Frequency Regulation of Multi Area Renewable Energy Source System with Practical Constraints under Fractional-Order Fuzzy Controller

Ch. Naga Sai Kalyan[1], A. N. Venkateswarlu[2], Ch. Rami Reddy[3], B. Srikanth Goud[4‡], A. Giri Prasad[5], Ch. Sriram[6], Flah Aymen[7]

[1]Department of Electrical and Electronics Engineering, Vasireddy Venkatadri Institute of Technology Guntur, India-522 508

[2]Department of Electrical and Electronics Engineering, Vignan's Lara Institute of Technology and Science, Vadlamudi, Guntur, India, 522213

[3]Department of Electrical and Electronics Engineering, Malla Reddy Engineering College, Maisammaguda, Secunderabad, Telangana, India 500100

[4]Department of Electrical and Electronics Engineering, Anurag College of Engineering Ghatkesar, Telangana, India-501301

[5]Department of Electrical and Electronics Engineering, VNR Vignana Jyothi Institute of Technology, Hyderabad, India.

[6]Department of Electrical and Electronics Engineering, Guru Nanak Insititute of Technology, Ibrahimpatnam, Hyderabad, India 501506

[7]Research Unit of Energy Processes Environment and Electrical Systems, National Engineering School of Gabes, University of Gabes, Gabes,Tunisia 6029

(kalyanchallapalli@gmail.com, atyam2000@gmail.com, crreddy229@gmail.com, srikanth.b@anuraghyd.ac.in, giriprasad_a@vnrvjiet.in, cholletisriram6@gmail.com, flahaymening@yahoo.fr)

[‡] Corresponding B. Srikanth Goud, Anurag College of Engineering Ghatkesar, Telangana, India-501301, Tel: +91-9030937167, srikanth.b@anuraghyd.ac.in

Received: 18.08.2021 Accepted:08.09.2021

Abstract- This paper introduces a novel control strategy of fractional order (FO) fuzzy (F) PID (FOFPID) controller optimized with the latest soft computing technique of seagull optimization algorithm (SOA) for power system frequency regulation. Initially, a simple and widely accepted power system of dual area photovoltaic (PV) and reheat thermal (RT) (PVRT) system is perceived and named as test system-1 in this paper. The performance of FOFPID fine-tuned with SOA mechanism is tested on PVRT system for a step load disturbance of 10% (SLD) on area-2 along with other controllers reported in the literature. Dynamical analysis of the PVRT system reveals the potency of the proposed controller over others. Further, the SOA based FOFPID controller is extended to frequency regulation of multi-area system with hybrid generating sources (MAHS) named as test system-2 in this paper for 10% SLD on area-1. MAHS system is constituted with realistic constraints to conduct research close to realistic practice. The potentiality of SOA based FOFPID is demonstrated by comparing it with traditional controllers of PID/FPID/FOPID on MAHS system. Finally, robustness analysis is perpetuated to reveal the presented control scheme robustness.

Keywords FOFPID Controller, Seagull Optimization Algorithm, MAHS system, Practical Constraints, 10% SLD.

1. Introduction

The reliability and security maintenance in interconnected modern power systems have been becoming one of the powerful tools of ancillary services. These services maintain power quality and provide an uninterrupted electric supply. Stabilizing frequency is the key measure for power quality. Load frequency control (LFC) takes part a

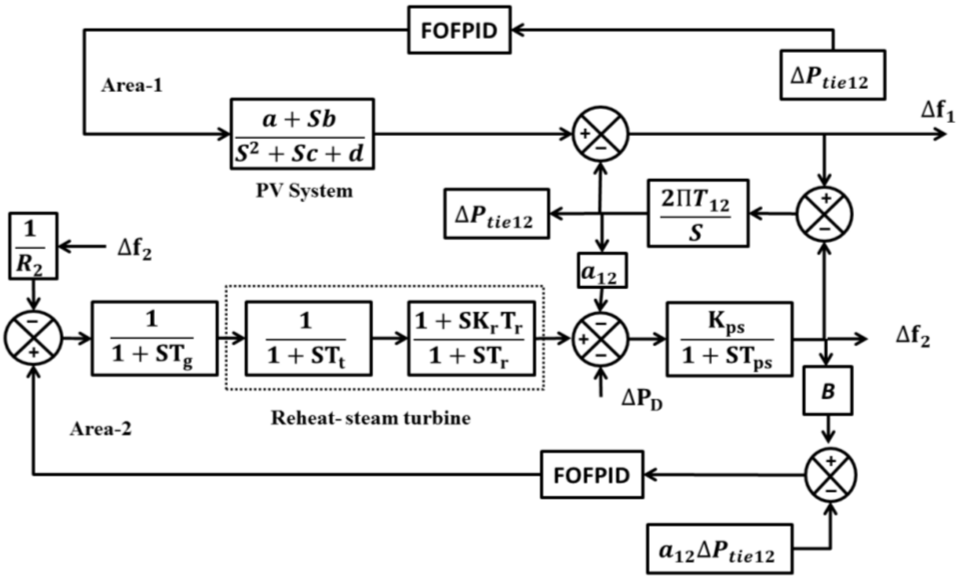

Fig.1. Model of Dual area PVRT system (test system-1) [4]

triumphant role in the control and operation of the power system to generate quality power. LFC tries to reduce the deviations in system area frequency by altering the operating point of the power generation unit to match the generation of real power with varying load demands. For this, an intelligent and advanced LFC control mechanism is necessitated to revoke the effect of load fluctuations to hold the generation, system frequency and line power flow within a specified range [1].

Researchers have proposed several state of the art control structures for LFC study like conventional I/PI[2]/PID[3]/PIDN, fuzzy (F) FPI[4]/FPID[5]/FPIDF , modified (M) PID (MPID) [6], model predictive control (MPC) [7], Tilt-Integral-Derivative (TID) [8], internal model control (IMC) [9], degree of freedom (DOF) 2DOFPI/3DOFPI/2DOFPID/3DOFPID [10], fractional order (FO) FOPID [11], sliding mode controller [12], Traditional PID with accelerator (A) (PIDA) [13], linear vector quantization (LVQ) [14], fuzzy predictive PID [15], cascade controllers like F-TIDF/FPIDF-(1+PI)/FFOPI-FOPD [16-17] etc. are available.

However, the design of the regulator is not enough to get the optimal LFC of the power system. Selection of suitable optimization techniques to get the parameters of the designed controller is having equal weightage in the domain of LFC. Different optimization techniques that have been employed by the researchers in the LFC domain are firefly algorithm (FA) [2], population extremal optimization (PEO) [3], Imperialist competitive algorithm (ICA) [4], grasshopper optimization (GO) [6], water cycle algorithm (WCA) [8], Modified JAYA optimizer [10], sine-cosine algorithm (SCA) [11], Marine predator algorithm (CSA) [13], whale optimizer (WO) [15], artificial electric field (AEFA) [18], grey wolf optimizer (GWO) [19-20], frog leaping algorithm (FLA) [21], harries hawks optimizer (HHO) [22], particle swarm optimization (PSO) [23], craziness based PSO (CBPSO) [24], bacterial foraging optimization (BFO) [25], water cycle algorithm (WCA) [26], Cuckoo search optimization (CSO) [27], atom search optimization (ASO) [28], Jaya optimization (JO) [29] etc. but, most of the above-mentioned algorithms possesses the drawback of complex computation, premature convergence and parametric sensitivity.

To get prevail of the aforementioned drawbacks, in this paper a new intelligent controller named FOFPID controller is presented with a new meta-heuristic approach of seagull optimization algorithm (SOA). SOA is proved as one of the best nature-inspired optimization techniques from the behaviour of seagulls and is implemented in other engineering optimizations [30]. In this paper, FOFPID using SOA approach is implemented to MAHS system considered with practical constraints of generation rate constraint (GRC) and communication time delays (CTDs). Most of the work contributed by the researchers in the LFC study is the power system models without taking into account of CTDs. However, a few contributions in LFC study with CTDs are available but limited to conventional generation units only [31-32]. This motivates the authors, to implement LFC strategies to power system models with renewable energy integration and perceiving CTDs. This is one of the most significant contributions of this paper and the other contributions are listed below.

a) FOFPID controller based on SOA algorithm is implemented for LFC study.
b) SOA tuned FOFPID controller supremacy is revealed by comparing with other controllers implemented on the PVRT system reported in the literature.
c) Performance of presented regulator is further assessed by implemented on MAHS system with realistic constraints and sovereignty is demonstrated with PID/FPID and FOPID controllers.
d) The necessity of considering realistic constraints are demonstrated and justified.
e) A robustness test is conducted to reveal SOA tuned FOFPID controller robustness.

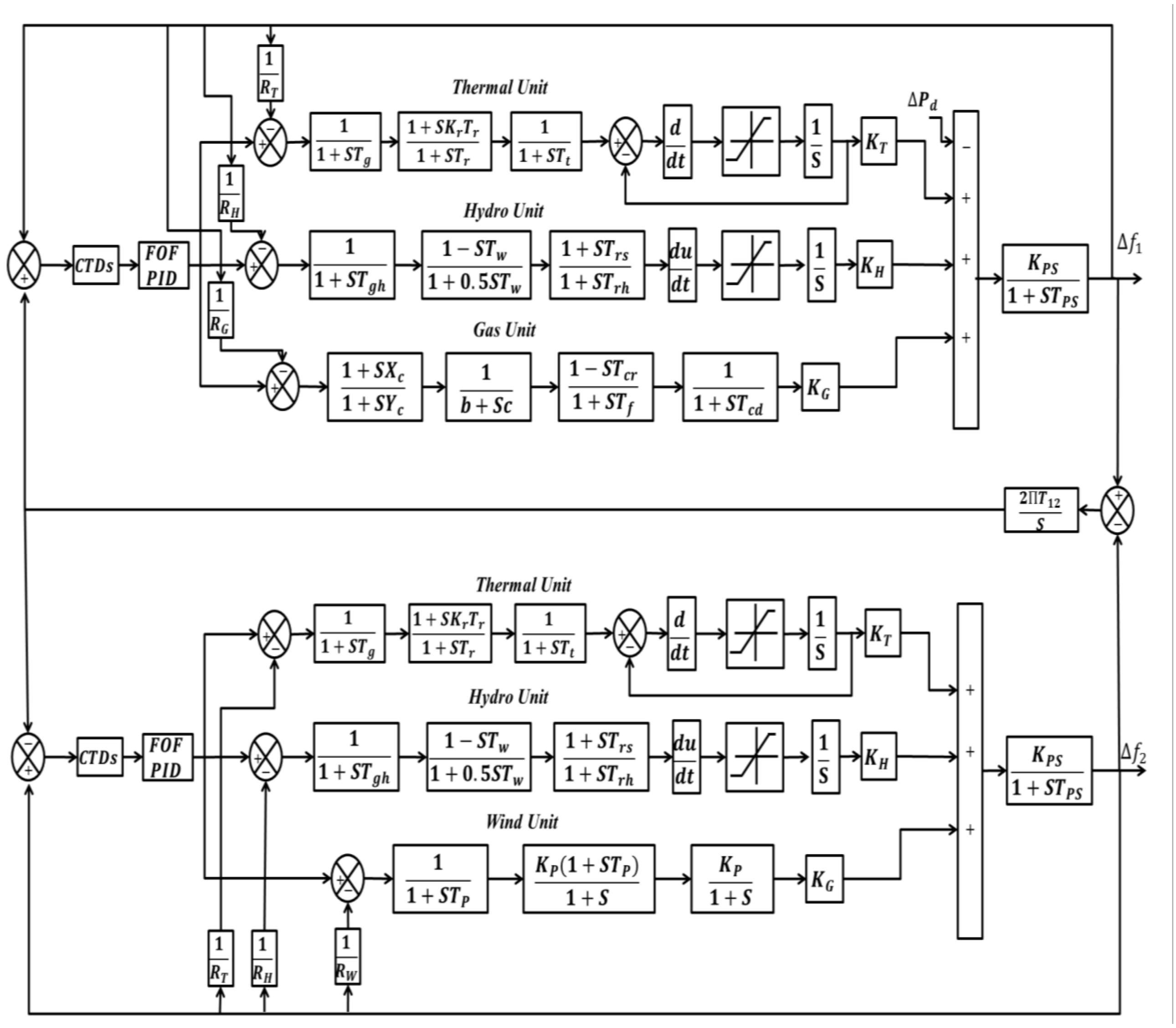

Fig.2. Model of multi-area hybrid source system (test system-2) [19]

2. Power System under Investigation

Two power system models that have been examined in this paper are dual area PVRT system as test system-1 is shown in Fig.1, [4] and multi-area hybrid source system (MAHS) as test system-2 is rendered in Fig.2 [19]. Test system-1 consists of two areas, area-1 is comprised of a solar photovoltaic system and area-2 is equipped with a reheat thermal unit. Test system-1 is a widely accepted power system model by the researchers with a total capacity of 2000MW that have been analysed in this paper for 10%SLD on area-2. Test system-2 comprises two areas with unique generation capacities; area-1 consists of traditional Hydro-Thermal units along with Gas unit incorporation, area-2 comprises of Hydro-Thermal units along with wind power units. The practical constraint such as generation rate constraint (GRC) is considered for Hydro-Thermal units in both areas. GRC of 10%/min is chosen for a thermal unit for both lowering and raising as for the hydro unit is concerned it is 360%/min and 270%/min for lowering and raising. Despite that, communication time delays (CTDs) are the other inherits practical constraints that affecting the modern power system significantly. The interconnected system employs a huge quantity of measurement and sensor devices usually installed at faraway points. Data from measuring devices will be transferred to the command control location for appropriate command signal generation. The command control signal from the control location will be transmitted to generation units for appropriate action. The transmitting and receiving of signals between different entities cannot be done instantly, involves some delay that delay is coined as CTDs. Because of these CTDs, there will be a delay in changing the power system operating point which greatly affects the power system and sometimes the system may lead to unstable. To overcome the above condition, CTDs are needed to be taken into count for the LFC study. The transport type of CTDs is conceived in this paper and is given in Equation (1).

$$e^{-s\tau_d} = \frac{1-\frac{\tau_d}{2}s}{1+\frac{\tau_d}{2}s} \quad (1)$$

3. Controller and Objective Function

In a study of LFC, researchers are rigorously concentrated on traditional PID techniques due to design simplicity. However, the traditional controllers are no longer suitable for power system models with practical constraints. On the other hand, fuzzy logic controllers (FLC) are befitting for optimal frequency regulation of realistic power system models. From the literature review, it has been revealed that the FLC very comfortably change the power system operating point subjected to load demands compared to other control techniques. Area control error (ACE) and its derivative have been given input to the FLC system. Moreover, the FPI controller shows inferior performance, especially at the transient phase. This urges the authors to concentrate on FPID regulators and to further enhance the regulator ability FO nature is added in this work. The structure of FOFPID employed in this paper is displayed in Fig. Membership functions (MFs) deliberated for FLC interface are Zero (Z), big positive (BP), small positive (SP), big negative (BN) and small negative (SN) shown in Fig.4. [33]. The Centre of gravity method of defuzzification is employed to calculate the output of FLC. The rule base of FLC is noted in Table-1. Moreover, the error squared over the integral (ISE) [34] index is chosen to optimize FOFPID control parameters given in Equation (2).

$$J_{ISE} = \int_0^T (\Delta f_1^2 + \Delta P_{tie,12}^2 + \Delta f_2^2)dt \tag{2}$$

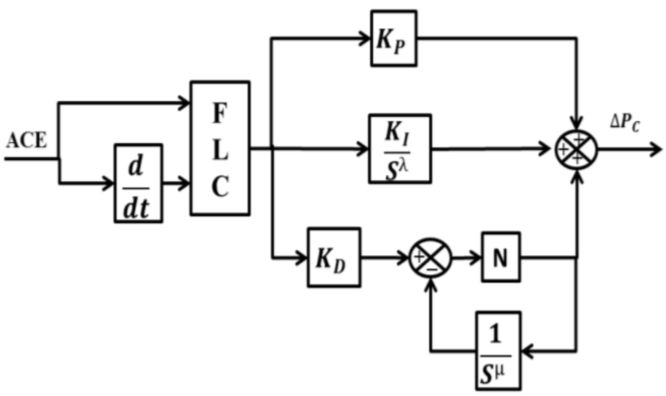

Fig.3. FOFPID controller structure

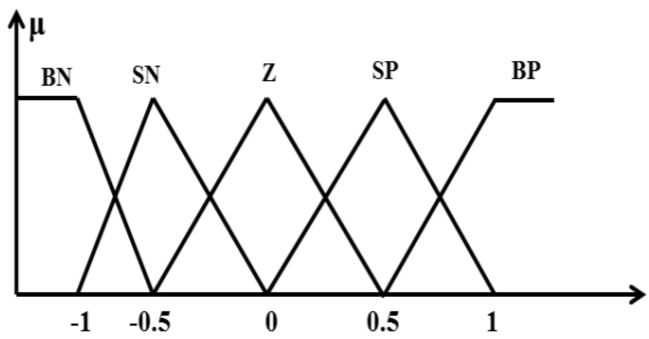

Fig.4. MFs implemented for FLC

Table 1. FLC input and output rules

ACE	ΔACE				
	BN	***SN***	***Z***	***SP***	***BP***
BN	BN	BN	BN	SN	Z
SN	BN	BN	SN	Z	SP
Z	BN	SN	Z	SP	BP
SP	SN	Z	SP	BP	BP
BP	BP	Z	SP	BP	BP

4. Seagull Optimization Algorithm

Dhiman and Kumar in the year 2019 [35], proposed the bio-inspired meta-heuristic approach of the seagull optimization algorithm. Seagulls come under the family of sea birds that usually live at the banks of sea and oceans can be technically called Laridae. Seagulls are very smart and intelligent birds normally feed on birds, earthworms, fish, and insects. They feed on fish by trapping through the spreading of bread crumbs that are gathered from the nearby locality and can make rain sound to catch earthworms lying beneath the earth surface. Seagulls can feed on both salt and fresh water that no other animal or bird can do. The design of this SOA algorithm mimics the intelligent searching behaviour of seagulls for attacking the prey and migration strategies. Seagulls usually migrate to abundant food areas and their seasonal movement is so tactful. The behaviour is formulated mathematically as follows:

Collision avoidance in SOA be induced among searching particles by incorporating a special parameter 'N' and the new agent position $(\vec{F}_S)$ will be founded as

$$\vec{F}_S = N\chi\vec{D}_S(k) \tag{3}$$

The searching agent present position is indicated with $\vec{D}_S$ and iteration with 'k'. The modelling of parameter 'N' be done as

$$N = E_c - (k*(E_c/Max.Iter)) \tag{4}$$

The parameter 'N' is chosen as 2 in this paper. Later, the searching agents try to move towards the positions of the individually best solution which can be calculated using

$$\vec{M}_S = A\chi(\vec{P}_{bs}(k) - \vec{D}_S(k)) \tag{5}$$

'A' is a random parameter utilized to impart the tendency of balance between the nature of searching expedition and effective utilizing of search space.

$$A = 2*N^2*rand() \tag{6}$$

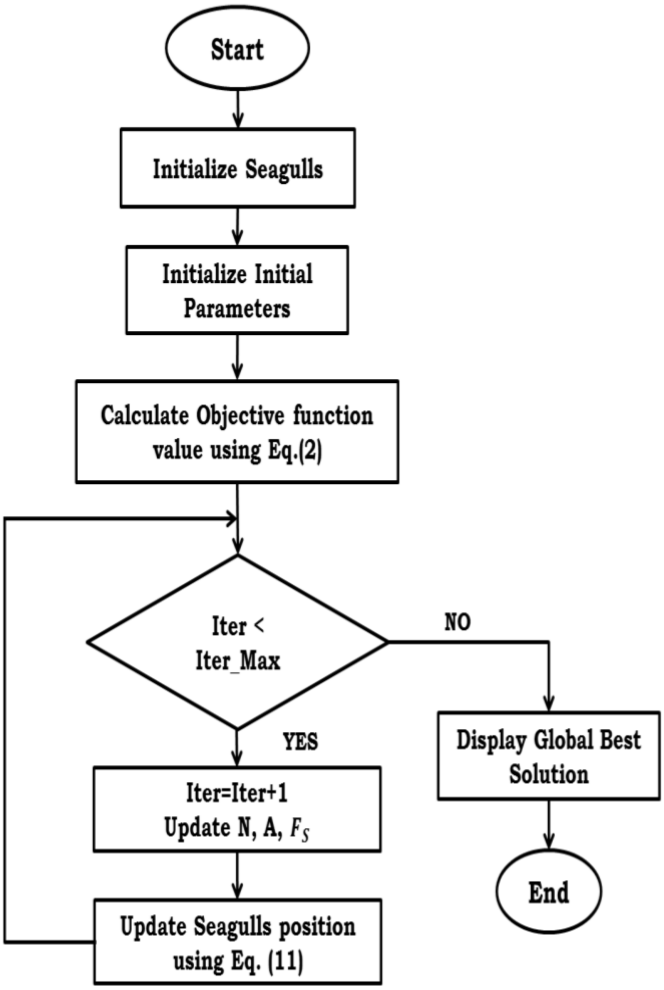

Fig.5. SOA flowchart

Thereby, the positions of searching agents will be updated as follows:

$$\vec{R}_S = \left|\vec{F}_S + \vec{M}_S\right| \tag{7}$$

At the time of migration, the movement of seagulls is very intelligent and smart as they employ spiral movement based on experience while attacking the prey. In three dimensional, that can be mathematically given as

$$P' = r * Cos(x) \tag{8}$$

$$Q' = r * Sin(x) \tag{9}$$

$$R' = r * x \tag{10}$$

The radius of spiral movement enacted by seagulls is represented with 'r', and 'x' is a random number selected from [0-2]. The position of the search agent which gives the best outcome will be saved and based on that the position of the remaining seagulls will be updated as

$$\vec{D}_S(k) = (\vec{M}_S * P' * Q' * R') + \vec{P}_{bs}(k) \tag{11}$$

The procedural of SOA is depicted in Fig.5, and the population of 100 for 100 iterations is employed to execute the SOA approach in this paper to optimally retrieve FOFPID controller parameters.

5. Simulation Results

5.1. Case-1: Analysis of PVRT system with various control approaches

Initially, the presented SOA based FOFPID control technique is implemented on rigorously accepted power system model of dual area PVRT system shown in Fig.1. PVRT system dynamical behaviour is assessed by inserting a disturbance on area-2 with 10%SLD. Responses of the PVRT model is analyzed because of frequency deviations in area-1 (Δf1), area-2 (Δf2) and line power flow variations (ΔPtie12). Along with the proposed control technique, other controllers such as PI optimized with FA [2], PID tuned with PEO [3], FPI fine-tuned using ICA [4] and FPIDF optimized using ICA [5] that are reported in the literature are also implemented to the power system model one at a time. PVRT model dynamical responses under all these control techniques for the same load disturbance are compared in Fig.6. PVRT system responses are interpolated numerically in terms of settling time (Ts) provided in Table-2 along with the optimal parameters of various control techniques employed for the system. Settling time of the responses in Table-2 and responses in Fig.6, clearly demonstrated the efficacy of SOA tuned FOFPID in bringing back the deviations to steady-state and diminishing responses under/overshoots compared to distinct techniques in recent literature.

5.2. Case-2: Analysis of MAHS system without taking CTDs

Further, the implementation of the presented SOA based FOFPID technique is extended for the MAHS system to assesses its performance. In this subsection, MAHS dynamical behaviour is analyzed without taking CTDs into account. Various regulators like PID/FPID/FOPID/FOFPID controllers are enacted one after the other as regulators for the MAHS system in both areas tuned with the SOA mechanism. Analysis of the MAHS system is compassed by inserting a disturbance of 10% on area-1. Responses for this case are displayed in Fig.7, and the respective Ts are reported in Table-3. After interpreting the data reported in Table-3, very much clear that the responses of MAHS system deviations are finely and effectively mitigated by the presented control technique in bringing responses back to steady condition. Moreover, with the presented approach the ISE function value is enhanced by 75.34% with traditional PID, 48.55 with FPID and 28.83% with FOPID techniques.

5.3. Case-3: Analysis of MAHS system with taking CTDs

Later, the MAHS system is conceived with CTDs and dynamical analysis is carried out for the same disturbance conditions. Controllers like PID/FPID/FOPID/FOFPID optimized with SOA are implemented to the MAHS system with CTDs to analyze the control techniques performance. MAHS system responses for this case are rendered in Fig.8.

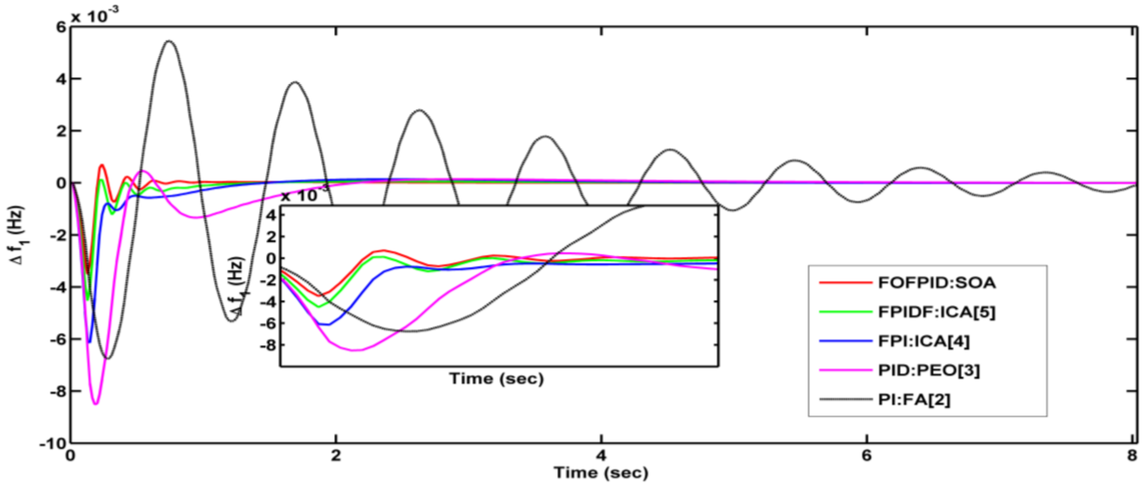

Fig.6(a)

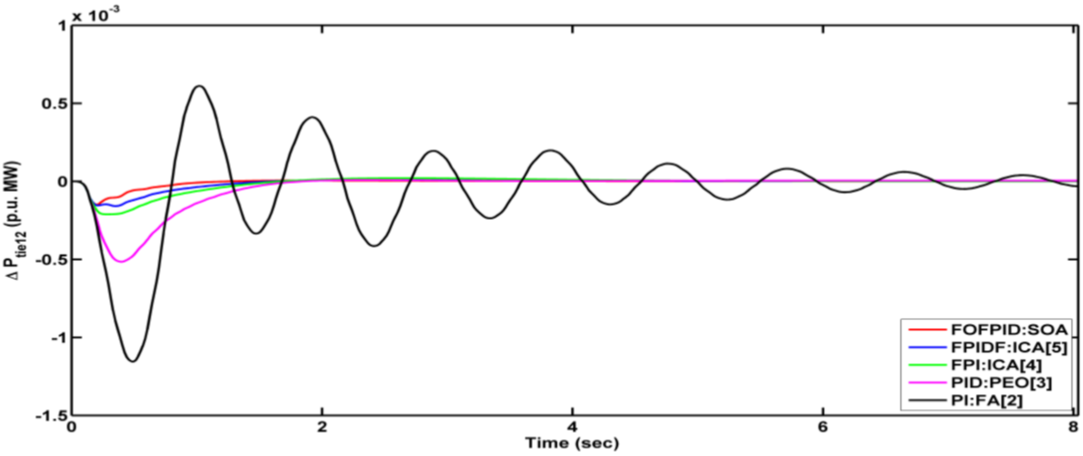

Fig.6(b)

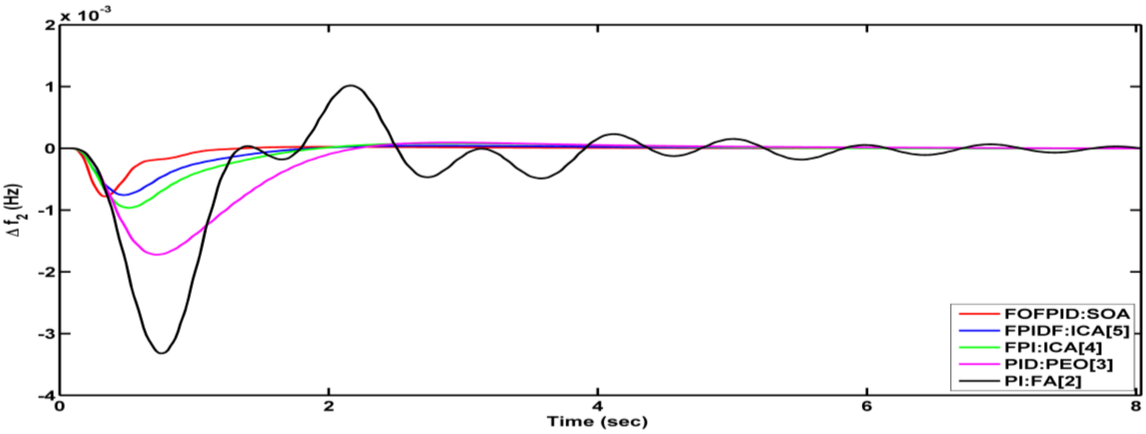

Fig.6(c)

Fig.6. Responses for case-1. (a) Δf_1, (b) ΔP_{tie12}, (c) Δf_2.

Table 2. Optimal controller gains utilized for dual area PVRT system (test system-1) and settling time of responses.

Parameters	Controller				
	FA:PI[2]	PEO:PID[3]	ICA:FPI [4]	ICA:FPIDF [5]	SOA:FOFPID
Area-1	K_P=1.404 K_I=0.0873	K_P=1.5710 K_I=0.4262 K_D=0.8931	K_P=0.9193 K_I=0.9087	K_P=1.1716 K_I=0.9375 K_D=0.4140 N=129.786	K_P=1.4332 K_I=0.4978 K_D=0.8391 λ=0.2567 μ=0.2717 N=141.76
Area-2	K_P=1.539 K_I=0.0521	K_P=1.5227 K_I=0.2862 K_D=0.3133	K_P=0.9072 K_I=0.8955	K_P=1.6510 K_I=0.9863 K_D=0.3294 N=134.23	K_P=1.4955 K_I=0.4590 K_D=0.3852 λ=0.4140 μ=0.2765 N=139.36
Δf_1	22.71	5.548	4.51	2.248	1.472
ΔP_{tie12}	23.76	5.672	4.75	2.65	2.064
Δf_2	21.32	5.401	4.49	2.611	2.02
ISE*10^{-3}	120.281	81.178	43.221	36.769	14.026

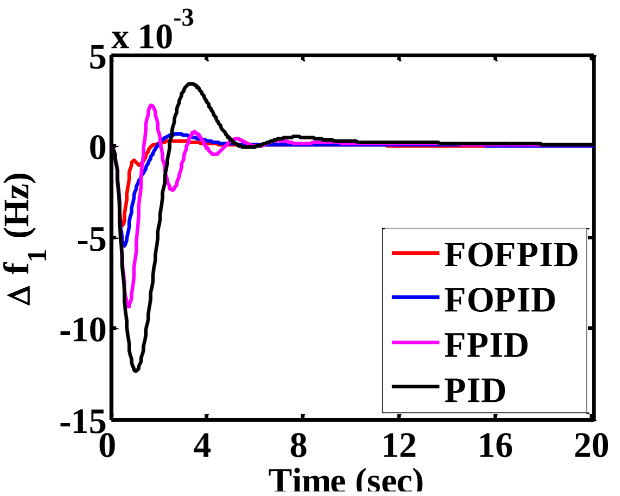

Fig.7(a)

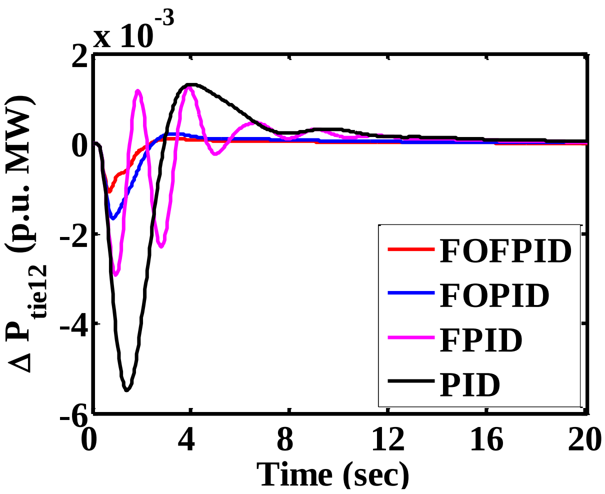

Fig.7(b)

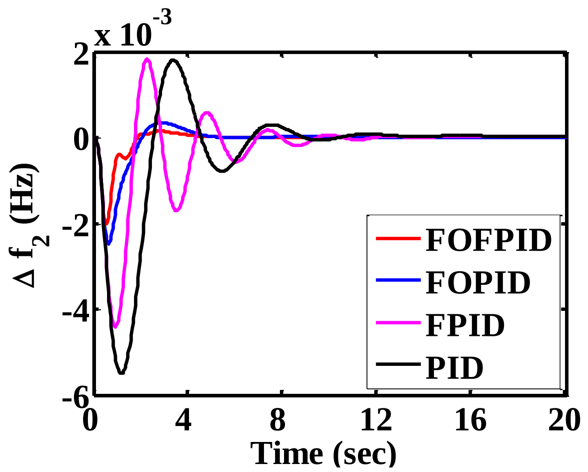

Fig.7(c)

Fig.7. Responses for case-2. (a) Δf_1, (b) ΔP_{tie12}, (c) Δf_2.

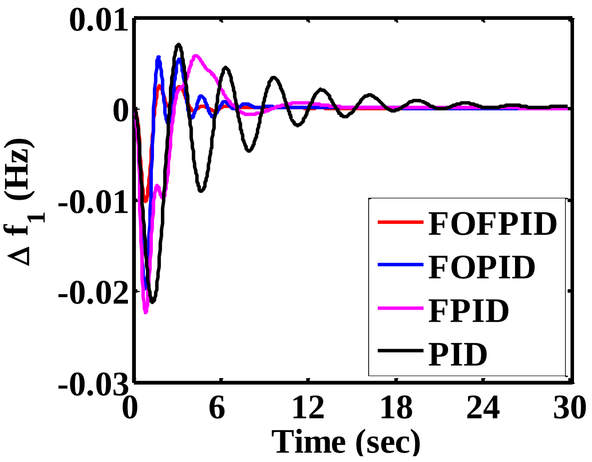

Fig.8(a)

Table 3. Settling time of MAHS system responses for case-2 and case-3.

Settling time (Sec)		PID	FPID	FOPID	FOFPID
Case-2	Δf_1	18.57	15.95	10.772	7.132
	ΔP_{tie12}	19.45	16.17	10.88	7.75
	Δf_2	17.14	14.29	10.78	6.534
	ISE*10^{-3}	22.665	19.202	16.653	12.926
Case-3	Δf_1	33.13	18.39	15.14	10.786
	ΔP_{tie12}	32.99	18.32	15.73	11.28
	Δf_2	32.34	21.19	15.94	10.95
	ISE*10^{-3}	48.866	42.336	37.405	27.752

Table 4. Optimal controller gains utilized for MAHS system (test system-2) using SOA

Parameters		Optimum values									
		K_{P1}	K_{I1}	K_{D1}	λ_1	μ_1	K_{P2}	K_{I2}	K_{D2}	λ_2	μ_2
Case-2	PID	2.092	1.686	1.696	-	-	2.074	1.553	1.314	-	-
	FPID	1.263	1.819	1.121	-	-	1.216	1.804	1.254	-	-
	FOPID	1.078	1.884	1.132	0.407	0.356	1.187	1.872	1.291	0.518	0.278
	FOFPID	1.098	1.588	1.183	0.162	0.388	1.307	1.597	1.316	0.239	0.247
Case-3	PID	1.793	1.889	1.061	-	-	1.651	1.887	1.007	-	-
	FPID	1.192	1.945	1.057	-	-	1.310	1.124	1.217	-	-
	FOPID	1.102	1.699	1.027	0.518	0.368	1.477	1.195	1.622	0.425	0.326
	FOFPID	1.089	1.689	0.899	0.247	0.268	1.237	1.786	1.786	0.329	0.357

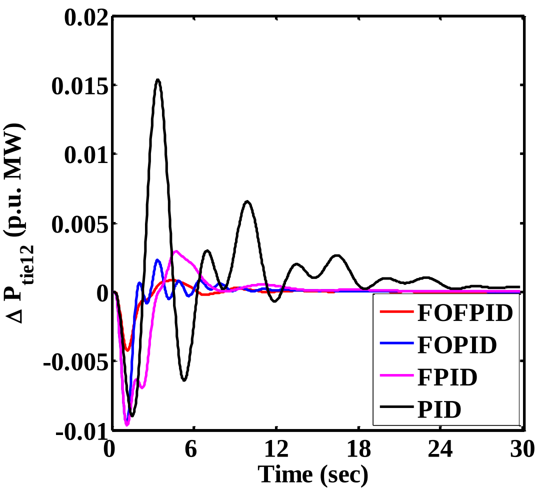

Fig.8(b)

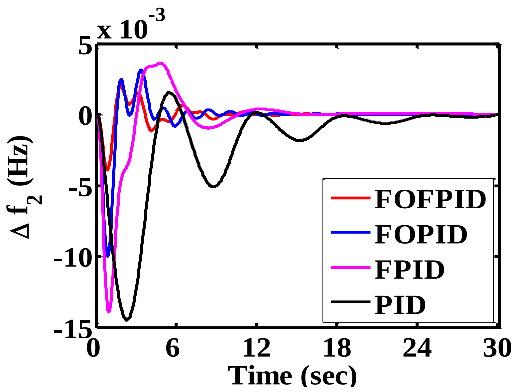

Fig.8(c)

Fig.8. Responses for case-3. (a) Δf_1, (b) ΔP_{tie12}, (c) Δf_2.

Investigating the responses in Fig.8 demonstrates the sovereignty of SOA based FOFPID in mitigating response deviations compared to others even when the system is taken with practical constraints. Further, the ISE index value with FOFPID is enhanced by 75.08% with PID, 52.55 with FPID, 34.78% with FOPID approaches. Optimal gains of various controllers tuned with the SOA mechanism are provided in Table-4.

5.4. Case-4: Demonstrating the effect of CTDs on MAHS system performance

Under the same loading conditions, MAHS responses with and without taking CTDs into account are compared in Fig.9, to demonstrate its impact on performance. Responses compared in Fig.9, are retrieved for the MAHS system under the supervision of FOFPID tuned with SOA proved as best in the above sub-sections. Analysing Fig.9, it is very much clear that MAHS system responses are more deviated by considering the practical constraints of CTDs compared to the case of not taking CTDs into account. This happens, because of the delay in signal transmission and receiving among the command control room and plant location. With these delays, the altering of real power generation with regards to the variations in load demand is unable to endure comfortably. Hence, the mismatch of real power demand and generation develops deviations in system frequency. So, while constructing the regulator for LFC of interconnected power systems it is desired to adopt the practical constraints of CTDs with the system to avoid system instability. The controller which had been designed with taking CTDs into account may no longer handle the realistic power system. Thus, this paper recommends adopting CTDs with a power system while designing the LFC controller.

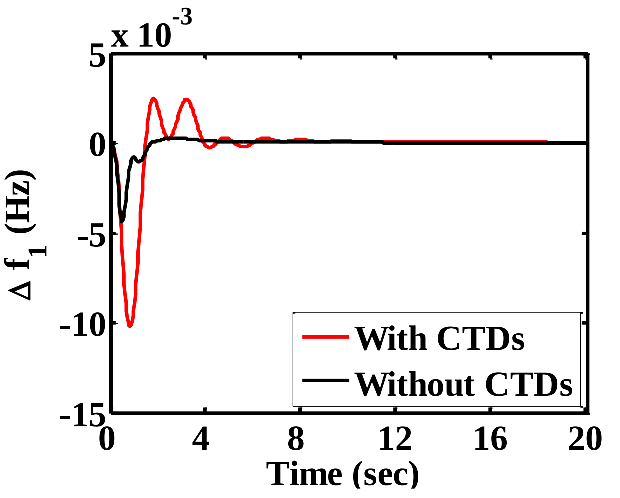

Fig.9(a)

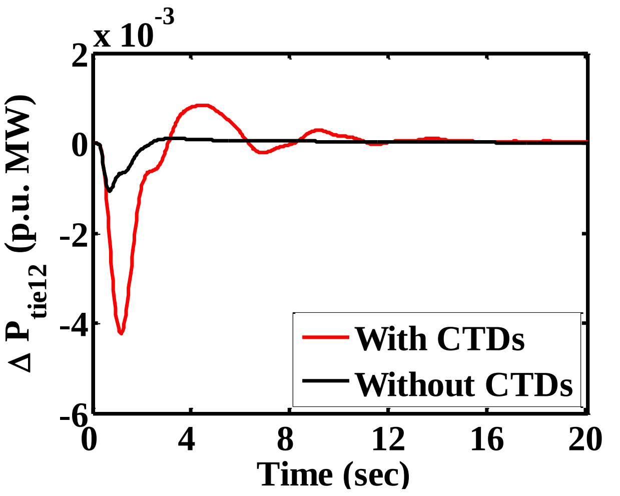

Fig.9(b)

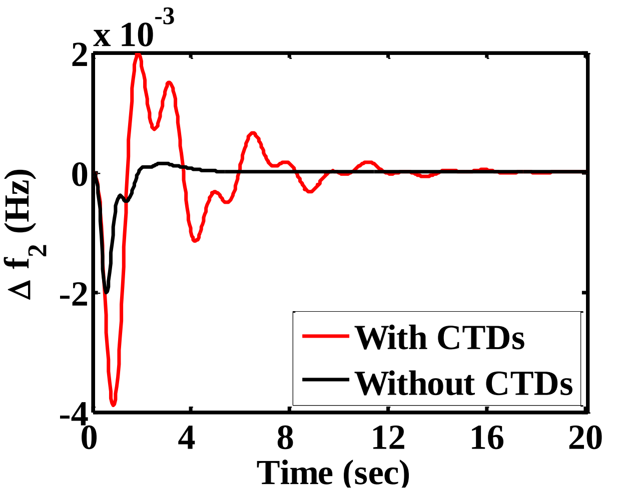

Fig.9(c)

Fig.9. Responses for case-4. (a) Δf_1, (b) ΔP_{tie12}, (c) Δf_2.

5.5. Case-5: Robustness analysis

To check the withstanding capability of the LFC controller for uncertainties, one needs to perform a robustness analysis. In this test, the MAHS system with practical constraints under the supervision of FOFPID using the SOA approach has been targeted with different loadings like 10%SLD on area-1 only, 10%SLD on both areas and 30%SLD on both areas. Responses for this case are displayed in Fig.10 and evoked that the presented control technique is capable of handling the system performance even it is subjected with loading uncertainties. Thus, the FOFPID controller parameters are need not to be changed even the system loading is greatly varied. Hence, the presented control technique is robust.

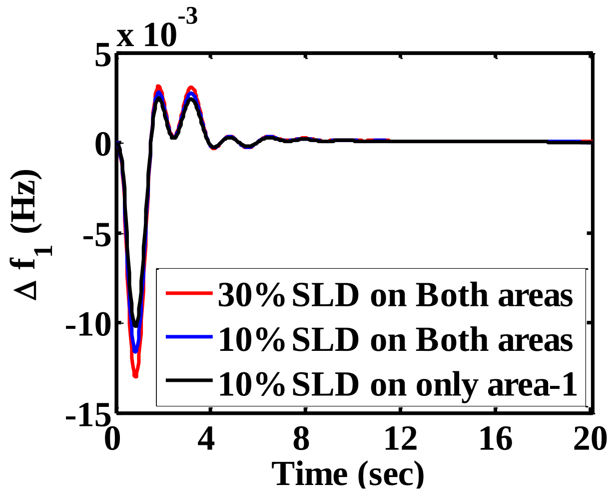

Fig.10(a)

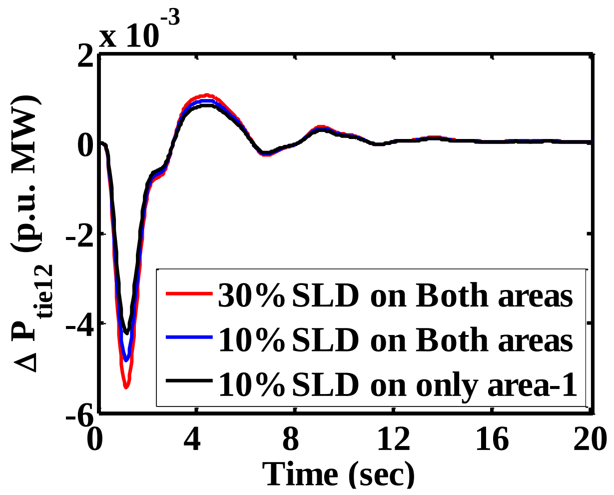

Fig.10(b)

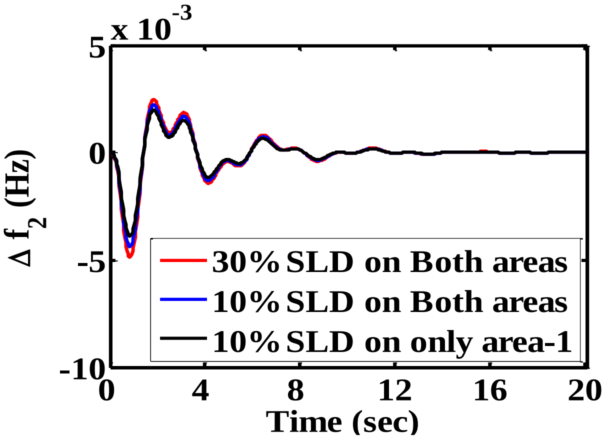

Fig.10(c)

Fig.10. Responses for case-5. (a) Δf_1, (b) ΔP_{tie12}, (c) Δf_2.

6. Conclusion

A new control strategy of FOFPID controller based on soft computing methodology of SOA approach is implemented successfully for maintaining the stability of MAHS realistic power system under fluctuating load demands. Presented regulator efficacy is validated on dual are PVRT system prevalent in literature. SOA tuned FOFPID regulator outperforms the performance of FA based PI, PEO based PID, ICA based FPI and FPIDF techniques that are proposed for test system-1 by the researchers in literature. Further, the presented regulator is also applied to the MAHS system with realistic constraints and again the performance is validated with PID/FPID/FOPID controllers. Later, the importance of considering practical constraints and their significance on power system performance is vindicated. Finally, the robustness test revealed the presented controller robustness even the system is targeted with different loadings.

References

[1] C. N. S. Kalyan, and G. S. Rao, "Frequency and Voltage Stabilization in Combined Load Frequency Control and Automatic Voltage Regulation of Multi Area System with Hybrid Generation Utilities by AC/DC Links", International Journal of Sustainable Energy, Vol.39, No.10, pp.1009-1029, (2020).

[2] S. M. Abd-Elazim, and E. S. Ali, "Load frequency controller design of a two-area system composing of PV grid and thermal generator via firefly algorithm", Neural Comput Appl, Vol.30, No.02, pp.607-606, (2018).

[3] G. Q. Zeng, X. Q. Xie, and M. R. Chen, "An adaptive model predictive load frequency control method for multi-area interconnected power system with photovoltaic generations", Energies, Vol.10, No.11, pp.18-40, (2017).

[4] Y. Arya, "Automatic generation control of two-area electrical power systems via optimal fuzzy classical controller", J.Frankin Inst., Vol.355, No.5, pp.2662-2688, (2018).

[5] Y. Arya, "AGC of two-area electric power systems using optimized fuzzy PID with filter plus double integral controller", J.Frankin Inst., Vol.355, No.11, pp.4583-4617, (2018).

[6] S. M. Nosratabadi, M. Bournapour, and M. A. Gharaei, "Grasshopper optimization algorithm for optimal load frequency control considering predictive functional modified PID controller in restructure multi-resource multi-area power system with redox flow batteries", Control engineering Prcatice, Vol.89, pp.204-227, (2019).

[7] A. M. Ersdal, L. Imsland, K. Uhlen, D. Fabozzi, and N. F. Thornhill, "Model predictive load frequency control taking into account imbalance uncertainty", Control Engineering Practice, Vol.53, pp.139-150, (2016).

[8] S. Kumari, and G. Shankar, "Maiden application of cascade tilt-integral-derivative controller in load frequency control of deregulated power system", International transactions on Electrical energy systems, https://doi.org/10.1002/2050-7038.12257, (2019).

[9] B. Sonker, D. Kumar, and P. Samuel, "Design of two degree of freedom-internal model control configuration for load frequency control using model approximation", International Journal of Modelling and Simulation, Vol.39, No.01, pp.27-37, (2018).

[10] D. Guha, P. K. Roy and S. Banerjee, "Quasi-opposiional JAYA optimized 2-degree-of-freedom PID controller for load-frequency control of interconnected power systems", International Journal of Modelling and Simulation, https://doi.org/10.1080/02286203.2020.1829444.

[11] W. Tasnin, and L. C. Saikia, "Performance comparison of several energy storage devices in deregulated AGC of a multi-area system incorporating geothermal power plant", IET Renewable Power generation, Vol.12, No.07, pp.761-772, (2018).

[12] S. Trip, M. Cucczuzella, C. D. Persis, A. Ferrerra, and J. M. A. Scherpen, "Robust load frequency control of nonlinear power networks", International Journal of Control, Vol.93, No.02, pp.346-359, (2020).

[13] A. H. Yakout, M. A. Attia, and H. Kotb, "Marine predator algorithm based cascaded PIDA load frequency controller for electric power systems with wave energy conversion systems", Alexandria Engineering Journal, Vol.60, pp.4213-4222, (2021).

[14] R. Elyas, "Intelligent linear-quadratic optimal output feedback regulator for a deregulated automatic generation control system", Electric Power Comp Syst, Vol.40, No.05, pp.513-533, (2013).

[15] S. Sahoo, S. S. Dash, N. K. Jena, B. K. Sahu, N. C. Patel, and R. Bayindir, "SHO designed fuzzy logic based controller for AGC study with capacitor energy storage", 8th International conference on Renewable Energy Research and applications (ICRERA), Brasov, Romania, Nov.3-6, pp.845-850, November, (2019).

[16] Y. Arya, "Impact of hydrogen acqua electrolizer fuel cell units on automatic generation control of power systems with a new optimal fuzzy TIDF-II ontroller", Renewable Energy, Vol.139, pp.468-482, (2019).

[17] Y. Arya, "A new optimized fuzzy FOPI-FOPD controller for automatic generation control of electric power systems", J.Frankin Inst., Vol.355, pp.5611-5629, (2019).

[18] C. N. S. Kalyan, and G. S. Rao, "Coordinated SMES and TCSC Damping Controller for Load Frequency Control of Multi Area Power System with Diverse Sources", International Journal on Electrical Engineering and Informatics, Vol.12, No.04, pp.747-769, (2020).

[19] P. C. Sahu, R. C. Prusty, and S. Panda, "Approaching hybridized GWO-SCA based type-II fuzzy controller in AGC of diverse energy source multi area power system", Journal of King Saud University-Engineering Sciences, Vol.32, No.03, pp.186-197, (2020).

[20] M. Moazzami, M. Ghanbari, H. Shahinzadeh, J. Moradi and G. B. Gharehpetian, "Application of multi objective grey wolf algorithm on energy management of micro grids with techno-economic and environmental considerations", 3rd IEEE Conference on swarm intelligence and Evolutionary Computation, pp:1-9, March, (2018).

[21] M. Moazzami, G. B. Gharehpetian, H. Shahinzadeh, and S. H. Hosseinian, "Optimal location and sizing of DG and D-STATCOM using modified shuffled frog leap algorithm", 2nd IEEE Conference on swarm intelligence and Evolutionary Computation, pp:54-59, March, (2017).

[22] D.Yoursi, T. S. Babu, and A. Fathy, "Recent methodology based harris hawks optimizer for designing load frequency control incorporated in multi-interconnected renewable energy plants", Sustainable Energy, Grids and Networks, Vo.22, 100352, (2020).

[23] C. N. S. Kalyan, and G. S. Rao, "Performance Comparison of Various Energy Storage Devices in Combined LFC and AVR of Multi Area System with Renewable Energy Integration", International Journal of Renewable Energy Research (IJRER), Vol.10, No.02 , pp.933-944, (2020).

[24] P. Dahiya, P. Mukhija, A. R. Saxena and Y. Arya, "Comparative performance investigation of optimal controller for AGC of electric power generating systems", Automatika, Vol.57, No.04, pp.902-921, (2016).

[25] S. K. Gupta, Y. Arya, S. Shukla, and P. Chawla, "Two area AGC in interconnected system under the restructured power system using BFO controller", 6th IEEE Power India International Conference, December 5, pp:1-6, (2014).

[26] C. N. S. Kalyan, B. S. Goud, C. R. Reddy, H. S. Ramadan, M. Bajaj, and Z. M. Ali, "Water Cycle Algorithm Optimized Type II Fuzzy Controller for Load Frequency Control of a Multi-Area, Multi-Fuel System with Communication Time Delays", Enegies, 14, 5387, https://doi.org/10.3390/en14175387, (2021).

[27] B. S. Goud, P. S. Varma, B. L. Rao, M. S. K. Reddy, A. Pandian, and C. R. Reddy, "Cuckoo search optimization based MPPT for integrated DFIG- wind energy system ", International conference on decession Aid Sciences and application (DASA), pp.636-639, 10.1109/DASA51403.2020.9317072, (2020).

[28] B. S. Goud, and B. L. Rao, "Power quality enhancement in grid- connecetd PV/wind/battery using UPQC: Atom search optimization", J. Electr. Eng. Technol., Vol.16, pp.821-835, https://doi.org/10.1007/s42835-020-00644-x, (2021).

[29] S. Bhongade, and V. P. Paramar, "Automatic generation control of two-area ST-thermal power system using Jaa algorithm", International Journal of Smart Grid, Vol.2, No.2, pp. 99-110, (2018).

[30] Y. Che, and D. He, "A Hybrid whale optimization with seagull algorithm for global optimization problems", Mathematical Problems in Engineering, https://doi.org/10.1155/2021/6639671, (2021).

[31] C. N. S. Kalyan, and G. S. Rao, "Impact of Communication Time Delays on Combined LFC and AVR of a multi-area Hybrid system with IPFC-RFBs Coordinated Control strategy", Protection and Control of Modern Power Systems, Vol.06, No.1, pp.1-20, (2020).

[32] C. N. S. Kalyan, and G. S. Rao, "Coordinated control strategy for simultaneous frequency and voltage stabilization of the multi-area interconnecetd system considering communication time delays", International Journal of Ambient Energy, https://doi.org/10.1080/01430750.2021.1967192, (2021).

[33] C. N. S. Kalyan, and C. V. Suresh, "Differential Evolution based Intelligent Control approach for LFC of Multiarea Power system with Communication Time Delays", 2021 International conference on Computing, Communication, and Intelligent Systems, April, 2021, 10.1109/ICCCIS51004.2021.9397112.

[34] C. N. S. Kalyan, "UPFC and SMES based coordinated control strategy for simultaneous frequency and voltage stability of an interconnected power system", 2021 1st International Conference on Power Electronics and Energy (ICPEE), pp.1-6, doi: 10.1109/ICPEE50452.2021.9358576. (2021).

[35] G. Dhiman, V. Kumar, "Seagull Optimization algorithm: Theory and its applications for large-scale industrial engineering problems", Knowledge Based Systems, Vol.165, pp.169-196, (2019).

Appendix

Test system-1 [3-5]: PV Unit: Grid parameters- a=800, b=-18, c=100, d=50. Power system: Gain constant= K_{PS}=120, time constant=T_{PS}=20sec. Thermal unit: bias constant=B=0.8puMW/Hz, Thermal regulator=R_2=2.4Hz/puMW, reheat gain constant=Kr=0.33, reheat time constant=Tr=10sec, governor time constant=Tg=0.08sec, turbine time constant=Tt=0.3sec.

Test system-2: Thermal: Tg=Governor time constant=10.2sec, Tr=reheat time constant=0.08sec, Tt=Turbine time constant=3sec, Kr=reheat gain constant=0.3. Hydro unit: Tgh=governor time constant=0.3sec, Tw=water starting time in penstock=0.025sec, Trs=governor reset time=5sec. Gas unit: Xc= lead time of governor=0.6, Yc=lag time of governor=1sec, T_f= time constant of fuel=0.23sec, T_{CD}= compressor discharge time=0.2sec, b and c are valve position parameters= 0.05 and 1sec respectively. Wind unit: Kp=wind turbine gain=1.25, Tp=wind turbine time constant=0.041sec. B_i=bias parameter=0.0425, R_T=R_H=R_G= speed regulator constant=2.4Hz/puMW. T_{12}=synchronizing coefficient=0.545pu.