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Multiverse optimized fuzzy-PID controller with a derivative filter for load frequency control of multisource hydrothermal power system

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Abstract: In this paper, a multiverse optimized (MVO) fuzzy PID controller with a derivative filter (fuzzy-PIDF) is proposed for the load frequency control (LFC) of a two-area multisource hydrothermal power system. The superiority of the MVO algorithm is demonstrated by comparing the system LFC performance with integral and fuzzy-PIDF controllers, both optimized using MVO, as well as some of the recent heuristic optimization techniques such as the ant lion optimizer, gray wolf optimizer, differential evolution, bacterial foraging optimization algorithm, and particle swarm optimization. To the best of the knowledge of the authors, the use of the MVO technique has not yet been reported for LFC studies. Among many of the controllers implemented here for comparison, the proposed MVO fuzzy-PIDF controller exhibits the best performance under different operating conditions in terms of settling times, maximum overshoot, and values of cost function, i.e. integral time absolute error. Furthermore, the robustness of the proposed control scheme is also investigated against variation of system parameters within $\pm 10\%$, along with random step load disturbances. The proposed control scheme is not very sensitive to parametric variations and therefore keeps providing effective performance even under $\pm 10\%$ variations in system parameters. System modeling and simulations are carried out using MATLAB/Simulink.

Key words: Fuzzy logic controller, load frequency control, multisource hydrothermal power system, multiverse optimized, proportional-integral-derivative controller

1. Introduction

The prime objective of load frequency control (LFC) is to regulate the generation vis-à-vis load so as to maintain balance, which minimizes the frequency deviation and helps regulate tie-line power flows. In a multiarea power system, LFC controls the active power generation of the generators in each area as per variations in the load. The area control error (ACE) is taken as the input to the controller that tries to bring the ACE to zero, which means both frequency and tie-line power errors will reduce to zero [1–3]. A very elaborate and thorough review of the literature on LFC is presented in [1], which may be referred to for further understanding.

Over the years, LFC has been established to be a very effective scheme in regulating the frequency in a power system to ensure reliable and quality electrical power to consumers [4]. The design of the LFC scheme has always been one of the major issues in electrical power system studies and is becoming all the more critical in recent years with the growing size, complexity, and varying structure of the interconnected power system. In the past decades, several LFC approaches were proposed for improved performance in respect to the stability, optimality, and robustness of power systems [5–7].

Most of the LFC studies in the past decades have used classical control concepts; however, those

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techniques have some limitations, especially when power system models are considered with nonlinearities [8]. Two fuzzy rules for integral and proportional gains of the PID controller [9], genetic algorithm (GA) [10], particle swarm optimization (PSO) [11], bacterial foraging (BF) optimization algorithm [12], differential evolution (DE) [13], hybrid gravitational and pattern search algorithms [14], firefly algorithm [15], teaching–learning-based optimization [16], hybrid LUS-TLIB optimized fuzzy-PID controller [17], gray wolf optimizer (GWO) [18], and ant lion optimizer (ALO) [19] are some of the many control and optimization methodologies that have been proposed for LFC studies of multiarea power systems. Recently, inspired by the Big Bang theory, another powerful optimization technique, called the multiverse optimization (MVO) technique, was developed by Mirjalili et al. [20], in which the authors demonstrated the advantages of MVO over GWO, PSO, GA, and the gravitational search algorithm. It has been observed that the same has not yet been applied in LFC for the optimization of variables. Another new algorithm, called the dragonfly algorithm (DA), has been proposed [21] but has not yet been applied for optimization in LFC studies.

The multiarea power system structure is nonlinear in nature; therefore, classical controllers, optimized at a particular operating condition, do not do well under changing operating conditions [22]. In such situations, intelligent controllers have been proposed that are reported to provide optimal performance under changing operating conditions by updating the controller parameters [23,24] as needed. Fuzzy logic control is one of the main constituent methodologies of intelligent control that has been successfully applied to LFC applications. However, the optimal choice of parameters such as inputs, scaling factors, membership functions, and the rule base of the fuzzy controller is of paramount importance and critical.

In view of the above discussion, this paper proposes the application of the MVO algorithm for optimal tuning of I/PI/PIDF/Fuzzy-PIDF controllers for LFC of a multisource hydrothermal power system. Sensitivity analysis of the system has also been studied with regard to wide variations in system parameters and loading patterns. Simulation results and analysis are presented to show the effectiveness of the MVO algorithm for LFC studies under different operating conditions.

2. System description

The two-area interconnected multisource hydrothermal power system whose transfer function model is shown in Figure 1 is considered for the LFC study, in which I, PI, PIDF, and fuzzy-PIDF are the secondary controllers implemented. Nominal parameters of the system are given in the Appendix. System dynamics are investigated under 1.5% step load perturbation in area 1. The controller gains are optimized using the MVO technique. Integral time absolute error (ITAE), given by Eq. (1), is the cost function used for optimization because it reduces both settling time and peak undershoot/overshoot [23]:

$$ITAE = \int \left(|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie12}| \right) \cdot t \cdot dt. \tag{1}$$

3. Control structures and optimization methodologies

The control structures and the optimization algorithm implemented in this work are discussed under the following subheadings.

3.1. Control structures

The PIDF and fuzzy-PIDF control structures are implemented in this work along with the conventional I and PI for comparison purposes. The gain parameters of these controllers are optimally tuned using MVO.

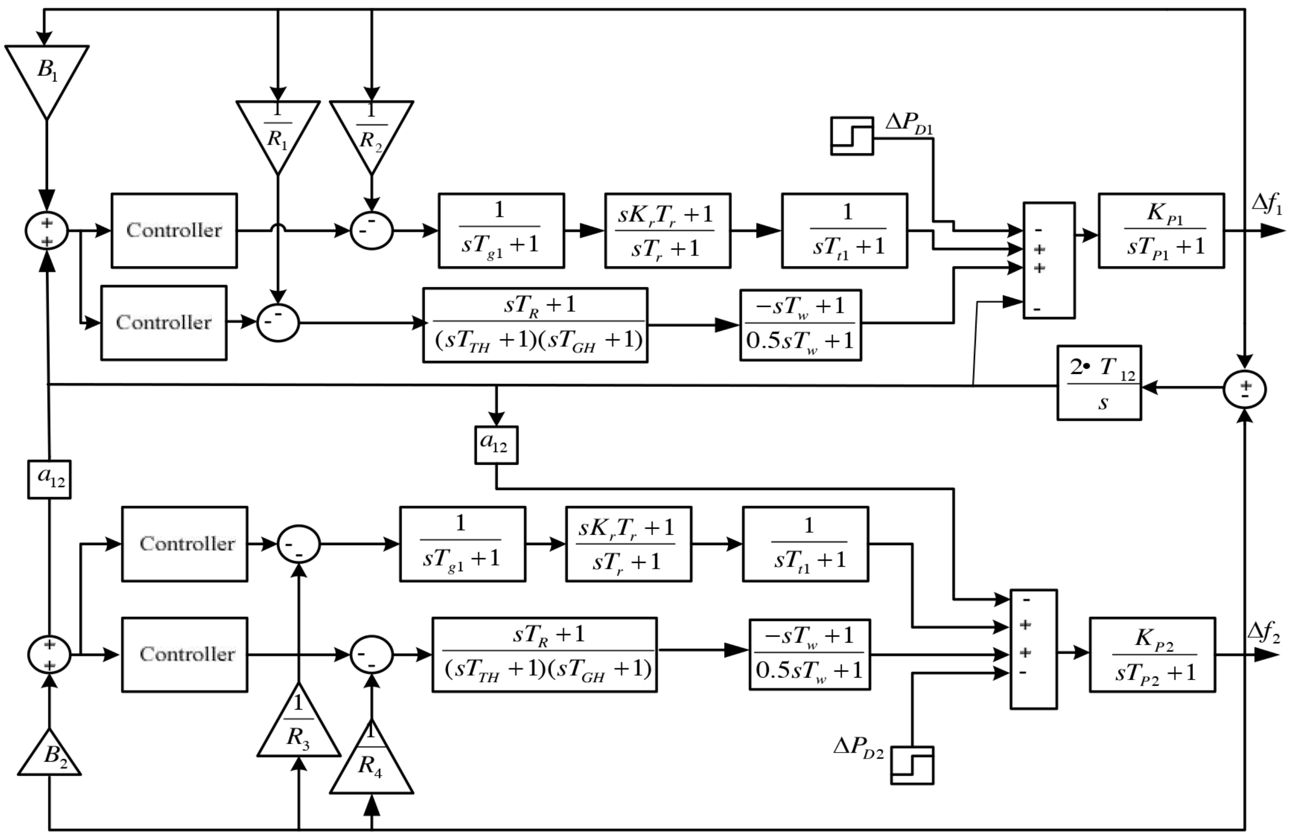

Figure 1. Block diagram representation of the multisource hydrothermal power system.

In a steady state, fuzzy-PI type control is known to be more practical than the fuzzy-PD type, whereas, in a transient state, fuzzy-PD type control is a better option if the controllers are to be individually used. However, the fuzzy-PIDF type control results in enhancement of the performance as compared to the individual fuzzy-PI or fuzzy-PD type control [25,26]. The application of fuzzy logic, in general, to the design of fuzzy-PIDF can be classified into two broad categories as per their construction:

1. The gains of the fuzzy-PIDF are tuned online utilizing the knowledge base and fuzzy inference mechanism, and the controller then generates the control signal [27].

2. A typical fuzzy logic controller (FLC) is constructed as a set of heuristic control rules, and the control signal is directly deduced from the knowledge base and the fuzzy inference mechanism as is done in the McVicar–Whelanor diagonal rule base generation approaches [28].

The controllers in the second category are referred to as PID type FLCs because their structures are analogous to that of the PID controller with a derivative filter from the input–output relationship point of view.

In the present work, the structure of the proposed fuzzy-PIDF controller is as shown in Figure 2. The structure of the fuzzy-PIDF controller, as shown in Figure 2, is conceptually based on the working of the fuzzy PI and fuzzy PD controllers [22], where K_1 and K_2 are the input scaling factors of the FLC. As can be seen in Figure 2, the FLC output U is obtained, having been processed through K_P, K_I, K_D, and the derivative filter coefficient N, as given by:

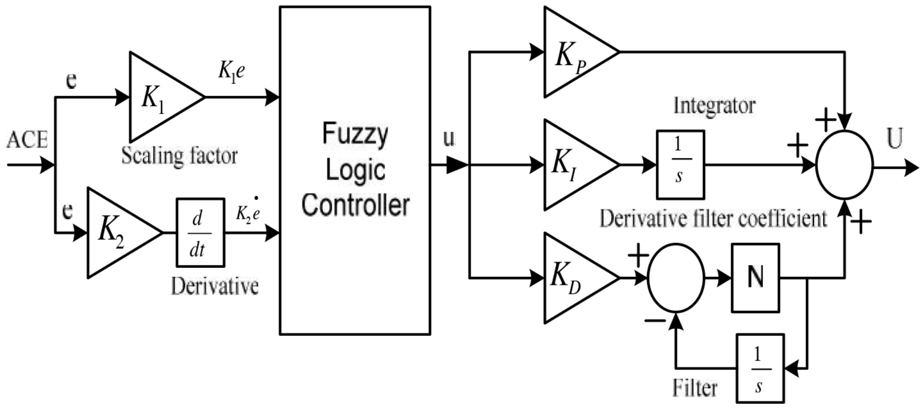

Figure 2. Structure of the proposed fuzzy-PIDF controller.

$$U = K_P u + K_I \int u\, dt + K_D \frac{du}{dt}, \tag{2}$$

where u is the output of the FLC. As shown in [29], for the fuzzy controllers with a product–sum inference mechanism, the center of gravity defuzzification method, the use of triangular membership functions for the inputs and a crisp output, and the relation between the input and the output variables of the FLC can be described as:

$$u = A + K_1 Pe + K_2 D\dot{e}, \tag{3}$$

where K_1 and K_2 are the scaling factors of e and $\dot{e}$, respectively. Therefore, from Eqs. (2) and (3), the controller output is obtained as:

$$U = K_P\,(A + K_1 Pe + K_2 D\dot{e}) + K_I \int (A + K_1 Pe + K_2 D\dot{e})dt + K_D \frac{d}{dt}(A + K_1 Pe + K_2 D\dot{e}). \tag{4}$$

The design parameters K_1, K_2, K_P, K_I, K_D, and N are optimally tuned using MVO. Figure 2 and Eqs. (2) and (3) clearly show the relationships between the input and output variables of the controller. Triangular membership functions have been considered to represent the input linguistic variables ACE, the derivative of ACE, and the FLC output variable U. Each linguistic variable consists of five linguistic terms, namely negative large (NL), negative small (NS), zero (ZZ), positive small (PS), and positive large (PL), as shown in Figure 3. The Mamdani fuzzy inference mechanism with a center of gravity method of defuzzification is selected. The appropriate fuzzy rule base is shown in Table 1, accurately representing the relationship between two inputs and one output.

Table 1. Fuzzy rule base.

e \ de/dt	NL	NS	ZZ	PS	PL
NL	NL	NL	NL	NS	ZZ
NS	NL	NL	NS	ZZ	PS
ZZ	NL	NS	ZZ	PS	PL
PS	NS	ZZ	PS	PL	PL
PL	ZZ	PS	PL	PL	PL

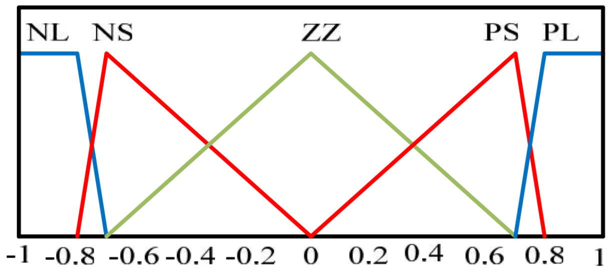

Figure 3. Membership functions for inputs and output.

3.2. Multiverse optimization algorithm

The MVO algorithm was proposed by Mirjalili et al. [16] and was demonstrated to be very effective. Inspired by its reported effectiveness for optimization, this study used the MVO algorithm for optimal tuning of the parameters of the controllers implemented for the LFC study of the power system considered. The MVO algorithm is an iterative optimization algorithm based on three phenomena observed in cosmology, namely white holes, black holes, and worm holes, with these phenomena being mathematically modeled to perform exploration, exploitation, and local search, respectively. Important parameters involved in the iterative process are the dimension of the system (the number of variables of interest and the range of these variables) and the number of the universe (the search agents). A detailed description of the algorithm can be referred to in [16].

4. Results and discussion

The model of the system under study (Figure 1 and its variants as per different case studies) is developed in a MATLAB/Simulink environment, and the different optimization algorithms and controllers are implemented with varying operating conditions. The simulation results are investigated and presented under the following case studies:

- Comparative performance analysis of the MVO algorithm
- Comparative performance analysis of the proposed fuzzy PIDF controller
- Sensitivity analysis against parameter variations and random load changes

The optimization algorithms are implemented through MATLAB programs (.mfiles). In the implementation of the MVO algorithm, the number of universes was taken as 50, the number of iterations as 50, the minimum worm hole existence probability as 0.2, the maximum worm hole existence probability as 1, and the iteration time counter as 1. In the present work, scaling factors, controller gains, and derivative filter coefficients are chosen in the ranges of [0–1], [0–2] and [5–30], respectively. A 1.5% step load change is considered in area 1. The fuzzy PIDF controller optimized by the MVO algorithm constitutes the proposed novel control strategy implemented along with the others.

4.1. Comparative performance analysis of the MVO algorithm

The LFC performance of the system in Figure 1, in terms of frequency and tie-line power deviations, is investigated with the integral controller and also with the proposed fuzzy-PIDF controller, whose gains are optimized by the MVO algorithm and for comparison purposes by other algorithms, namely PSO, BF, DE, GWO, and ALO, respectively. The optimization process was repeated 30 times for all of the algorithms.

Dynamic response with all of these algorithms is shown in Figures 4–6 for the integral controller and Figure 7 for the fuzzy-PIDF controller. For quantitative comparative analysis, the values of different performance parameters are presented in Tables 2 and 3 for the integral controller and the proposed fuzzy-PIDF controller, respectively. From Figures 4–7 and Tables 2 and 3, it is clearly evident that the MVO algorithm provides the best results compared to all other algorithms, both with the integral controller and the proposed fuzzy-PIDF controller.

4.2. Comparative performance analysis of the proposed fuzzy-PIDF controller

In this case, the I/PI/PIDF/fuzzy-PIDF controllers, optimized by the MVO algorithm, are implemented for each source in both areas, and the LFC performance is investigated under the impact of a step load change of 1.5% in area 1 at t = 0 s for the system in Figure 1. The comparative performance is depicted in Figures 8–10 in terms of deviations of frequency in both areas and tie-line power. Comparative analysis is presented quantitatively in Table 4, with respect to standard performance measures such as settling times with a 2% tolerance band, maximum overshoot, and minimum values of the cost function (ITAE).

It is established that in the study of LFC maximum overshoot is more significant than settling time. From the comparison of results (Figures 8–10 and Table 4), it can be deduced that the PIDF is very effective

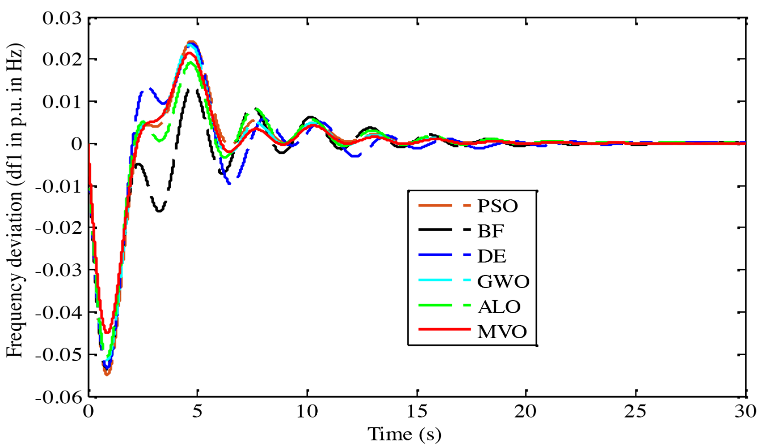

Figure 4. Frequency deviation of area 1 vs. time with integral controller.

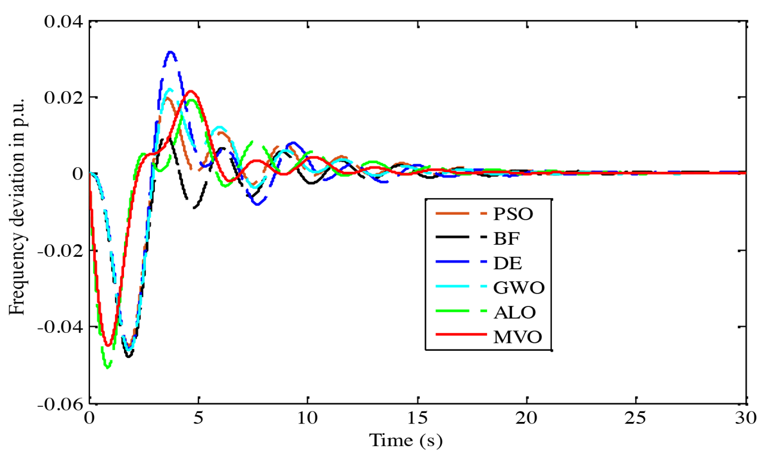

Figure 5. Frequency deviation of area 2 vs. time with integral controller.

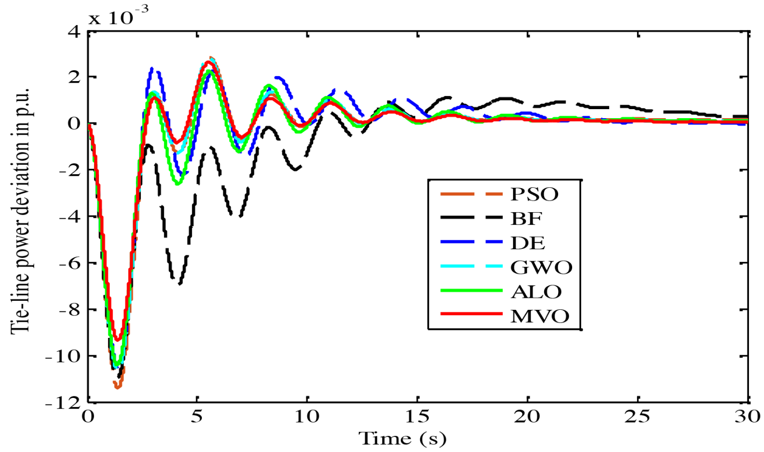

Figure 6. Tie-line power deviation vs. time with integral controller.

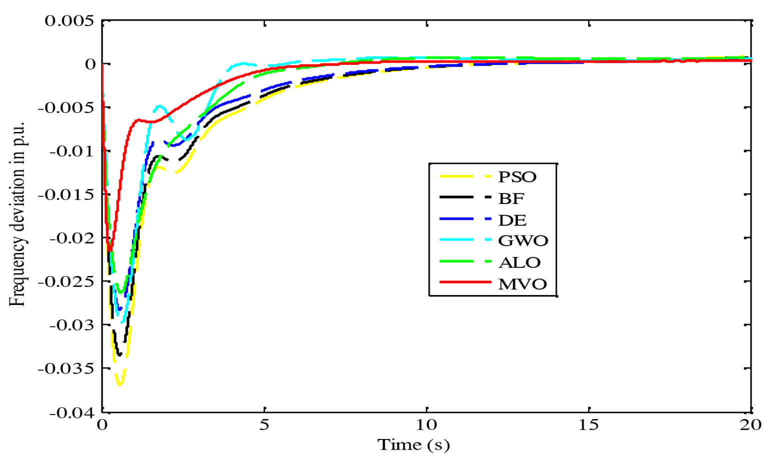

Figure 7. Frequency deviation of area 1 vs. time with fuzzy-PIDF controller.

Table 2. Comparative analysis of different optimization algorithms with integral controller.

Algorithm			PSO	BF	DE	GWO	ALO	MVO
$ITAE$			1.3517	1.4653	1.4086	1.1822	1.1587	0.9920
Settling time (t_s)								
Δf_1			16.6367	16.1538	16.5557	16.2083	14.9860	14.1417
Δf_2			15.9997	15.9627	15.9451	14.1447	13.6560	13.4213
ΔP_{tie}			26.5697	25.7644	23.0405	17.1447	15.0652	14.3783
Maximum over shoot (M_P)								
Δf_1			0.0549	0.0535	0.0527	0.0514	0.0501	0.0433
Δf_2			0.0996	0.0479	0.0449	0.0442	0.0392	0.0390
ΔP_{tie12}			0.0114	0.0110	0.0107	0.0103	0.0101	0.0090
Controller gain parameter								
Area 1	Thermal	K_I	0.3613	0.2952	0.4519	0.3874	0.3356	0.4055
	Hydro	K_I	1.4551	0.0478	0.6313	1.4752	1.4032	0.0013
Area 2	Thermal	K_I	0.2257	0.6747	0.1499	0.0208	0.6167	1.7157
	Hydro	K_I	-0.0681	0.1100	0.1021	0.0064	0.1389	0.0584

Table 3. Comparative analysis of different optimization algorithms with fuzzy-PIDF controller.

Algorithm			PSO	BF	DE	GWO	ALO	MVO
$ITAE$			2.6537	2.3852	1.9833	1.6881	1.5503	0.7122
Settling time (t_s)								
Δf_1			10.7937	10.7816	10.7654	14.0258	8.3106	5.8170
Δf_2			12.7747	12.6047	12.3113	11.9114	11.7656	6.1872
ΔP_{tie}			18.7188	18.6443	18.5214	17.9483	14.3430	10.0091
Maximum over shoot (M_P)								
Δf_1			0.0365	0.0335	0.0282	0.0298	0.0263	0.0216
Δf_2			0.0226	0.0205	0.0173	0.0195	0.0172	0.0064
ΔP_{tie12}			0.0066	0.0059	0.0050	0.0054	0.0050	0.0030
Controller gain parameter								
Area 1	Thermal	K_1	0.8720	1.1807	0.8926	1	0.8171	1
		K_2	0.6706	0.0020	1.5925	0.9995	0.6225	0.9795
		K_P	0.4240	1.1084	1.6275	2	1.8634	2
		K_I	0.0122	0.3424	0.6060	0.7262	0.8071	0.7700
		K_D	0.4356	1.1738	0.4937	0.0723	0.9499	0.1789
		N	15.5390	8.2274	12.7787	5.2847	22.8270	9.0136
	Hydro	K_1	0.2933	0.4671	0.3286	0.0078	0.0110	0.8411
		K_2	1.0032	1.1519	1.5024	0.0781	0.9928	0.7696
		K_P	1.5099	0.8415	0.1211	1.5681	1.2048	1.9986
		K_I	1.6780	1.6574	0.1827	0.2074	1.6525	0.0010
		K_D	0.8270	0.5680	1.8798	0.2049	1.4721	1.7815
		N	12.4362	13.0768	11.1673	28.0655	26.2824	29.7108
Area 2	Thermal	K_1	0.9711	0.9516	1.7160	1	0.8660	0.4777
		K_2	0.8823	0.3197	0.7606	0.0652	0.8691	0.9764
		K_P	0.9863	1.8392	0.7207	0.3033	1.6697	0.8918
		K_I	1.0407	0.6209	0.5842	1.9559	1.5325	1.6904
		K_D	0.9038	1.6642	0.1712	0.0696	1.3906	1.1649
		N	22.5810	23.1267	11.2912	18.3895	22.4046	21.2890
	Hydro	K_1	0.8944	0.1080	1.8664	1	0.9898	0.9989
		K_2	0.8976	1.0913	1.0888	0.1277	0.3718	0.8771
		K_P	1.3923	1.1155	1.3399	0.7769	1.3750	0.0236
		K_I	0.4318	0.9445	1.8502	1.9751	1.8241	1.9800
		K_D	1.0125	0.9158	1.1493	1.3879	1.8465	1.5311
		N	8.4974	6.1739	11.8256	8.1400	16.3178	5.2139

in successfully improving the performance compared to the conventional I and PI controllers. However, the fuzzy-PIDF controller improves LFC performance further and outperforms all other controllers implemented in this work as is visible in the dynamic response of area frequencies and tie-line power exchanges.

4.3. Sensitivity analysis against parameter variations and random load changes

Sensitivity analysis is performed to assess the effectiveness of the proposed MVO-tuned fuzzy-PIDF control scheme. Figure 11 shows the responses of frequency deviation of area 1 with ±10% variation in all time constants of the system, while leaving the optimum values of the fuzzy-PIDF controller gains unchanged. It is clear that the proposed control scheme provides a robust and stable control operation over a wide range of system parameters without the need to change the optimal values of the controller gains.

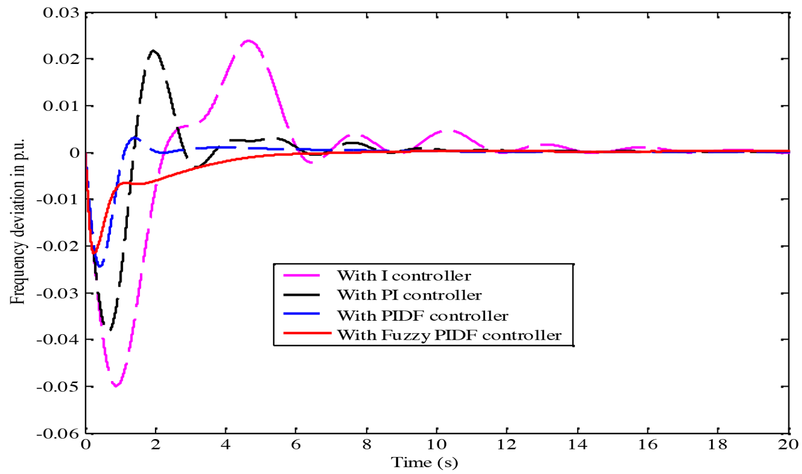

Figure 8. Frequency deviation of area 1 vs. time.

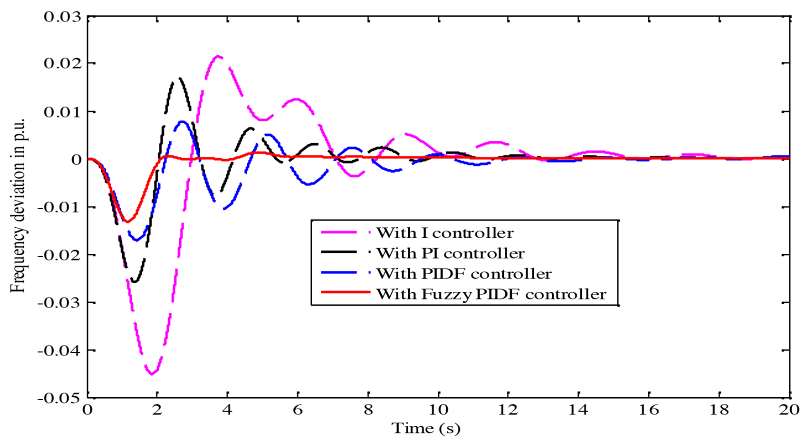

Figure 9. Frequency deviation of area 2 vs. time.

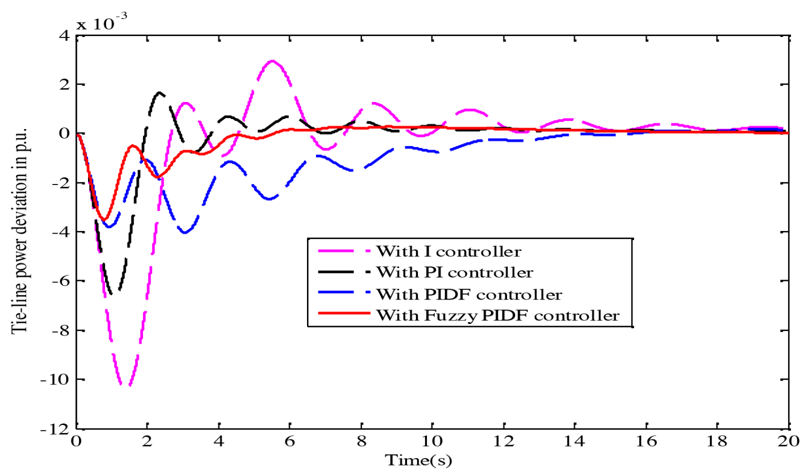

Figure 10. Tie-line power deviation vs. time.

Furthermore, to investigate the effectiveness of the proposed control scheme against random load disturbances, the random step load pattern, as shown in Figure 12, is applied to area 1 of the power system. The step

Table 4. Comparative analysis of different controllers.

Controllers			I	PI	PIDF	Fuzzy-PIDF
$ITAE$			0.9920	0.8641	0.8553	0.7122
Settling time (t_s)						
Δf_1			14.1417	9.8825	7.0573	8.8170
Δf_2			13.4213	12.5820	10.8777	6.1872
ΔP_{tie}			14.3783	12.0569	14.0196	10.0091
Maximum over shoot (M_P)						
Δf_1			0.0433	0.0384	0.0244	0.0216
Δf_2			0.0390	0.0259	0.0121	0.0094
ΔP_{tie}			0.0090	0.0066	0.0034	0.0030
Controller parameters						
Area 1	Thermal	K_1	—	—	—	1
		K_2	—	—	—	0.9795
		K_P	—	0.7964	2	2
		K_I	0.4055	1.3177	2	0.7700
		K_D	—	—	0.7523	0.1789
		N	—	—	9.3599	9.0136
	Hydro	K_1	—	—	—	0.8411
		K_2	—	—	—	0.7696
		K_P	—	0.0012	2	1.9986
		K_I	0.0013	2	4.9410×10^{-4}	0.0010
		K_D	—	—	0.0311	1.7815
		N	—	—	18.1263	29.7108
Area 2	Thermal	K_1	—	—	—	0.4777
		K_2	—	—	—	0.9764
		K_P	—	0.0001	1.1023	0.8918
		K_I	1.7157	1.1845	1.9808	1.6904
		K_D	—	—	0.0244	1.1649
		N	—	—	15.5915	21.2890
	Hydro	K_1	—	—	—	0.9989
		K_2	—	—	—	0.8771
		K_P	—	2	1.6162	0.0236
		K_I	0.0584	0.0010	1.0533	1.9800
		K_D	—	—	0.9370	1.5311
		N	—	—	7.1421	5.2139

load is random both in magnitude and time scales. For comparison, the results of the proposed fuzzy-PIDF controller are compared to that of a PIDF controller with gains of both controllers optimized through MVO. It can be seen from Figure 13 that the proposed controller is robust and gives satisfactory performance under random load disturbances. It is also evident that, compared to the PIDF controller, the proposed controller results in a better transient response.

5. Conclusion

In this paper, the MVO algorithm is used to optimize the gains of a fuzzy-PIDF controller proposed for the LFC problem of a two-area interconnected multisource hydrothermal power system. The power system is investigated under different operating conditions categorized as three different cases. The performance of the MVO algorithm is compared to other optimization algorithms (PSO, BF, DE, GWO, and ALO), considering

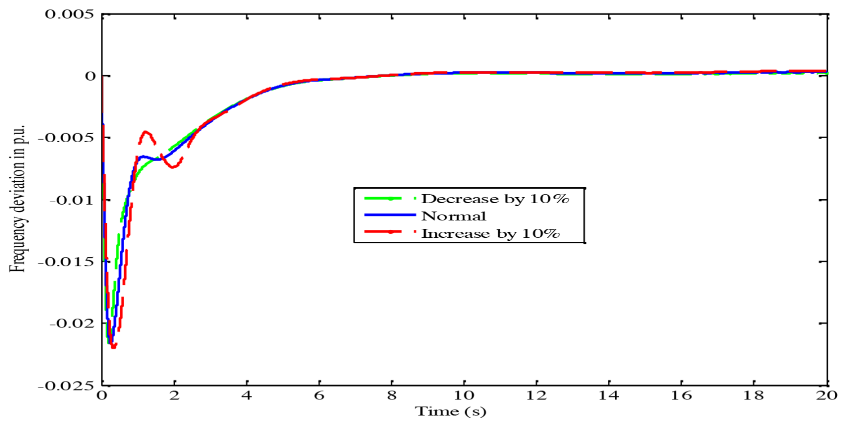

Figure 11. Frequency deviation of area 1 vs. time.

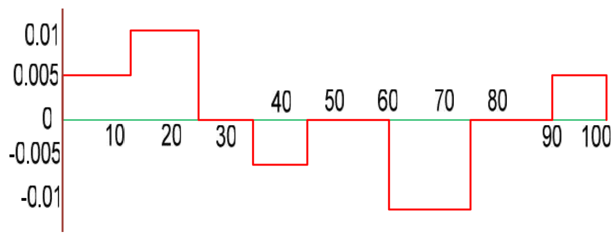

Figure 12. Random loading pattern.

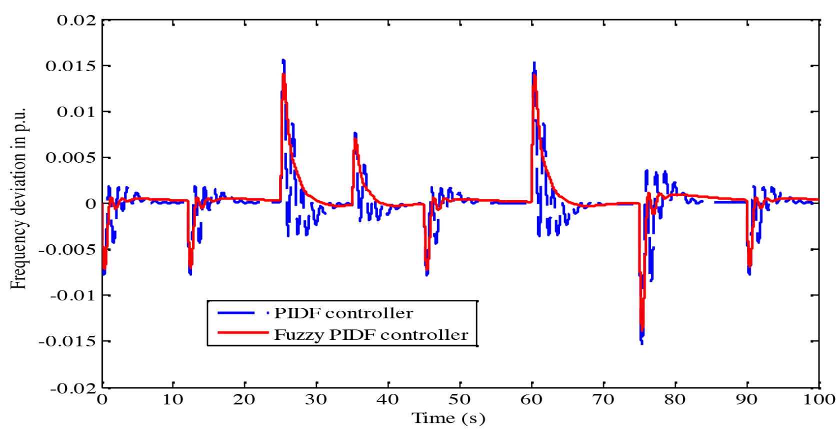

Figure 13. Comparison of frequency deviation in area 1 with random loading pattern.

the optimal tuning of the integral controller and the proposed fuzzy-PIDF controller for the LFC of the power system investigated. It is observed that with both controllers the performance of the MVO algorithm was superior. Having established the superiority of the MVO algorithm, the proposed fuzzy-PIDF controller is optimally tuned by the MVO algorithm, and the results are compared with MVO-tuned I/PI/PIDF controllers for the LFC of the power system. It is proved that the MVO-tuned fuzzy-PIDF controller outperforms other controllers in terms of undershoot, overshoot, and settling time. In addition, sensitivity analysis is carried out with respect to wide variations in system parameters and against random step load perturbations. It is observed that the proposed MVO-tuned fuzzy-PIDF controller is robust and performs well in different situations.

References

[1] Ibraheem N, Kumar P, Kothari DP. Recent philosophies of automatic generation control strategies in power systems. IEEE T Power Syst 2005; 20: 346-357.

[2] Pandey SK, Mohanty SR, Kishor N. A literature survey on load-frequency control for conventional and distribution generation power systems. Renew Sust Energ Rev 2013; 25: 318-334.

[3] Parmar KPS, Majhi S, Kothari DP. Load frequency control of a realistic power system with multi-source power generation. Int J Elec Power 2012; 42: 426-433.

[4] Kundur P. Power System Stability and Control. 8th ed. New York, NY, USA: McGraw-Hill Education, 2009.

[5] Hassan B. Takashi H. Intelligent Automatic Generation Control. 1st ed. Boca Raton, FL, USA: CRC Press, 2011.

[6] Hassan B. Robust Power System Frequency Control. 1st ed. New York, NY USA: Springer, 2009.

[7] Sönmez S, Ayasun S. Stability region in the parameter space of pi controller for a single-area load frequency control system with time delay. IEEE T Power Syst 2016; 31: 829-830.

[8] Nanda J, Mangla A, Suri S. Some new findings on automatic generation control of an interconnected hydrothermal system with conventional controls. IEEE T Energy Conver 2006; 21: 187-194.

[9] Visioli A. Tuning of PID controllers with fuzzy logic. IEE Proc-D 2001; 148: 1-8.

[10] Daneshfar F, Bevrani H. Multiobjective design of load frequency control using genetic algorithms. Int J Electr Power 2012; 42: 257-263.

[11] Jadhav AM, Vadirajacharya K, Toppo ET. Application of particle swarm optimization in load frequency control of interconnected thermal-hydro power systems. International Journal of Swarm Intelligence 2013; 1: 91-113.

[12] Ali E, Abd-Elazim S. BFOA based design of PID controller for two area load frequency control with nonlinearities. Int J Elec Power 2013; 51: 224-231.

[13] Storn R, Price KV. Differential evolution–a simple and efficient heuristic for global optimization over continuous spaces. J Global Optim 1997; 11: 341-359.

[14] Sahu RK, Panda S, Padhan S. A novel hybrid gravitational search and pattern search algorithm for load frequency control of nonlinear power system. Appl Soft Comput 2015; 29: 310-327.

[15] Pradhan PC, Sahu RK, Panda S. Firefly algorithm optimized fuzzy PID controller for AGC of multi-area multi-source power systems with UPFC and SMES. Engineering Science and Technology 2016; 16: 338-354.

[16] Sahu BK, Pati S, Mohanty PK, Panda S. Teaching–learning based optimization algorithm based fuzzy-PID controller for automatic generation control of multi-area power system. Appl Soft Comput 2015; 27: 240-249.

[17] Sahu BK, Pati TK, Nayak JR, Panda S, Kar SK. A novel hybrid LUS–TLBO optimized fuzzy-PID controller for load frequency control of multi-source power system. Int J Elec Power 2016; 74: 58-69.

[18] Guha D, Roy PK, Banerjee S. Load frequency control of interconnected power system using grey wolf optimization. Swarm and Evolutionary Computation 2016; 27: 97-115.

[19] Omar M, Soliman M, Abdel Ghany A, Bendary F. Optimal tuning of PID controllers for hydrothermal load frequency control using ant colony optimization. International Journal on Electrical Engineering and Informatics 2013; 5: 348-360.

[20] Mirjalili S, Mirjalili SM, Hatamlou A. Multi-verse optimizer: a nature-inspired algorithm for global optimization. Neural Comput Appl 2016; 27: 495-513.

[21] Mirjalili S. Dragonfly algorithm: a new meta-heuristic optimization technique for solving single-objective, discrete, and multi-objective problems. Neural Comput Appl 2016; 27: 1053-1073.

[22] Mudi KR, Pal RN. A robust self-tuning scheme for PI-and PD-type fuzzy controller. IEEE T Fuzzy Syst 1999; 7: 2-16.

[23] Sahu RK, Panda S, Padhan S. Optimal gravitational search algorithm for automatic generation control of interconnected power systems. Ain Shams Engineering Journal 2014; 5: 721-733.

[24] Woo ZW, Chung HY, Lin JJ. A PID type fuzzy controller with self-tuning scaling factors. Fuzzy Set Syst 2000; 115: 321-326.

[25] LI HX, Gatland HB. Conventional fuzzy control and its enhancement. IEEE T Syst Man Cy B 1996; 26: 791-796.

[26] Das S, Pan I, Gupta A. A novel fractional order fuzzy PID controller and its optimal time domain tuning based on integral performance indices. Eng Appl Artif Intel 2012; 25: 430-442.

[27] Zhao ZY, Tomizuka M, Isaka S. Fuzzy gain scheduling of PID controllers. IEEE T Syst Man Cyb 1993; 23: 1392-1398.

[28] Palm R, Driankov D, Hellendoorn H. Model Based Fuzzy Control. Berlin, Germany: Springer-Verlag, 1997.

[29] Wu ZQ, Mizumoto M. PID type fuzzy controller and parameters adaptive method. Fuzzy Set Syst 1996; 78: 23-36.

Appendix. System parameters [8]

$B_1 = B_2 = 0.4312$ p.u. MW/Hz; $P_{rt} = 2000\,MW$; $P_L = 1840$ MW; $R_1 = R_2 = 2.4$ Hz/p.u.; $T_g = 0.08$ s; $T_t = 0.3$ s; $K_r = 0.3$; $T_r = 10$ s; $K_{P1} = K_{P2} = 120$ Hz/p.u. MW; $T_{P1} = T_{P2} = 20$ s; $T_{12} = 0.0433$; $a_{12} = -1$; $T_W = 1$ s; $T_R = 5$ s; $T_{TH} = 28.75$ s; $T_{GH} = 0.2$ s.