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Fitness Dependent Optimizer-Based Automatic Generation Control of Multi-Source Interconnected Power System With Non-Linearities

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ABSTRACT This paper proposed an improved structure of Proportional Integral Derivative (PID) controller called as Integral Proportional Derivative (I-PD), applied for Automatic Generation Control (AGC) of Multi-Source Interconnected Power System (IPS). The parameters of the proposed controller are optimized with a newly developed, powerful, nature-inspired meta-heuristic technique known as Fitness Dependent Optimizer (FDO). To show the efficacy of the proposed controller and the technique used, they have been tested on three different system models. Initially, a two-equal area of diverse source generation including reheat-thermal, gas, and hydro power system is considered. In the second scenario, the same power system model is used with addition of two non-linearities; Generation Rate Constraint (GRC) and Governor Dead Band (GDB). Lastly, multiple non-linearities including Governor Dead Band (GDB), Time Delay (TD), Generation Rate Constraint (GRC), and Boiler Dynamics (BD) have been considered to make the initial system more realistic and practical. The outcome from the proposed techniques is also compared with some recently meta-heuristic algorithms such as Teaching Learning Based Optimization (TLBO), Particle Swarm Optimization (PSO) and Firefly Algorithm (FA). From the results, it has been perceived that the proposed technique shows superior performance in respect of Overshoot (O_{sh}), Undershoot (U_{sh}) and Settling Time (T_s) of the system frequency.

INDEX TERMS Automatic generation control, fitness dependent optimizer, integral-proportional derivative (I-PD) controller, multi-source, proportional integral derivative controller, load frequency control.

I. INTRODUCTION

Power system is typically built from interconnection of various complex electrical networks composing of electrical generation, transmission and distribution system. A properly designed power system must be able to support the customer demands at all times, taking into account the load variation. A balanced power system composes of two components; active and reactive power. The active power is responsible for Automatic Generation Control (AGC) or Load Frequency Control (LFC) while the reactive power is called Automatic Voltage Regulator (AVR). For reliable and quality power supply AGC plays an important role for balancing output power of a generator considering the change in load pattern, controlling the frequency of Interconnected Power System (IPS) and to keep the tie-line power, at the desired values [1]–[3].

Problem related to AGC has gained significant attention among the researchers which include regulating the frequency at pre-determined values in order to tackle the issue. Literature review reveals that different work has been conducted in AGC of IPS. For instance, Kusic *et al.* [4] considered an AGC for single area network of hydropower system designed with digital computers to monitor the frequency and output power of generator. The work has been extended by many researchers to multi area IPS, such as Mohanty *et al.* [5], which he proposed PID controller for

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AGC with different source generation comprising of hydro, gas, and reheat thermal with two IPS areas. Authors in [6] highlighted reheat thermal with three areas IPS by employed PID controller and the parameters are tuned with firefly algorithm. Barisal and Mishra in [7] have used two unequal area IPS with multiple sources. Area 1 contains multi-unit of hydro, wind and reheat whereas area 2 comprises of diesel, hydro, and reheat power plants for IPS. Similarly, authors in [8] extended the work of AGC to five areas IPS considering a single source of thermal power system by applying a PIDN controller. Meanwhile, several authors also investigate the non-linearities of AGC for IPS. For instance, Arya and Kumar [9] suggested fractional order with fuzzy based PID controller to investigate multi-area of thermal, gas and hydro generation units using GRC and GBD. Naidu *et al.* [10] suggested a wavelet based PI controller for single source of reheat thermal with three area IPS considering GRC, BD and TD. Similarly, AGC of multi-source power system with GDB and GRC was conducted in [11], [12]. Authors in [13] proposed PID controller tuned with Salp Swarm Algorithm (SSA) for LFC of multi-area IPS including GRC, GDB and Communication Delay (CD) as physical constraints. Delassi *et al.* [14] proposed fractional order fuzzy based PID controller using Differential Evolution (DE) technique considering three non linearities such as GRC, BD and GDB for LFC of three area with single source reheat-thermal unit. However, in literature multiple non linearities such as GDB, GRC, TD and BD have not been addressed collectively for multi area with multiple source power generation.

In the last few decades, a nature inspire meta-heuristic techniques were continuously gained considerable attention from researchers in the area of power system engineering especially in parameters optimization of various controllers. In this regards, different meta-heuristic optimization methods have been used to tackle the AGC problem of IPS. For Instance Sahu *et al.* [15] proposed a Tilt Integral Derivative (TID) controller for LFC of multi-area IPS considering the single source generation of reheat-thermal unit. The gains of the controller are optimized with DE and compare the results with Genetic Algorithm (GA), FA and PSO. Authors in [16] extended the work of single source to multi- source generation considering two area power system by employing PIDD controller and the parameters of the controllers are tuned with teaching learning based optimization algorithm. Guha *et al.* [17] suggested a Backtracking Search Algorithm (BSA) for the tuning of PI/PID controller considering two area IPS including reheat-thermal and hydro power units with BD, GRC and GBD. Arya [18] suggested Imperialist Competitive Algorithm (ICA) for AGC of multi-area with hydro- thermal power units including GRC, GDB and TD as a non linearities. Similarly, some of the other techniques have also been introduced by the authors to solve the AGC problem of IPS such as Grey Wolf Optimizer (GWO) [19], Cuckoo Search Algorithm (CSA) [20], Artificial Bee Colony (ABC) [21], Symbiotic Organisms Search (SOS) [22], Quasi-Oppositional Harmony Search (QOHS) [23], Whale Optimization Algorithm (WOA) [24], and Seeker Optimization Algorithm (SOA) [25]. Moreover, some of the authors also used the hybridized form of the meta-heuristics techniques like hybrid FA with Pattern Search (FA-PS) [26], Bacteria Foraging Optimization Algorithm with PSO (BFOA-PSO) [27], PSO hybridized with Levy Flight Algorithm (PSO-LFA) [7], hybrid TLBO with Pattern Search (TLBO-PS) [28], TLBO hybrid with Local Unimodal Sampling (LUS-TLBO) [29] and hybridization of DE–GWO [30]. Therefore, it is necessary to develop such an algorithm which has the ability to find the optimal solution.

Literature has suggested that a properly designed controller with adoption of appropriate and robust technique to tune the controller's parameters would further enhance the performance of AGC. Hence, this paper proposes a modified structure of PID known as I-PD controller, designed and implemented in AGC of two similar areas of diverse source generation including reheat-thermal, gas and hydro power system. Parameters of the proposed controller are optimized with a recently developed nature inspired meta-heuristic techniques termed as Fitness Dependent Optimizer (FDO). The efficacy of proposed techniques have been tested on two area multi-source power units with three different scenarios. In first scenario, a linear system has been considered while, in second case the same system model is used with addition of two non linearities i.e Governor Dead Band (GDB) and Generation Rate Constraint (GRC). Finally, a multiple number of non linearities including Generation Rate Constraint (GRC), Boiler Dynamics (BD), Time Delay (TD) and Governor Dead Band (GDB) have been considered. The outcomes from the proposed method is also compared with reported techniques based on PSO, FA and TLBO. Furthermore, various performance indices such as Integral of Time weighted Square Error (ITSE), Integral Square Error (ISE), Integral of Time multiplied Absolute Error (ITAE), and Integral of Absolute Error (IAE) have been used as an objective function for the tested two area multi-source IPS.

The rest of paper is outlined as follows. Section 2 describes the methodology which further describes the controller structure and Fitness Dependent Optimizer techniques. Section 3 describes the implementation of proposed approach as well as the obtained results. Finally, the last section concludes the works with recommendations on the future work in this area.

II. METHODOLOGY

A. CONTROLLER STRUCTURE

Integral controller is typically used for automatic generation control due to its simple structure. However, it has a drawback of slow response time in which the use of Proportional Integral (PI) controller improves the setback. PI controller has the capability to improve the dynamic response of the integral controller, in addition to being low-cost, easy to implement as well as having a simple structure. PI controller however still exhibit a slow response time to a highly non-linear system. This problem however can be solved by using a Proportional

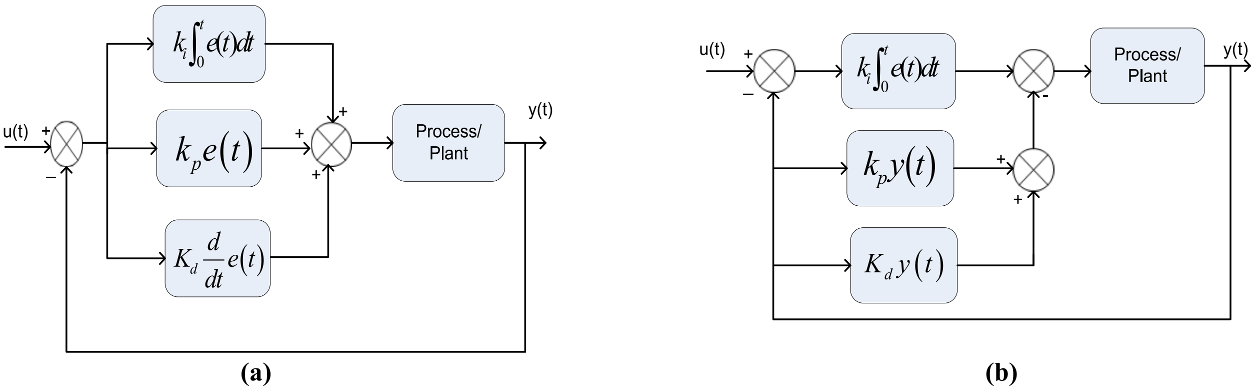

FIGURE 1. Structure of controller (a) PID (b) I-PD controller.

Integral Derivative (PID) controller. PID controller is used frequently in industries nowadays due to its strong dynamic performance, robustness, and its easy implementation. Typical structure of PID controller is depicted in Figure 1(a).

In this paper, an improved form of PID controller known as Integral-Proportional Derivative (I-PD) Controller is designed for AGC. I-PD controller has advantages of simplicity, functionality, easy to use and capability of improving the transient response of the controller, especially the overshoot time without affecting the other parameters of the controller. The structure of the proposed I-PD controller is shown in Figure 1(b). The output of the PID and I-PD controllers is given by Eq. (1) and Eq. (2) below, respectively.

$$u(t) = k_p e(t) + \int K_i e(t)dt + K_d \frac{d}{dt} e(t) \tag{1}$$

$$u(t) = \int K_i e(t) - [k_p y(t) + k_d \frac{d}{dt} y(t)] \tag{2}$$

The input of I-PD/PID controller for area 1 and 2 is the Area control error (ACE) which given by Eq. (3) and Eq. (4)

$$ACE_1 = \beta_1 \Delta F_1 + \Delta P_{tie12} \tag{3}$$

$$ACE_2 = \beta_2 \Delta F_2 + \Delta P_{tie21} \tag{4}$$

In order to attain a good system performance, it is vital to properly optimize the parameters of the controller while choosing appropriate performance criteria as an objective function. In literature four different performance indices are used including ITSE, ITAE, IAE, and ISE. However, ITAE [12], [16], [17], [31], ITSE [3], [10], [11], [21] and ISE [14], [18], [20], [28] are more frequently used for AGC problem. For the comparison among various performance indices Eq (5) to Eq (8) are implemented in matlab for two area multi-source IPS and achieved minimum fitness values for ITSE as compared to ITAE, ISE and IAE which is depicted in Table 1. Therefore, ITSE is used as cost function for the said AGC problem.

$$J_1 = ITSE = \int_0^t \left[\Delta F_1^2 + \Delta F_2^2 + \Delta P_{tie12}^2\right] tdt \tag{5}$$

TABLE 1. Comparative performance of different performance indices.

Controller with Techniques	Performance Indices (J)			
	ITSE	ISE	ITAE	IAE
PID-PSO	0.0185	0.0916	0.512	1.026
PID-FA	0.0132	0.0911	0.052	1.015
PID-TLBO	0.0129	0.0901	0.045	1.010
PID-FDO	0.0117	0.0834	0.047	0.976
I-PD (PSO)	0.0105	0.0812	0.232	0.985
I-PD (FA)	0.0108	0.0912	0.021	1.011
I-PD (TLBO)	0.0102	0.0808	0.187	0.910
I-PD (FDO)	0.0098	0.0759	0.151	0.898

$$J_2 = ISE = \int_0^t \left[\Delta F_1^2 + \Delta F_2^2 + \Delta P_{tie12}^2\right] dt \tag{6}$$

$$J_3 = ITAE = \int_0^t [|\Delta F_1| + |\Delta F_2| + |\Delta P_{tie12}|] tdt \tag{7}$$

$$J_4 = ITAE = \int_0^t [|\Delta F_1| + |\Delta F_2| + |\Delta P_{tie12}|] dt \tag{8}$$

B. FITNESS DEPENDENT OPTIMIZER

Fitness Dependent Optimizer (FDO), developed by Abdullah and Rashid [31] is applied for the tuning of controllers of AGC with multi-source IPS. FDO has fast convergence rate, dynamics and able to solve nonlinear problems. FDO consist of the following points:

1) A random population of scout bees are initialized in the search space, X_k (k = 1, 2, 3 . . . . n).

2) The scout bees are randomly searching for better hive. Once a better position is found, the previous one is discarded. Thus, at each position a new optimum solution is identified by the algorithm. However, if the current forward direction doesn't give any optimal solution it will go back to its previous direction looking for the best solution.

3) In searching for an optimal solution, a scout bees add pace to their current position and their moment can be shown

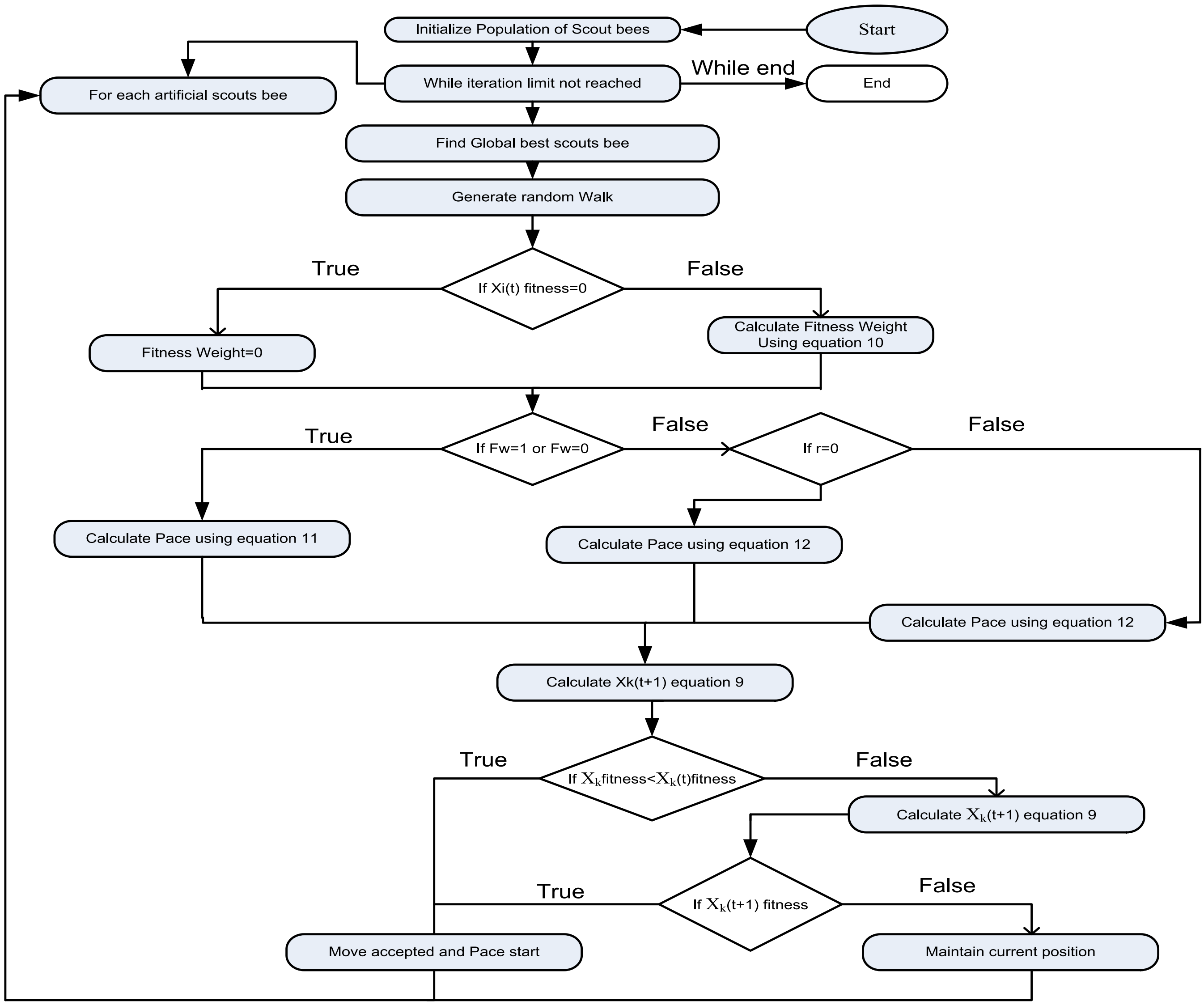

FIGURE 2. **Flow chart of fitness dependent optimizer.**

as follows.

$$X_{k,t+1} = X_k + P \tag{9}$$

where X indicates the scout bees, K is the current position, t is the iteration of scout bees and P represents the direction and the forward moment rate.

4) The pace depends upon a factor term known as fitness weight (FW). Though, the momentum of the pace is totally random. The FW can be expressed as

$$FW = \left| \frac{X^*_{K,t,f}}{X_{k,t,f}} \right| - \gamma \tag{10}$$

The $X^*_{K,t,f}$ denotes the value of fitness function for the global best solution, $X_{k,t,f}$ represents the fitness value for the current solution while γ is the weight factor taking the value of either 0 or 1 to control the FW. When $\gamma = 1$, it shows the high rate of convergence and if $\gamma = 0$, then it does not affect above equation. In many cases, γ is usually 0 for a stable search. However, this condition is problem dependent.

5) The FW should be in the range of [0, 1]. The value of FW will be one when $X^*_{K,t,f}$ and $X_{k,t,f}$ have the same values. The Value of FW will be zero when $X^*_{K,t,f} = 0$. To avoid $X_{k,t,f} = 0$ the following rules should be applied.

$$P = \alpha X_{K,t,f} : \text{ If WF} = 0, \quad \text{OR WF} = 0, \ \text{OR} X_{k,t,f} = 0 \tag{11}$$

$$P = \begin{Bmatrix} WF(X_{k,t,f} - X^*_{k,t,f}) - 1; \ If \text{ WF<1 AND WF>0 AND} \alpha < 0 \\ WF(X_{k,t,f} - X^*_{k,t,f}); \ \text{ If WF} < 1 \text{ AND WF} > 0 \text{ AND} \alpha \leq 0 \end{Bmatrix} \tag{12}$$

where α is a random integer in the range of [−1 1]. The basic steps for FDO flow chart as given in Figure 2.

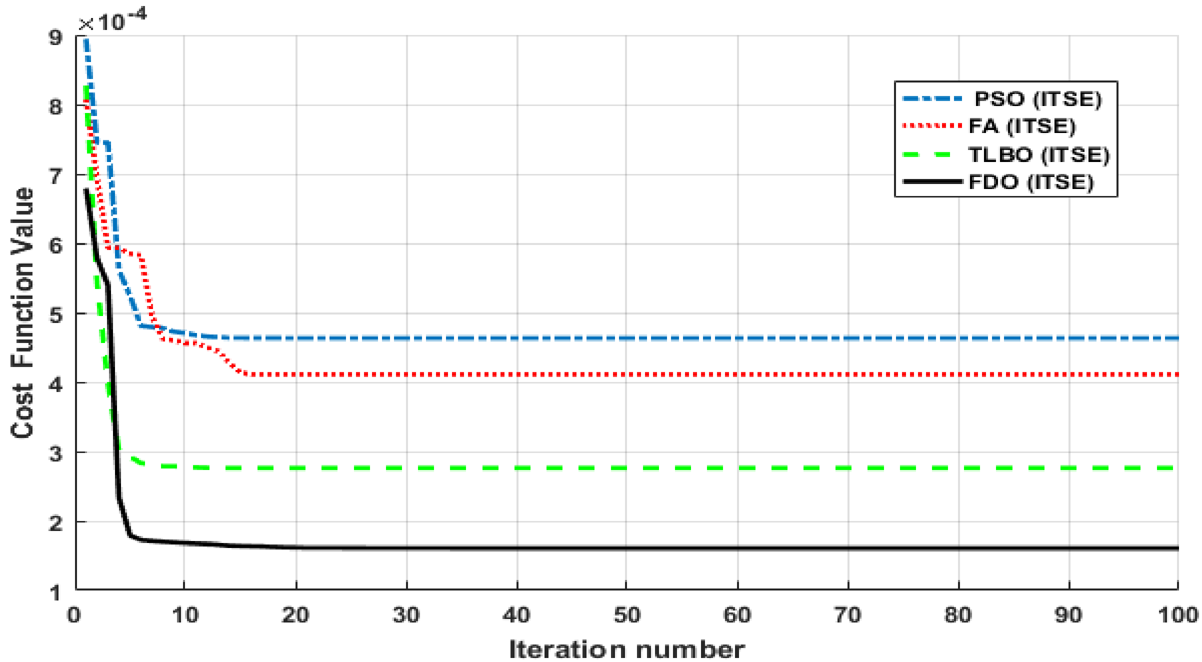

FIGURE 3. Convergence diagram for different tuning techniques using ITSE criteria.

TABLE 2. Optimum values of I-PD/PID controllers for multi –source generation with linear system (Case -1).

Controller with Meta-heuristic Techniques	Controller Parameters of Reheat -Thermal			Controller Parameters of Hydro Power System			Controller Parameters of Gas Power System		
	K_p	K_i	K_d	K_p	K_i	K_d	K_p	K_i	K_d
FDO-PID	1.06	0.33	-0.67	0.27	0.23	-0.38	1.36	0.23	0.67
FDO-I-PD	0.46	1.10	0.76	1.33	1.56	0.08	0.56	2.00	0.56
PSO-PID	0.53	1.20	-0.20	1.46	1.02	0.09	0.23	1.00	0.23
PSO-I-PD	1.09	1.76	0.23	1.53	1.80	1.04	1.19	1.56	0.12
FA-PID	0.39	0.41	-0.45	1.31	1.30	2.00	0.35	0.01	0.45
FA-I-PD	0.70	1.80	0.49	1.06	1.46	0.03	0.60	1.80	0.40
TLBO-PID	0.95	0.43	0.23	1.30	1.00	0.10	0.45	0.23	0.23
TLBO-I-PD	0.60	1.90	0.28	1.20	1.45	0.47	1.70	1.90	0.19

III. IMPLEMENTATION AND RESULTS

In this section, PID/I-PD controller is designed and implemented on two area, multi-source interconnected power system considering different generation source of hydro, reheat-thermal and gas power system. In order to show the effectiveness of the proposed technique, it has been simulated on two area multi-source IPS with 1% step load perturbation (SLP) in Area-1 considering three different scenarios. First scenario is a two area multi-source interconnected power system without considering nonlinearities. In second setup, the same system model is tested with addition of two non-linearities i.e GDB and GRC. Finally, in the last scenario, multiple non-linearities including TD, GRC, BD and GDB have been deliberated for the same model. Parameters of the controller are optimized with fitness dependent optimizer using ITSE as cost function. To optimize parameters of controller the values of FDO parameters has been considered from Appendix (Table 9). The optimization run were carried out 30 times and the best optimal values among the 30 runs is picked as an ultimate gains of controller. The best optimum value for two area multi-source with linear system are given in Table 2. While, the optimal values for two area multi-source unit with GDB and GRC are provided in Table 3. Similarly, the optimal values for multi-source with multiple non linearities such as GRC, GDB, TD and BD are provided in Table 4. Results achieved from the proposed technique are compared with a few other techniques such as TLBO, PSO, and FA used to develop and optimize the PID/I-PD controllers. The convergence diagram for fitness values with different techniques are provided in Figure 3.

TABLE 3. Optimum values of I-PD/ PID controllers for multi –source generation unit with GRC and GDB (Case 2).

Controller with Meta-heuristic Techniques	Controller Parameters of Reheat -Thermal			Controller Parameters of Hydro Power System			Controller Parameters of Gas Power System		
	K_p	K_i	K_d	K_p	K_i	K_d	K_p	K_i	K_d
FDO-PID	0.28	1.10	0.02	0.13	0.19	1.07	0.09	1.01	1.31
FDO-I-PD	1.37	0.90	0.80	0.67	0.67	-1.13	1.67	0.10	1.10
PSO-PID	0.49	0.10	1.02	0.23	0.09	1.47	1.32	1.89	0.49
PSO-I-PD	0.01	0.23	1.11	1.49	1.98	0.13	0.91	1.36	0.43
FA-PID	1.28	0.34	0.98	1.32	0.45	1.09	1.29	0.91	0.20
FA-I-PD	1.92	0.08	-0.31	1.90	1.56	1.30	0.67	1.92	0.35
TLBO-PID	0.96	1.43	1.30	0.45	1.34	0.01	0.33	1.33	1.10
TLBO-I-PD	0.09	0.80	-0.13	0.29	0.67	0.39	1.89	0.34	1.24

TABLE 4. Optimum values of I-PD/ PID controllers for multi –source unit with TD, GRC, BD and GDB (Case-3).

Controller with Meta-heuristic Techniques	Controller Parameters of Reheat -Thermal			Controller Parameters of Hydro Power System			Controller Parameters of Gas Power System		
	K_p	K_i	K_d	K_p	K_i	K_d	K_p	K_i	K_d
FDO-PID	0.17	1.21	0.91	0.13	1.29	0.45	0.32	0.99	1.09
FDO-I-PD	1.23	0.35	0.12	0.20	0.23	0.12	0.24	1.10	0.23
PSO-PID	0.09	0.11	0.23	1.03	0.01	-0.89	0.10	1.90	0.11
PSO-I-PD	1.56	1.78	0.12	1.59	0.82	1.98	1.01	1.06	0.31
FA-PID	0.04	0.22	0.14	0.11	0.52	1.34	0.04	0.01	1.55
FA-I-PD	0.64	0.98	1.11	0.33	1.09	0.12	0.30	2.80	1.60
TLBO-PID	0.04	0.23	1.34	1.19	0.99	-0.16	0.34	1.20	2.00
TLBO-I-PD	0.20	0.10	1.08	1.01	0.56	0.35	1.90	1.00	1.78

A. LINEAR SYSTEM MODEL

A two area multi-source IPS is considered in Figure 4 that has a combination of reheat- thermal, hydro, and gas power units, where the two areas are connected via tie line. In Figure 4, β_1 and β_2 represent the frequency bias constants of Area-1 and Area-2, respectively. ΔF_1 and ΔF_2 denote the change in frequency for Area 1 and Area 2, respectively.

While R_{th1}, R_{g1}, and R_{h1} while R_{th2}, R_{g2}, R_{h2} represent droop constant of Area 1 and Area 2, respectively for thermal, gas and hydro power system. On the other hand K_g, K_h and k_{th} denote the constant for gas, hydro, and reheat-thermal power system, respectively. Reheat-thermal unit is composed of governor, reheat and turbine with Transfer Function (TF) $\frac{1}{ST_t+1}$, $\frac{Sk_1T_r+1}{ST_r+1}$ and $\frac{1}{ST_1+1}$ respectively. While the hydropower system is comprised of governor, droop compensation and penstock turbine with TF of $\frac{1}{ST_{gh}+1}$, $\frac{ST_r+1}{ST_{rh}+1}$, and $\frac{-ST_w+1}{0.5ST_w+1}$, respectively. On the other hand, the gas power system is composed of valve position, governor, fuel combustion reaction and compressor discharge with TF $\frac{1}{Sb_g+x_g}$, $\frac{Sx_c+1}{Sy_c+1}$, $\frac{1}{ST_{cd}+1}$, and $\frac{ST_{cr}-1}{ST_f+1}$, respectively while the TF for the proposed power system model is $\frac{K_p}{ST_p+1}$.

In Figure 5 (a), (b) and (c) the results shows that FDO-PID controller suppresses frequency oscillation, responds quickly to reach its stable, final value and produces less overshoot as compared to optimized PID controllers with FA, TLBO, and PSO approaches for both Area 1, Area 2 and Tie- line power. From Table 5 it can be perceived that FDO-PID controller improves settling time by 17.4%, 3.05%, and 39.4%, reduces frequency overshoot by 92%, 41.6% and 96.72%, and frequency undershoot by 9.6%, 18.1 % and 89. 1% as compared to optimized FA-PID controller for variation in frequency of Area 1 (ΔF_1), Area 2 (ΔF_2) and tie-line power (ΔP_{tie}) respectively. On the other hands, results depicted in Figures 5 (d)-(f) show that FDO-I-PD controller outperforms the other type of optimized I-PD controllers in terms of frequency overshoot. In addition, FDO-I-PD controller also shows significant improvement in terms of T_S (55.27%, 44.2% and 11.01%) and U_{sh} (49%, 66.6% and 39.5%) as compared to reported LUS based TLBO with fuzzy PID [29] for Area-1, Area-2 and inter-connected power system with tie line, respectively. Similarly, FDO-IPD controller also shows improvement in settling time (39.63%, 72.03% and 77.54%) and undershoot (68.53%, 66.66%, and 73.63%) for ΔF_1, ΔF_2 and ΔP_{tie}, respectively as compared to LUS-TLBO-PID approach. From Table 5 it can be also observed that the proposed approach shows distinct improvement in terms of T_S for ΔF_1, ΔF_2 and ΔP_{tie} (83.3%, 80.2% and 77.5%) as compared to DE-PID [5].

B. NON LINEAR SYSTEM MODEL

A physical system is composed of several components that are interconnected and perform a specific task. Practically,

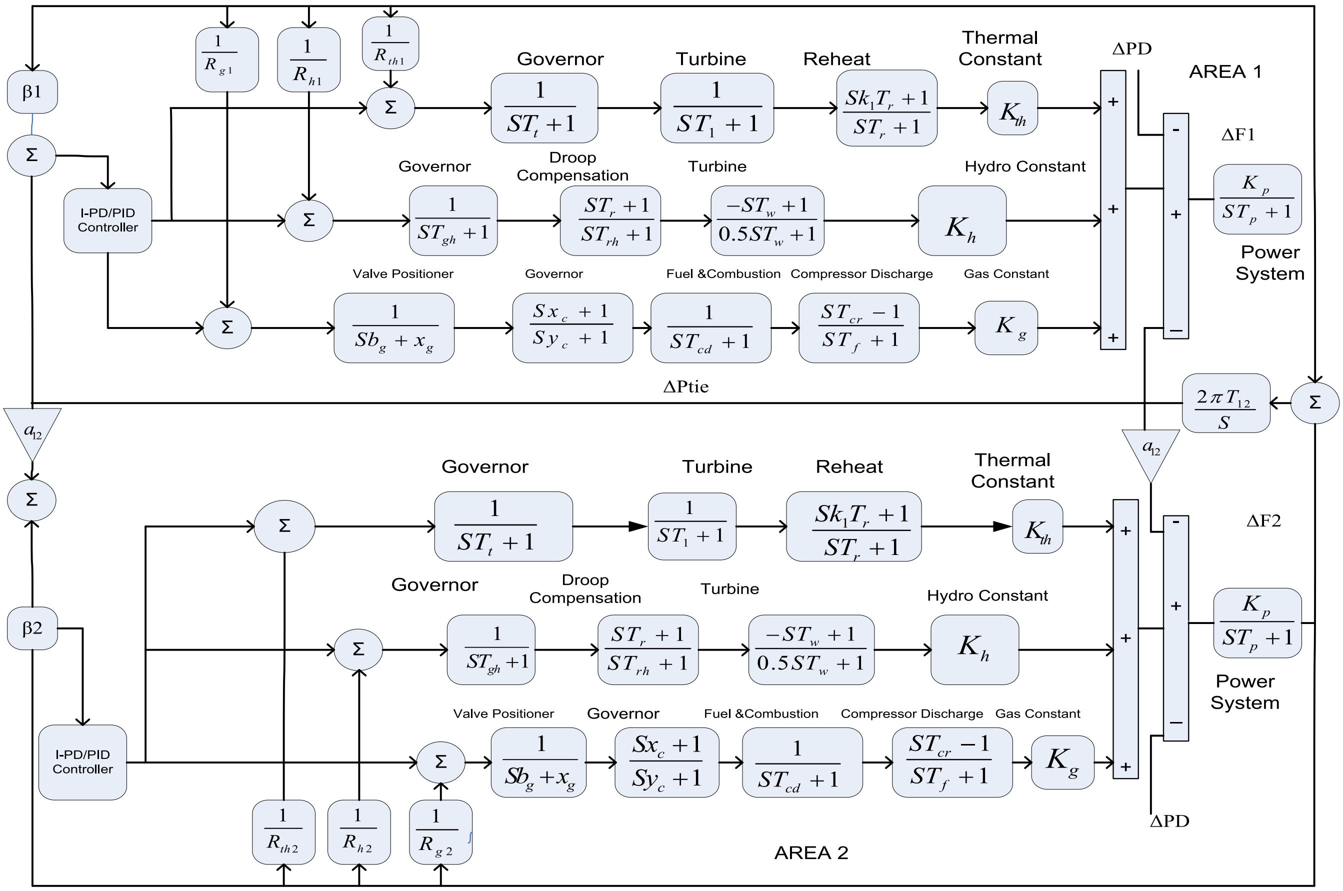

FIGURE 4. Multi-source interconnected power system with linearity.

TABLE 5. Comparative performance between different algorithms for two area multi-source power system.

Controller with Meta-heuristic Techniques	(Settling time) T_s			(Overshoot) O_{sh}			(Undershoot) U_{sh}		
	ΔF_1	ΔF_2	ΔP_{tie}	ΔF_1	ΔF_2	ΔP_{tie}	ΔF_1	ΔF_2	ΔP_{tie}
FDO-PID	**5.20**	**12.70**	**4.30**	**0.00000**	**0.00021**	**0.00020**	**-0.00047**	**-0.00130**	**-0.00056**
FDO-I-PD	**2.30**	**1.65**	**2.10**	**0.00000**	**0.00000**	**0.00000**	**-0.00450**	**-0.00500**	**-0.00058**
PSO-PID	5.90	13.40	9.30	0.00930	0.00250	0.00630	-0.00054	-0.00016	-0.00580
PSO-I-PD	2.90	9.20	6.80	0.00400	0.00400	0.00080	-0.00720	-0.05500	-0.00910
FA-PID	6.30	13.10	7.10	0.00021	0.00036	0.00610	-0.00052	-0.00110	-0.00510
FA-I-PD	4.30	4.10	5.90	0.00000	0.00000	0.00043	-0.00490	-0.00900	-0.00640
TLBO-PID	9.37	3.76	4.76	0.00172	0.00043	0.00017	-0.01972	-0.01279	-0.00307
TLBO-I-PD	2.20	2.20	2.20	0.00000	0.00000	0.00011	-0.00530	-0.00500	-0.00130
LUS-TLBO [29] Fuzzy-PID	5.26	2.96	2.36	0.00055	0.00021	0.00008	-0.00895	-0.00301	-0.00096
DE-PID [5]	13.84	8.35	9.35	0.00203	0.00077	0.00019	-0.02657	-0.02214	-0.00475

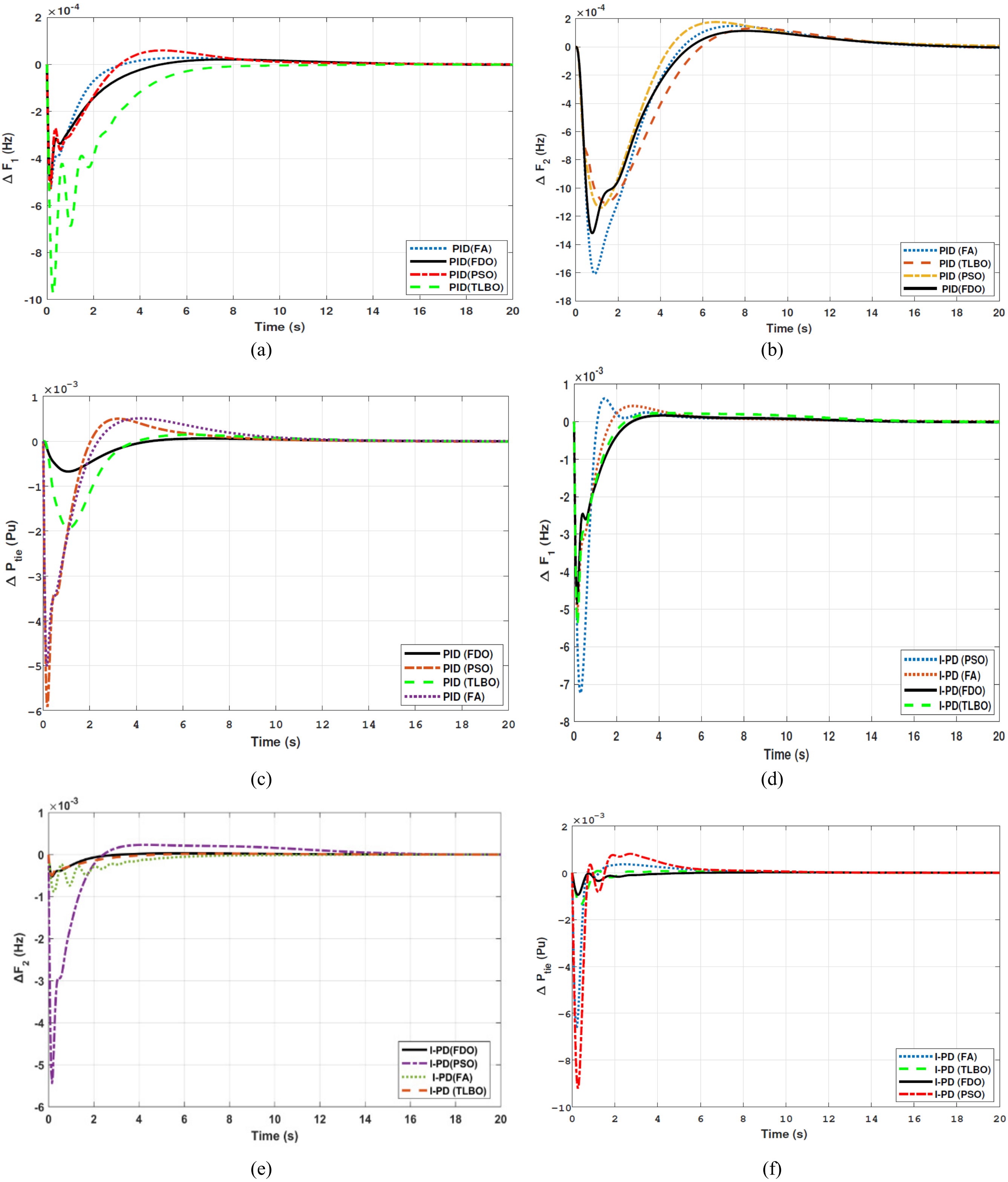

FIGURE 5. Results of multi-source power system. (a) ΔF_1 with PID controller (b) ΔF_2 with PID controller. (c) ΔP_{tie} with PID controller. (d) ΔF_1 with I-PD controller (e) ΔF_2 with I-PD controller. (f) ΔP_{tie} with I-PD controller.

it is difficult to identify all the components of the physical system. In this paper, we have attempt to consider all the probable non linearities such as Generation Rate Constraint (GRC), Governor Dead Band (GDB), Time Delay (TD), and Boiler Dynamics (BD) which make the system model more practical. In order to show effectiveness of the proposed

TABLE 6. Performance of multi-source with two area including two non linearities (GRC and GDB).

Controller with Meta-heuristic Techniques.	T_s (Settling time)			O_{sh} (overshoot)			U_{sh} (Undershoot)		
	ΔF_1	ΔF_2	ΔP_{tie}	ΔF_1	ΔF_2	ΔP_{tie}	ΔF_1	ΔF_2	ΔPt_{ie}
FDO-PID	**10.9**	**11.1**	**13.2**	**0.00115**	**0.000409**	**0.000554**	**-0.00968**	**-0.00972**	**-0.00682**
TLBO-PID	11.3	12.2	14.1	0.00224	0.000593	0.000660	-0.00968	-0.00673	-0.00686
FA-PID	11.9	11.1	16.2	0.00225	0.000823	0.00103	-0.00885	-0.00973	-0.00813
PSO-PID	11.1	12.9	17.1	0.00364	0.00107	0.00119	-0.0128	-0.00973	-0.00824
PSO-I-PD	13.3	12.8	7.9	0.000495	0.000559	0.000526	-0.00682	-0.00667	-0.01103
FA-I-PD	11.6	13.4	10.2	0.000393	0.000451	0.000518	-0.00891	-0.00934	-0.00460
TLBO-I-PD	13.1	11.4	9.3	0.000226	0.000391	0.000139	-0.00665	-0.00951	-0.00348
FDO-I-PD	**10.1**	**11.6**	**8.1**	**0.000147**	**0.000246**	**0.000340**	**-0.00887**	**-0.00597**	**-0.00342**

controller with FDO techniques the two area multi-source IPS with several non-linearities have been tested in which two cases is deliberated. In first case, a setting of linear system model is used which is illustrated in section 3 with addition of two non linearities i.e GRC and GDB have been examined and their outcomes are shown in Figure 7 (a)-(f) and Table 6. While in second case, various non linearities like GRC, TD, BD and GDB have been considered for the same generation sources. The TF model of multi- source IPS with various non linearities have been depicted in Figure 8 and their outcomes are given in Figure 9 (a)-(f). The comparative performance between different techniques are quantified in Table 7 where, the bold values indicates the best result. The brief discussion of various non linearities is given as follows:

1) GENERATION RATE CONSTRAINT (GRC)

This constraint is due to limitation of turbine on the rate of change in the power generation. It main effect is on the performance of power system due to its characteristic of non-linearity.

2) GOVERNOR DEAD BAND (GDB)

The GDB [17] is defined as the total amount of a continuous speed change within governor where the valve position of the turbine does not change. For larger steam turbine the typical values of GDB is 0.06%. The transfer function model for GDB is given below.

$$G(s) = N_1 + SN_2 \tag{13}$$

where $N_1 = 0.8$ and $N_2 = -\frac{0.2}{\pi}$ so equation 13 becomes

$$G(s) = 0.8 - S\frac{0.2}{\pi} \tag{14}$$

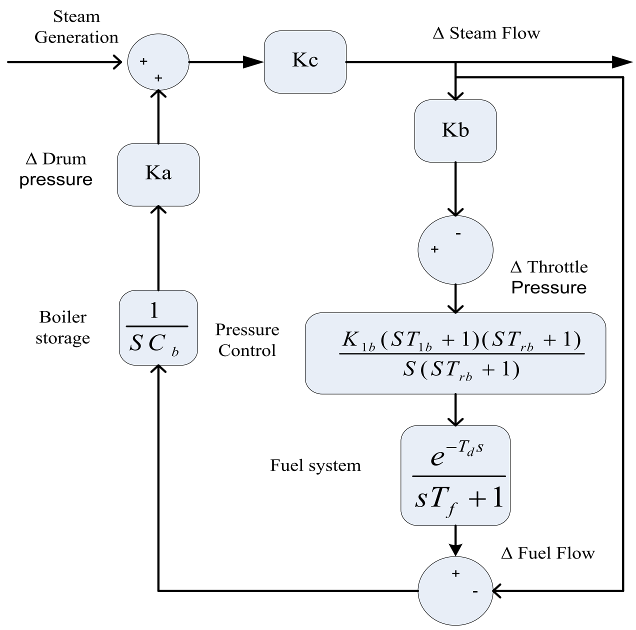

FIGURE 6. TF model of drum type boiler.

3) BOILER DYNAMICS (BD)

The blocked diagram of drum type boiler is given in Figure 6. The parameters of the value for BD are taken from [17] and are given in Appendix (Table 8).

4) TIME DEALY (TD)

The time Delay related with AGC can affect the performance of the system, if it is not addressed properly. However, in certain cases it may interrupt the stability of the system. In this paper we have considered the TD for AGC model is 2 second which is used more practically [18].

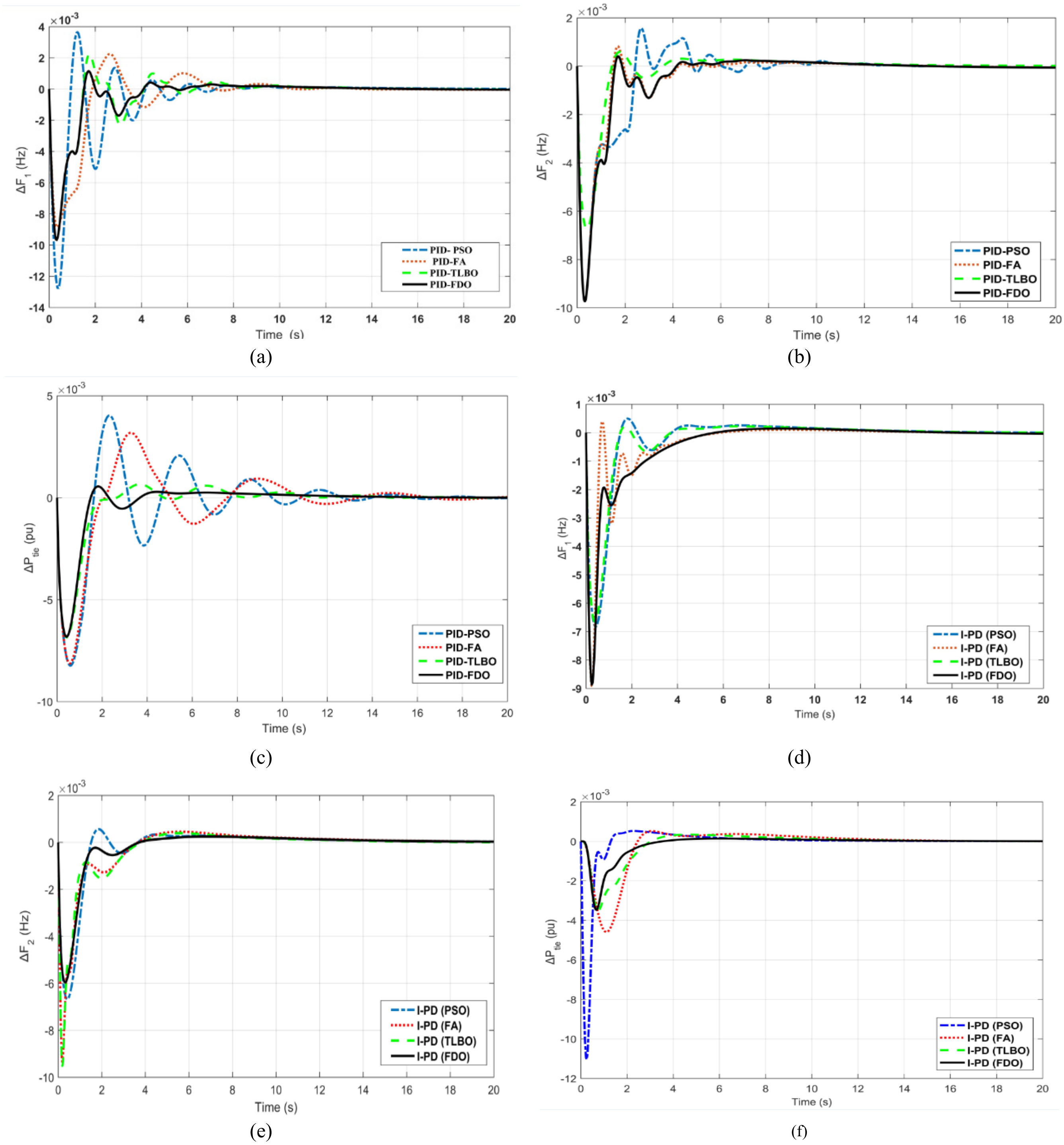

FIGURE 7. Results of multi-source power system with GRC and GDB. (a) ΔF_1 with PID controller (b) ΔF_2 with PID controller. (c) ΔP_{tie} with PID controller. (d) ΔF_1 with I-PD controller (e). ΔF_2 with I-PD controller. (f) ΔP_{tie} with I-PD controller.

From Table 6 it can be clearly observed that FDO-PID controller outperform in respect of settling time which shows the percentage improvement of 1.80%, 13.96%, and 22.80% for ΔF_1, ΔF_2 and ΔP_{tie} respectively as compared to PSO-PID. Similarly, a significant percentage improvement can be seen as compared to PSO-PID in terms of overshoot by (68.40%, 61.77%, and 86.25%) and undershoot by (24.37%, 0.102%, and 16.11%) for ΔF_1, ΔF_2 and ΔP_{tie} respectively. Furthermore the results obtained from Figure 7 (a)-(c) also reveals that FDO-PID controller has best performance in terms of T_s, O_{sh} and U_{sh} as compared to FA-PID and TLBO-PID. The results shown in Figures 7 (d)-(f) disclose that FDO-IPD

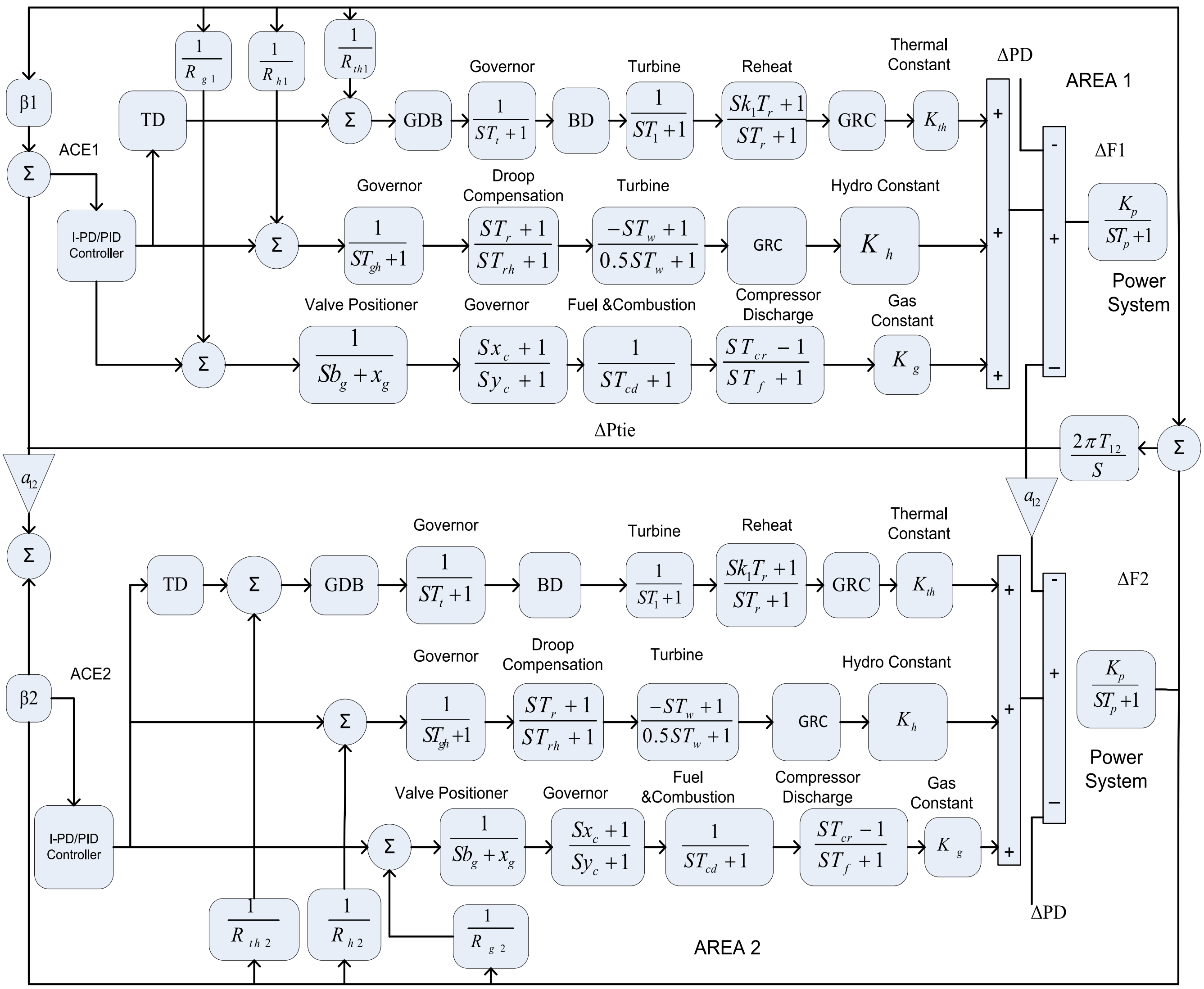

FIGURE 8. Multi-source interconnected power system with GRC, TD, BD and GDB.

outperform in terms of settling time and undershoot but, it also shows tremendous performance in term of overshoot as compared to other techniques such as PID/IPD-PSO, PID/I-PD-FA, and PID/I-PD -TLBO for identical power system. FDO-I-PD controller shows percentage improvement in terms of T_s by (9.01%, 11.62% and 45.61%), O_{sh} by (93.79%, 96.55% and 63.45%), and U_{sh} by (48.04%, 2.26% and 57.19%) as compared to PSO-PID for ΔF_1, ΔF_2 and ΔP_{tie} respectively. Similarly, FDO-I-PD controller also shows best results as compared to PID-FA controller in respect of settling time by (15.70 %, 2.13% and 42.59%), overshoot by (89.95%, 52.49% and 95.64%) and undershoot by (24.85%, 2.26% and 57.19%) for variation in Area 1, Area 2 and tie-line power respectively.

To illustrate the effectiveness of the suggested techniques, the best claimed outcome of FDO-PID/I-PD for two Area multi -source IPS with various non linearities is shown in Table 7. The results shown in Figures 9 (a)-(f) reveals that the proposed FDO optimized PID/I-PD controllers perform better response as compared to FA/PSO/TLBO with PID/I-PD controller. The settling time (2.72%, 25.86%, and 17.75%), Overshoot (18.44%, 82.63% and 38.28%) and undershoot (2.67%, 16.11% and 23.02%) for ΔF_1, ΔF_2 and ΔP_{tie} with FDO-PID controller are respectively improved compared to FA-PID. While FDO based I-PD controller shows a remarkable improvement in terms of settling time by (17.11%, 56.81% and 28.81%), overshoot by (92.64%, 99.92% and 63.71%) and undershoot by (86.55%, 74.15% and 44.27%) for ΔF_1, ΔF_2 and ΔP_{tie} respectively as compared to PSO-PID controller. Similarly, FDO based I-PD controller also show a percentage improvement in terms of settling time by (14.29%, 56.32% and 25.44%), overshoot by (88.07%, 99.27% and 61.26%) and undershoot (86.26%, 73.80 and 14.28%) for variation in frequency of

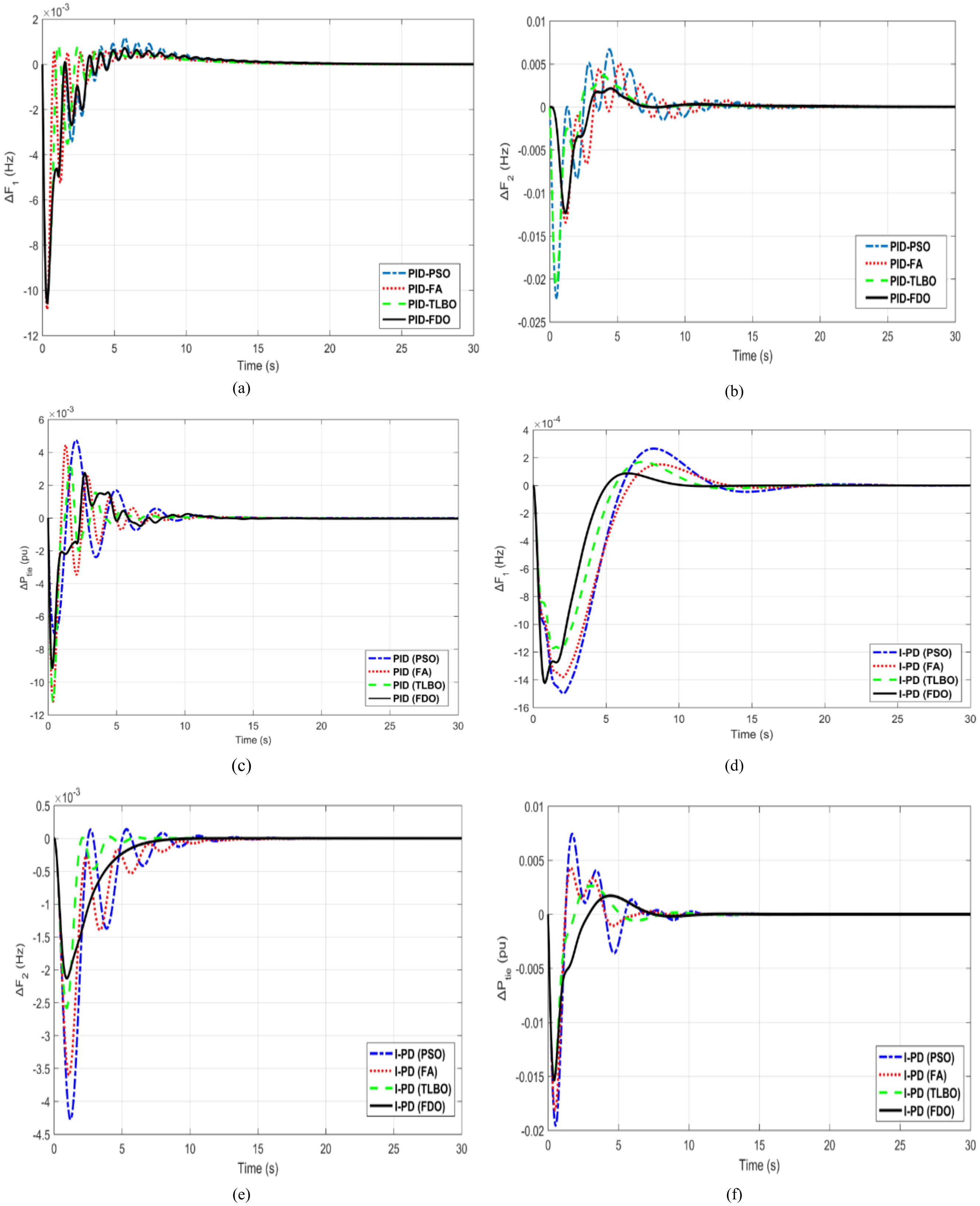

FIGURE 9. Results of multi-source power system with GRC, BD, TD and GDB. (a) ΔF_1 with PID controller (b) ΔF_2 with PID controller. (c) ΔP_{tie} with PID controller. (d) ΔF_1 with I-PD controller. (e) ΔF_2 with I-PD controller. (f) ΔP_{tie} with I-PD controller.

TABLE 7. Performance of multi-source with two area including all non linearities (GRC, BD TD and GDB).

Controller with Meta-heuristic Techniques	T_s (Settling time)			O_{sh} (overshoot)			U_{sh} (Undershoot)		
	ΔF_1	ΔF_2	ΔP_{tie}	ΔF_1	ΔF_2	ΔP_{tie}	ΔF_1	ΔF_2	ΔP_{tie}
FDO-PID	15.1	12.9	13.9	0.000588	0.000554	0.00274	-0.01056	-0.00682	-0.00916
TLBO-PID	14.8	12.7	15.4	0.000873	0.000660	0.00336	-0.01056	-0.00686	-0.0119
FA-PID	14.7	17.4	16.9	0.000721	0.00319	0.00444	-0.01085	-0.00813	-0.0119
PSO-PID	15.2	17.6	17.7	0.00117	0.00403	0.00474	-0.01056	-0.00824	-0.00707
PSO-I-PD	17.6	13.0	17.6	0.000226	0.000136	0.00742	-0.00150	-0.00428	-0.0196
FA-I-PD	15.1	12.9	15.1	0.000152	0.000000	0.00430	-0.00138	-0.00360	-0.0181
TLBO-I-PD	13.9	8.2	13.9	0.000169	0.000022	0.00263	-0.00118	-0.00258	-0.0152
FDO-I-PD	**12.6**	**7.6**	**12.6**	**0.000086**	**0.000003**	**0.00172**	**-0.00142**	**-0.00213**	**-0.0152**

TABLE 8. Parameter setting for two-area interconnected power system [18].

Parameters	Values	Parameters	Values	Parameters	Values
β_1 and β_2	0.4312 MW/Hz	R_{th1}, R_{th2}, R_{hy1}, R_{hy2}, R_{g1}, R_{g2}	2.4 Hzs	T_{gh}	0.08 s
T_t	0.3 s	K_I	0.3	T_r	10 s
K_P	68.956	T_p	11.49 s	T_{12}	0.0433
a_{12}	-1	T_w, y_c	1 s	T_{rs}	5 s
T_{rh}	28.75 s	T_{gh}, T_{cd}, T_{DC}	0.2 s	x_c	0.6 s
K_g	0.130438	K_{DC}, x_g	1	b_g	0.05 s
K_t	0.543478	T_{cr}	0.01 s	T_f	0.23 s
K_h	0.85	K_c	0.8243	K_b	0.950

TABLE 9. Values of FDO parameters.

Parameters	Values	Parameter	Values	Parameter	Values	Parameters	Values
Number of Population (Np)	30	Number of generations (Ng)	100	Lower bound	-2	Upper bound	2
Number of dimension	9	random number (α)	[1 -1]	Weight factor (ϒ)	0.0		

Area 1, Area 2 and tie-line respectively. FDO-I-PD controller also shows a significant improvement in respect of settling time by (90.14%, 99.54% and 48.80%), overshoot by (44%, 82.63% and 38.22%) and undershoot by (86.55%, 68.95% and 14.28%) for ΔF_1, ΔF_2 and ΔP_{tie} respectively as compared to TLBO with PID controller.

IV. CONCLUSION

In this research work, an improved form of PID controller known as I-PD controller has been designed and applied for multi-source of two area power system with diverse generation source such as reheat thermal, gas, and hydropower system. The gains of PID/I-PD controllers are tuned by recently developed meta-heuristic technique known as Fitness Dependent Optimizer (FDO). To show the preeminence of the proposed techniques a various constraints including GDB, GRC, TD, and BD have been considered. The transient response performance attained by the proposed controller provide significant improvement in respect of Overshoot (O_{sh}), Undershoot (U_{sh}) and Settling Time (T_s) as compared to other techniques such as TLBO, PSO and FA. It is observed that FDO-PID controller improved results as compared to FA/TLBO/PSO-PID in terms of T_s, O_{sh} and U_{sh} for ΔF_1, ΔF_2 and ΔP_{tie} respectively. Similarly, FDO based I-PD controller shows a remarkable improvement in terms of T_S, O_{sh} and U_{sh} compared to PSO/FA/TLBO-PID controller for ΔF_1, ΔF_2 and ΔP_{tie} respectively. The efficacy of FDO based PID /I-PD controllers clearly demonstrate the competency of these controllers to tackle the AGC problem effectively with sustained oscillation and quick response. In future we anticipate to apply PID/I-PD controllers optimized with FDO approach to more than two area interconnected power systems with various sources of generation. One may also endeavor these controllers for deregulated power system.

APPENDIX

See Tables 8 and 9.

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