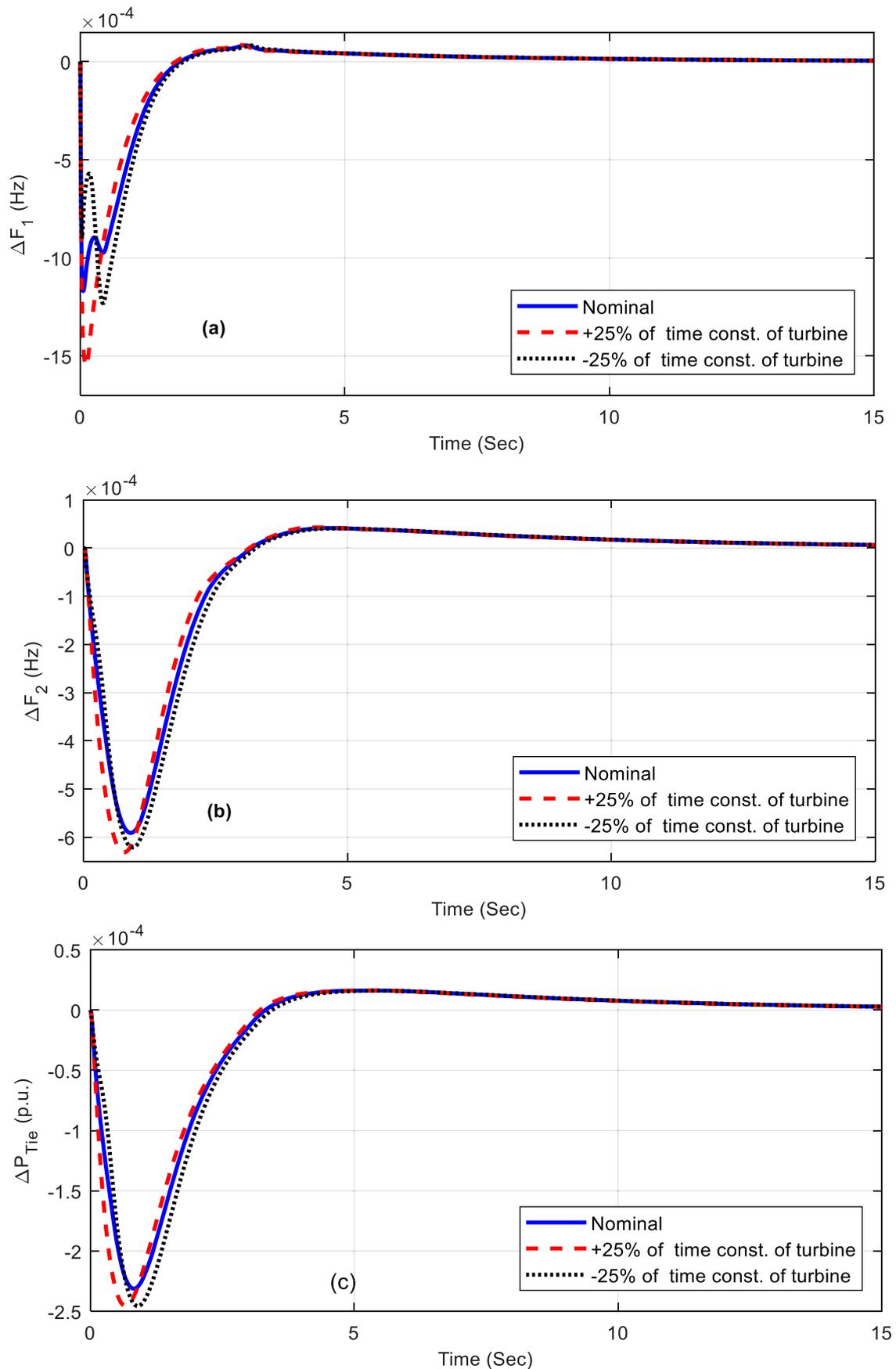


Figure 8. Dynamic responses at 1% change in area-1 for different time constant of turbine (a) ΔF_1 (b) ΔF_2 (c) ΔP_{Tie} .

with proposed hMOL-GSA-based fuzzy PID than GSA based fuzzy PID and others. Hence, it can be said that hMOL-GSA technique outclass GSA method.

To investigate the transient response of the proposed approach, an SLP of 1% is assumed at $t = 0$ s in area-1 and the dynamic responses are presented

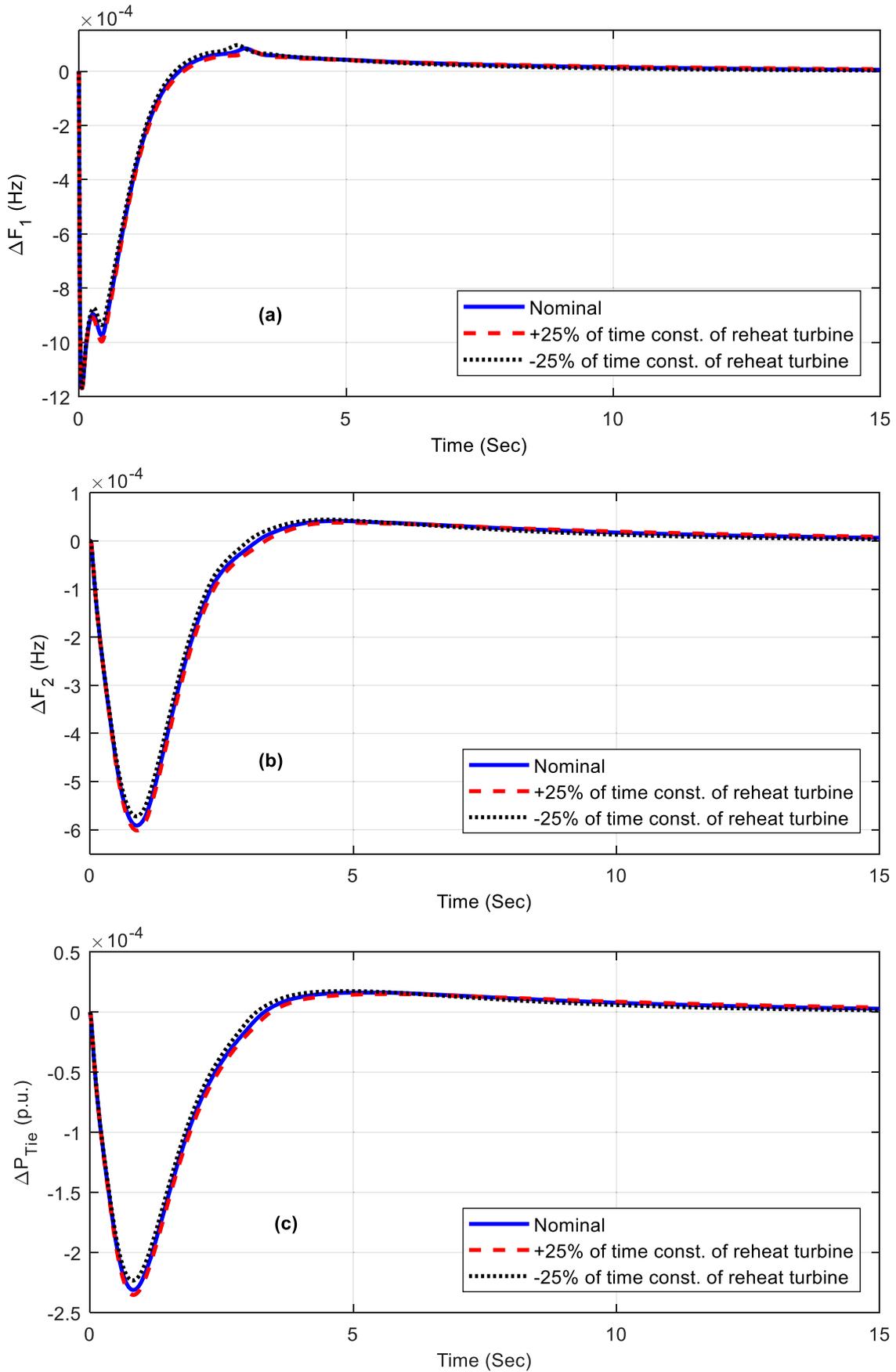


Figure 9. Dynamic responses at 1% change in area-1 for different time const. of reheat turbine (a) ΔF_1 (b) ΔF_2 (c) ΔP_{Tie} .

in Figure 4(a-c). For assessment, the same by ABC [21] optimized PID for the identical test system are also revealed in Figure 4(a-c). It is observed

from Figure 4(a-c) that suggested hMOL-GSA tuned fuzzy PID exhibits more performance dynamics over GSA-based PID, GSA-based fuzzy PI/PID and other

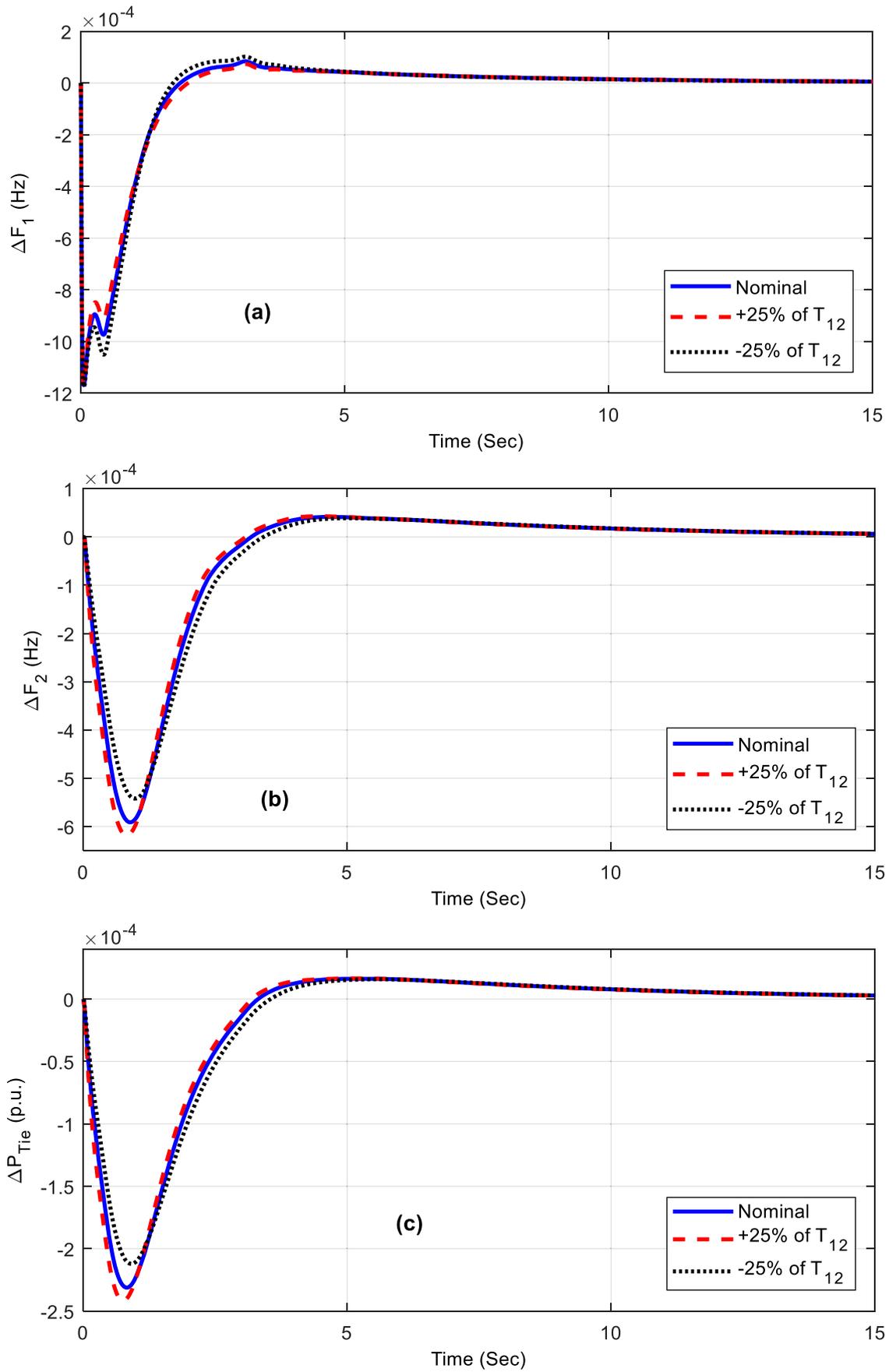


Figure 10. Dynamic responses at 1% change in area-1 for different of T_{12} (a) ΔF_1 (b) ΔF_2 (c) ΔP_{Tie} .

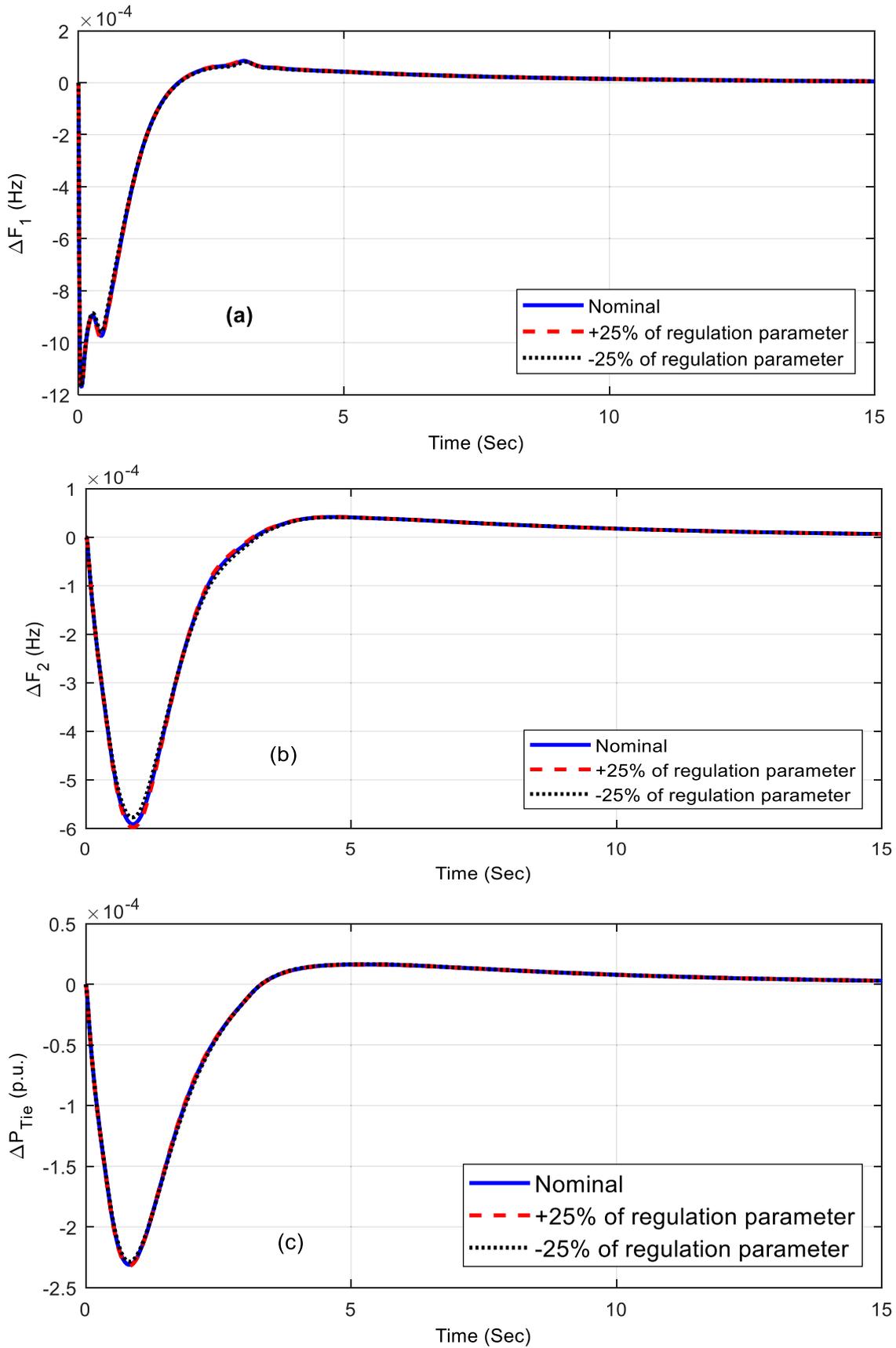


Figure 11. Dynamic responses at 1% change in area-1 for different of regulation parameter (a) ΔF_1 (b) ΔF_2 (c) ΔP_{Tie} .

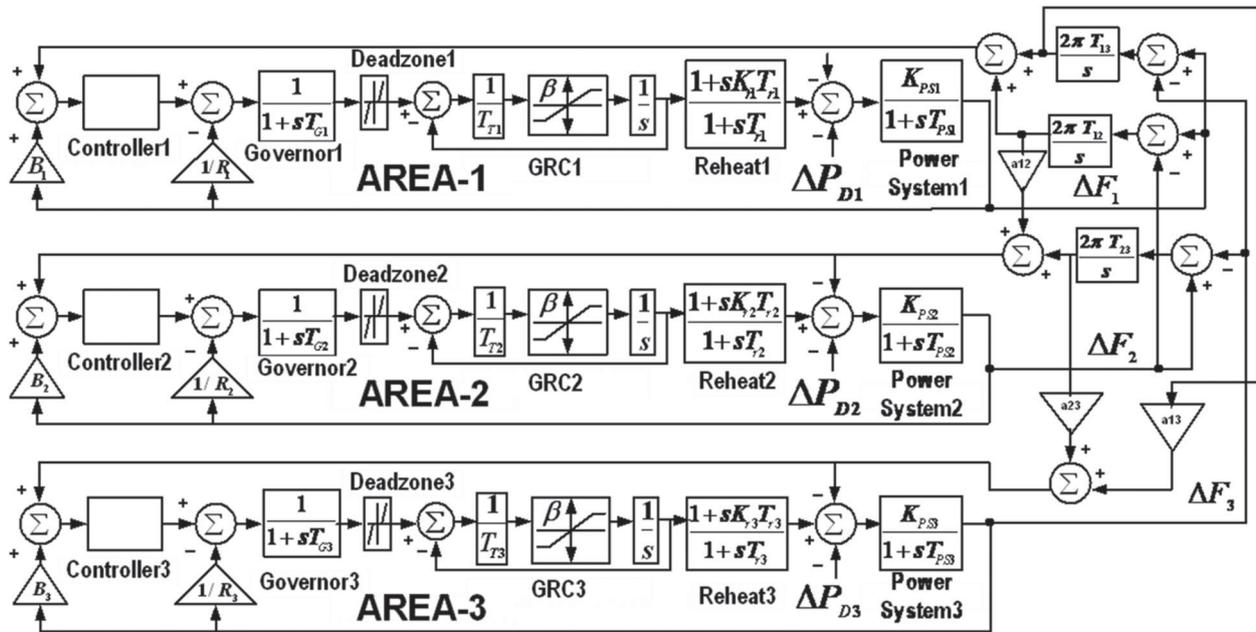


Figure 12. Three unequal area transfer function model.

approach reported in the literature. Thus, it may be said that hMOL-GSA surpasses GSA and ABC techniques.

Comparison of the control signals due to each strategy for the above disturbance are shown in Figure 5(a,b). It can be seen from Figure 5(a,b) that the control signal is effectively modulated by the proposed approach to improve the system performance.

4.3. Sensitivity study

To assess the sensitivity of the suggested method under varied conditions, operating load condition and system parameters are varied from +25% to -25% in the by considering one at a time [8,11,15,19]. The system with proposed hMOL-GSA-based fuzzy PID is taken for analysis in all the cases because of their better response. The performance indexes are given in Table 4 from which it is seen that the system time constants and variations on operating loading conditions over the system performance are insignificant. The transient response with varied loading condition, T_H , T_T , T_R , T_{12} and R are illustrated in Figure 6(a-c) to 11(a-c). From Figures 6–11(a-c), it is observed that the deviation in operating load condition and time constants on dynamic performance is insignificant. Therefore, it may be said, the suggested method offers a robust control with variations in system parameters or system loading.

4.4. Extension to three area system

To illustrate the capability of the suggested hMOL-GSA technique, the approach is employed in a three-unequal area test system [11,30] with Governor Dead Band (GDB) and Generation Rate Constraint (GRC)

Table 5. Tuned parameters for 3 area test system.

Controller gains	hGSA-MOL:Fuzzy-PID	
Area 1	K_1	1.5762
	K_2	1.9480
	K_{P1}	0.6410
	K_{I1}	0.8652
	K_{D1}	0.2250
Area 2	K_3	0.2977
	K_4	0.3040
	K_{P2}	1.0262
	K_{I2}	0.0010
	K_{D2}	1.9253
Area 3	K_5	1.2555
	K_6	1.1566
	K_{P3}	1.8301
	K_{I3}	1.4290
	K_{D3}	0.2941

nonlinearity as presented in Figure 12. The ratings of area1, 2 and 3 are 2000, 4000 and 8000 MW, respectively. In this work, a GRC of 3%/min and GDB of 0.06% (0.036 Hz) are assumed. The system data are taken from reference [11,30].

A 10% SLP is applied in area-1 at $t = 0.0$ s. The parameters of hMOL-GSA-based fuzzy PID parameters are found as before and given in Table 5. The performances using ITAE, and settling times (2%) is gathered in Table 6. To demonstrate the advantage of the suggested approach, the best reported outcomes of FA tuned PID [11] and TLBO [30] optimized Proportional-Integral-Double Derivative (PID) for the same test system are also provided in Table 6. It is noticeable from the results presented in Table 6 that, lowest ITAE value (ITAE = 17.3381) is achieved with suggested hMOL-GSA approach compared to FA (ITAE = 30.9001) and TLBO (ITAE = 20.4041) methods. It is obvious from Table 6 that, improved performance is achieved with less settling times with

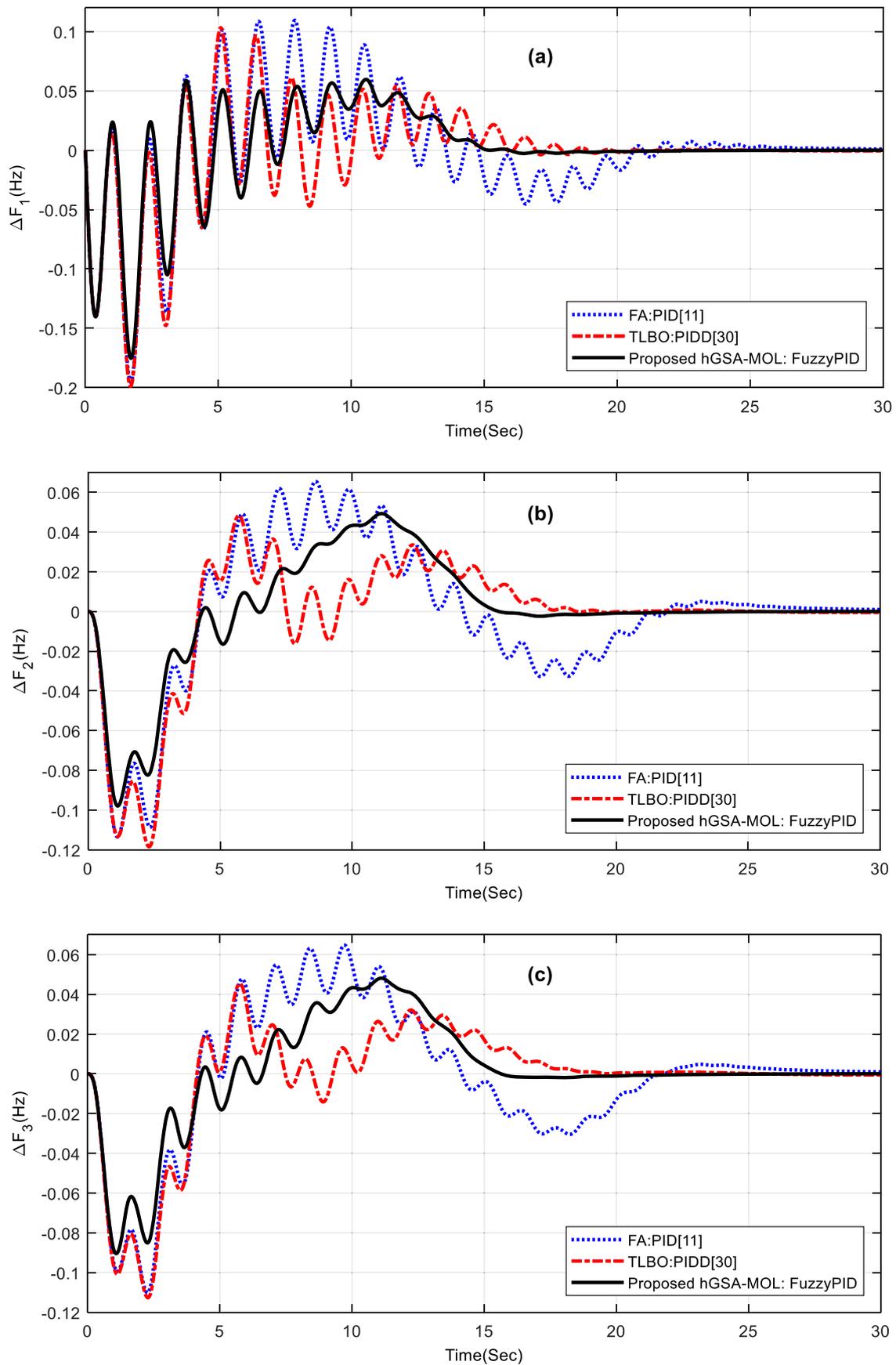


Figure 13. System responses of 3-unequal area test system at 10% change in area-1 (a) ΔF_1 (b) ΔF_2 (c) ΔF_3 (d) ΔP_{Tie1-2} (e) ΔP_{Tie1-3} (f) ΔP_{Tie2-3} .

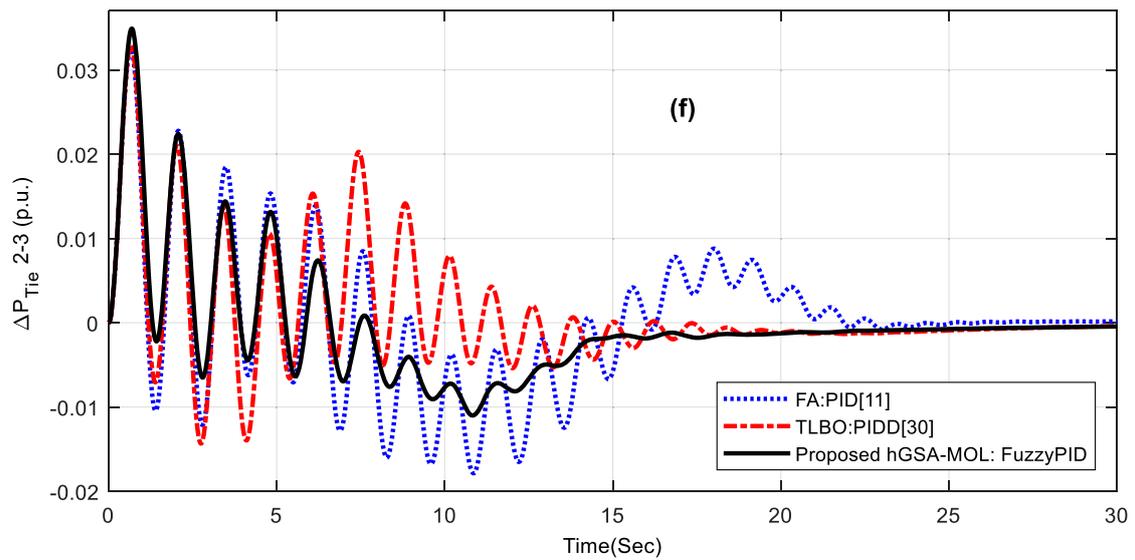
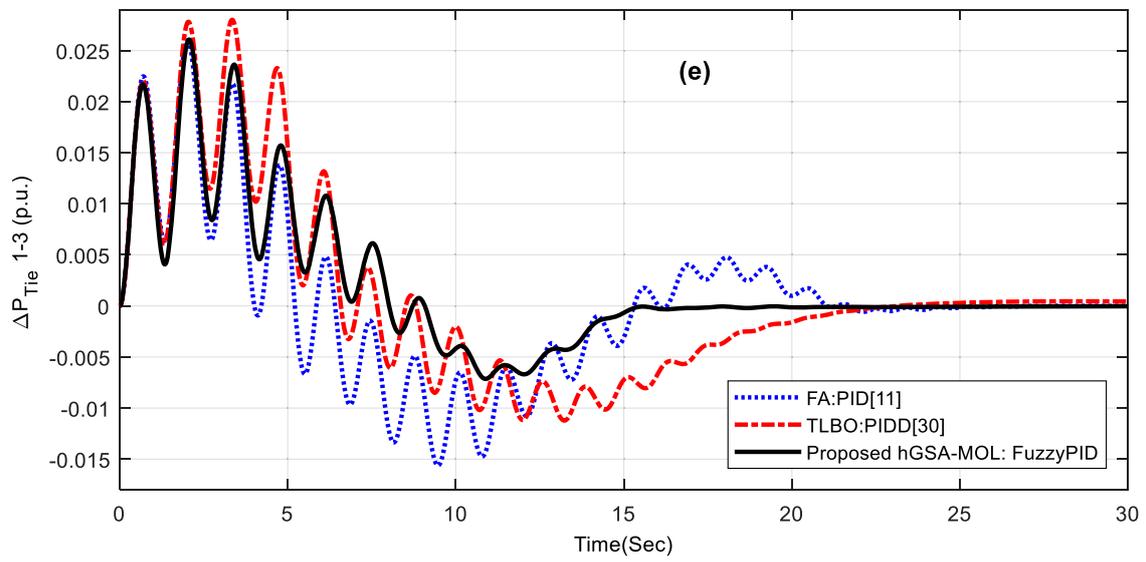
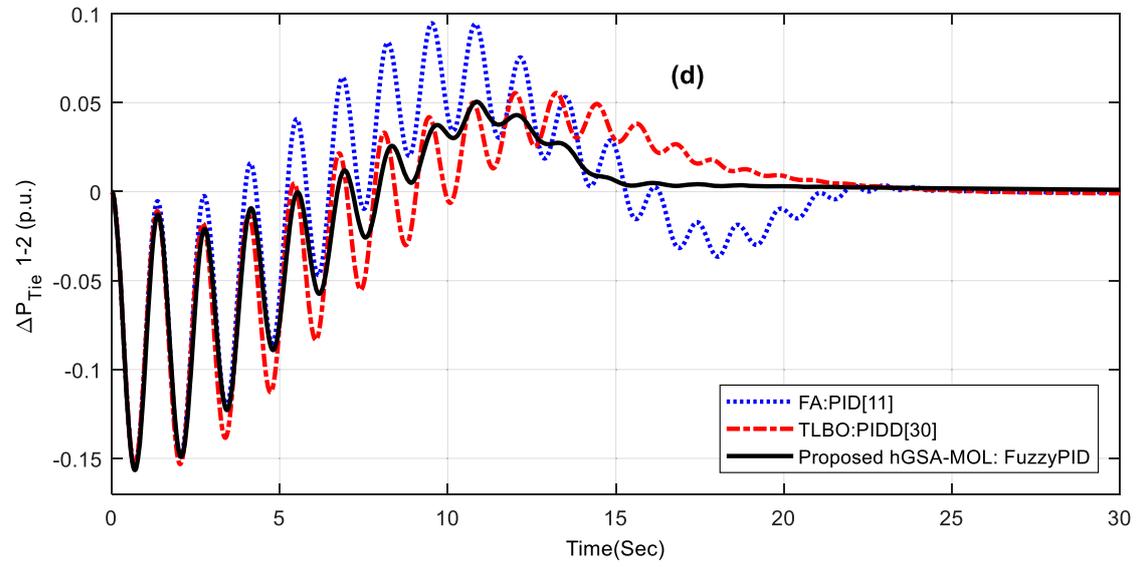


Figure 13. Continued.

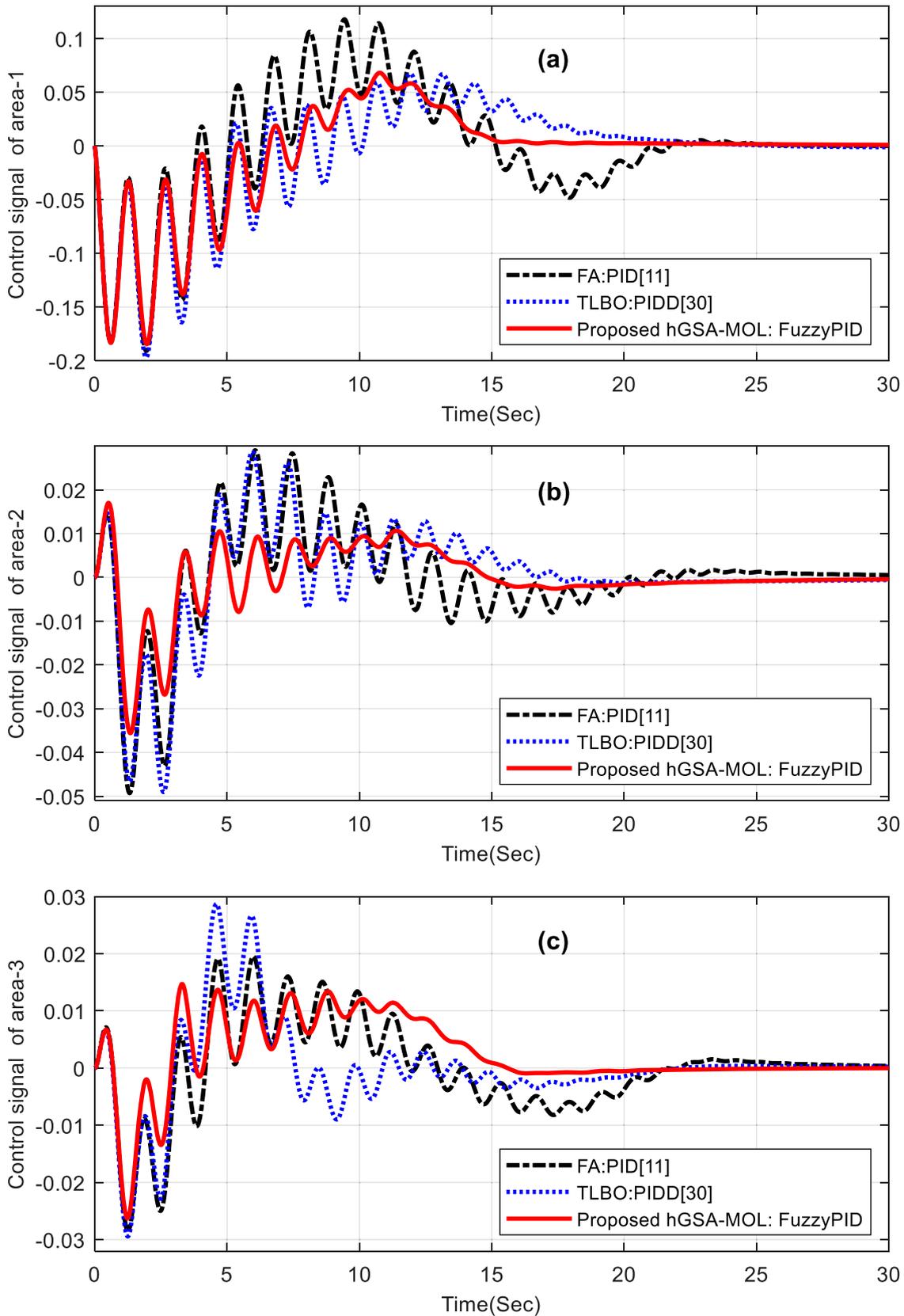


Figure 14. Comparison of control signals due to each strategy (a) Area-1 (b) Area-2 (c) Area-3.

the suggested approach than FA and TLBO methods. The dynamic response for above case is illustrated in Figure 13(a–f). It is observed from Figure 13(a–f) that suggested hMOL-GSA optimized fuzzy PID exhibits more performance dynamics compared to some newly

proposed approaches. Thus, it may be resolved that proposed hMOL-GSA approach surpasses FA and TLBO techniques.

For the above 10% SLP load disturbance, the control signals due to each strategy are shown in Figure 14(a–c)

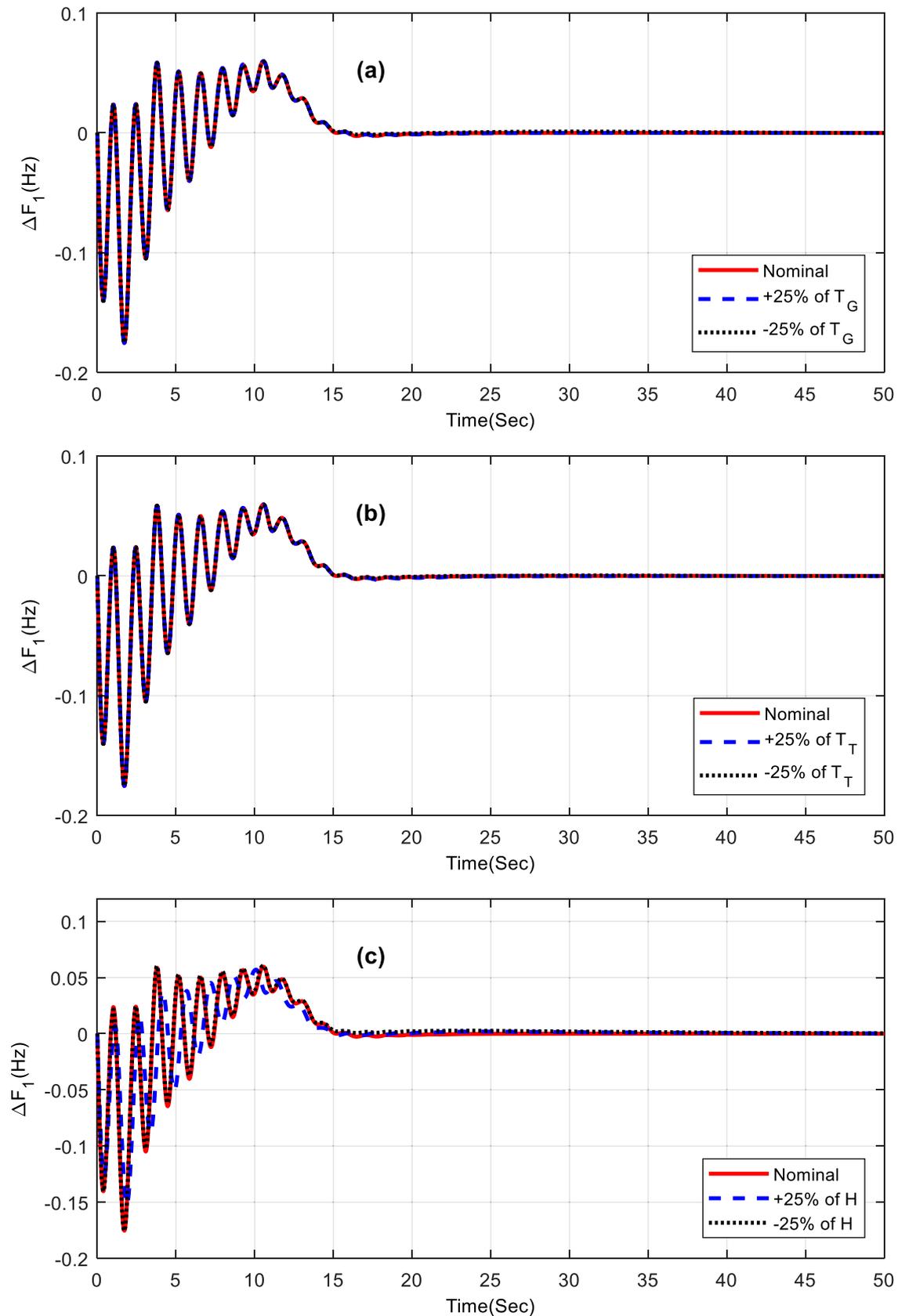


Figure 15. Frequency response in area-1 of three area test system with variation of (a) T_G (b) T_T (c) H .

from which it can be noticed that the control signal is effectively controlled by the proposed approach to enhance the system dynamic performance.

To analyse the effectiveness of the investigated system, sensitivity study is conducted with wide change

in the system parameters [11,30]. The nominal values are varied from +25% to -25% by considering one at a time. The different performance indices (settling time and ITAE) under normal and parametric alteration situations are presented in Table 7. It is clear

Table 6. Performance comparison for 3-area test system.

Techniques/controller	Settling time (s)						ITAE
	ΔF_1	ΔF_2	ΔF_3	$\Delta P_{Tie,12}$	$\Delta P_{Tie,13}$	$\Delta P_{Tie,23}$	
FA:PID [11]	26.56	26.72	26.55	24.03	19.66	20.70	30.9001
TLBO:PID [30]	19.28	18.06	18.31	23.39	19.23	15.84	20.4041
hGSA-MOL:Fuzzy-PID	18.04	17.50	15.31	23.31	14.03	14.32	17.3381

Table 7. Sensitivity analysis for 3-area test system.

Parameter variation	% Change	Settling time (s)						ITAE
		ΔF_1	ΔF_2	ΔF_3	ΔP_{Tie-12}	ΔP_{Tie-13}	ΔP_{Tie-23}	
Nominal	0	18.04	17.50	15.31	24.01	14.03	14.32	17.3381
T_G	+25	18.08	17.56	18.20	23.01	14.02	14.39	17.5156
	-25	14.94	15.22	15.37	27.17	14.04	14.31	19.7892
T_T	+25	19.29	17.78	18.53	21.77	14.04	14.35	17.9829
	-25	17.79	15.16	15.30	26.17	14.03	14.30	17.7682
H	+25	14.81	24.11	14.91	28.97	13.79	13.84	19.6657
	-25	19.89	18.34	17.45	27.67	13.98	14.32	22.9184

**Figure 16.** The real time experimental setup.

from Table 7 that settling time and ITAE values deviate within acceptable range and are close to the corresponding values found with nominal values. Thus, it may be resolved that the suggested approach provides satisfactory performance under varied conditions. As a sample, the frequency deviation of area-1 under $\pm 25\%$ variations in T_G , T_T and H of system is illustrated in Figure 15(a–c) from which, it is seen that the change in system time constants on dynamic response is insignificant. Therefore, the suggested approach offers a robust control with deviations in system parameters.

It is observed for simulation results that with conventional PID controller structure, the steady-state errors are eliminated. However, the system responses are oscillatory in nature with a large settling time and integral error. The Fuzzy PI controller increases the damping of the system and makes the system responses to have less settling times and integral errors. The proposed fuzzy PID controller further improves the performance of system as the oscillation of the system is strongly restrained and the settling time is shortened considerably with significant decrease in integral

errors. The proposed Fuzzy PID controller is also able to handle the nonlinearities, changes in the operating conditions and system parameters effectively.

4.5. Experimental results

All the parameters of proposed controllers are optimized by the hGSA-MOL technique. For experimental evaluation of the proposed control approach, the Hardware-In-the Loop (HIL) simulation approach is employed as illustrated in Figure 16. The real-time HIL approach is employed to emulate errors and delays that are absent in the classical off-line simulations and also to ensure that the proposed approach will run in real-time environment without overruns.

The HIL setup, contains of an OPAL-RT as a Real Time Simulator (RTS), which simulates the power system models shown in Figures 1 and 11; a PC as command station in which the Matlab/Simulink-based codes are generated for execution on the OPAL-RT and a router to connect all the setup devices in the same sub-network.

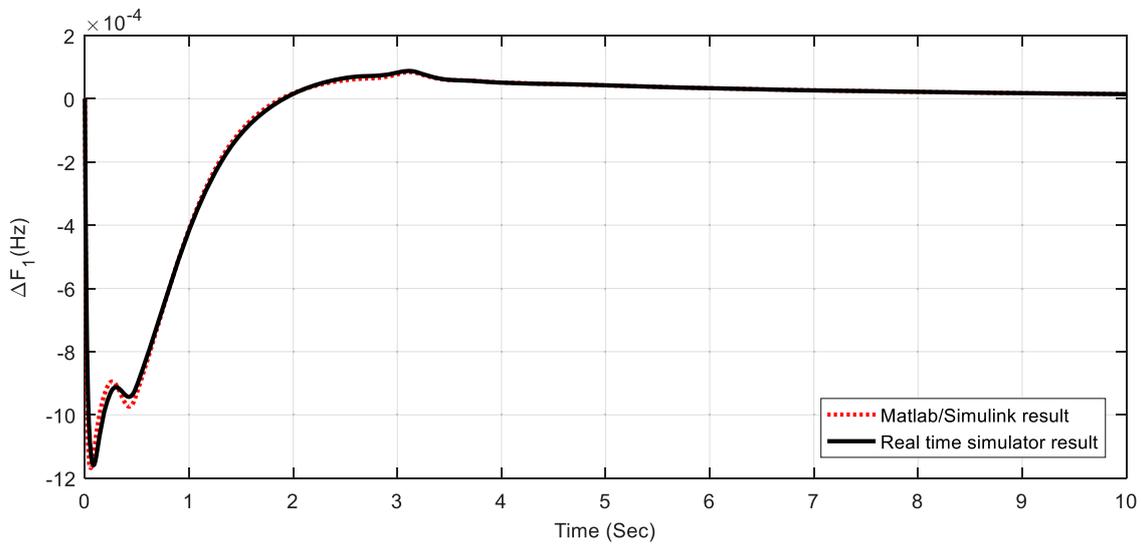


Figure 17. ΔF_1 for two-area test system.

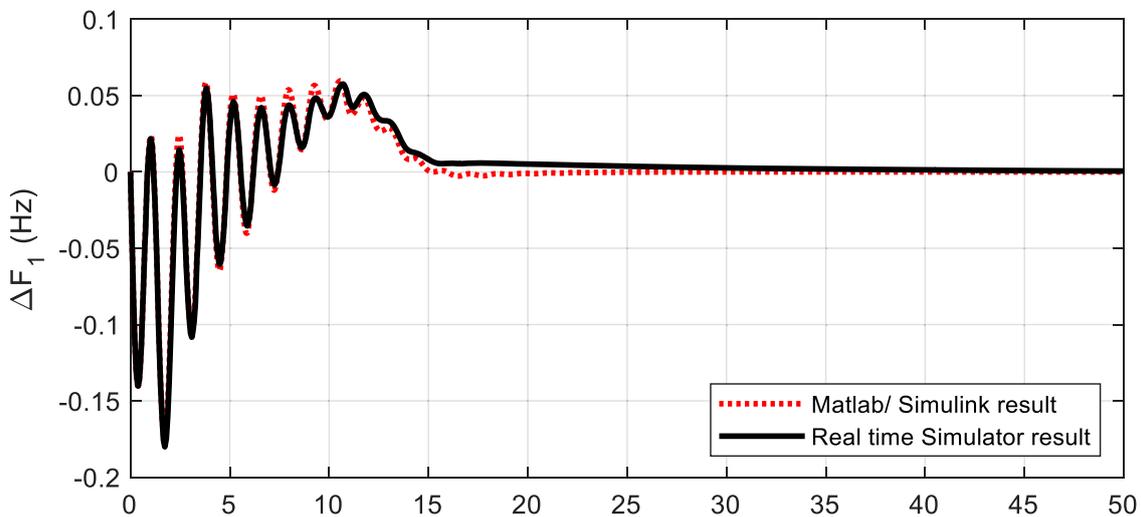


Figure 18. ΔF_1 for three-area test system.

The results of RTS and Matlab/Simulink are shown in Figures 17 and 18 for both the test systems. It can be seen from Figs that RTS results closely matches with the Matlab/Simulink results.

5. Conclusions

Design and performance investigation of hybrid fuzzy PID is studied for AGC of power systems. Firstly, a 2-area system is taken and the gains of PID are obtained using GSA technique. The advantage of the GSA optimized PID is demonstrated by comparing the outcomes with Artificial Bee Colony (ABC)-based PID for the identical test system and objective function. Then, different controller structures such as hybrid Fuzzy PI/PID are taken and controller parameters are obtained by GSA technique. The result reveals that GSA tuned fuzzy PID controller provides significant

improvement in the dynamic responses than the GSA tuned fuzzy PI controller. Further, a novel hybrid MOL and GSA techniques is employed to tune fuzzy PID parameters. The superiority of the hybrid MOL-GSA technique is established by comparing the outcomes with a GSA technique with identical test system and objective function. The result shows that proposed hybrid MOL-GSA tuned fuzzy PID controller provides significant improvement in the dynamic responses than the GSA tuned fuzzy PID. The suggested control design is extended to a 3-area test system. Outcomes are equated with some newly suggested methods in literature such as FA tuned PID- and TLBO-based PID controller for the same system to validate the advantage of the suggested approach. Finally, sensitivity study is done under varied conditions and it is noticed that system dynamic responses are satisfactory under varied conditions.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix. Two equal area thermal system [21]

$T_P = 20$ s; $K_P = 120$, $B = 0.425$ MW/Hz; $R = 2.4$ Hz/MW; $T_{12} = 0.086$ s; $T_T = 0.3$ s; $T_H = 0.08$ s; $T_r = 10$ s; $K_r = 0.5$ s.