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Application of backtracking search algorithm in load frequency control of multi-area interconnected power system

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Abstract This paper introduces a new powerful evolutionary algorithm called backtracking search algorithm (BSA) for solving load frequency control (LFC) problem in power system. Initially, two-area non-reheat thermal power plant is considered and gains of PI/PID controllers are optimized using BSA. This paper compares BSA's effectiveness in solving LFC problem with the performances of other optimization techniques reported in the literature. Nonlinearities of power system such as reheater, governor dead band, boiler dynamics and generation rate constraint are included in the system modeling to identify the system stability and its performance is compared with craziness based PSO technique. Additionally, two more test systems namely three-area and four-area hydro-thermal plant with nonlinearity are considered to demonstrate the efficiency of proposed algorithm. The comparative analysis of the performances indicates that the proposed controller gives better results than other techniques available in the literature. Sensitivity analysis showed robustness of proposed controller under loading and parameter uncertainty.

1. Introduction

The successful operation of an interconnected power system network requires balance between total power generation and total load demands plus losses incurred in the system. The high complexity and nonlinearity together with time-varying nature of power system network cause variations of an operating point w.r.t time which may result in variations of frequency and net interchanging power between neighboring control areas. Large variations of frequency and tie-line power may yield instability to the system [1]. Classical control

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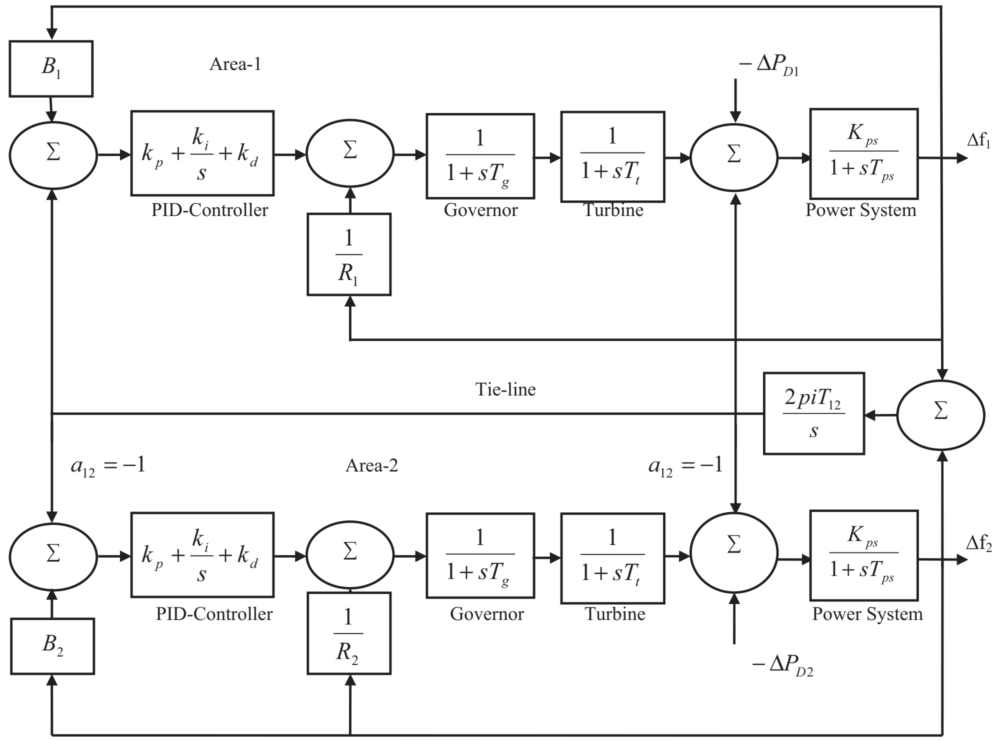

Figure 1 Block diagram of two-area interconnected non-reheat thermal–thermal power system (Test system-1).

scheme via flywheel governor of synchronous machine is no longer able to compensate these variations and hence, a supplementary control scheme using load frequency controller (LFC) is incorporated into the system. LFC not only maintains system stability with variation of load, but also satisfies other system constraints such as security and reliability.

The LFC problem of an interconnected power system network is enlarged by the several researchers from time to time over last few decades in order to present better dynamic responses. Several control mechanisms have been proposed in the literature to solve LFC problem, such as classical controller [2–10], sliding mode controller (SMC) [11], robust controller [12], non-integer controller [13–15], H_∞ controller [16], and intelligent controller [17–20]. In [11], authors presented a new discrete time SMC using full state feedback for an interconnected four area power system network. More recently authors of [13–15] proposed non-integer controller to solve LFC problem for an interconnected multi-area power system network and showed better system dynamics than the results available in the literature. Several intelligent controllers based on fuzzy logic [17], neuro-fuzzy [18], advance fuzzy [19], artificial neural network [20] were presented in the area of LFC and demonstrated their applicability to improve dynamic performances of the same. Moreover, these advanced techniques are complex and require sound knowledge about their internal structure, thus reducing their applicability in practical field. On the other hand, classical PID-controller and its variant are most popularly used in practice because of its simple structure, robustness, reliability, and easily understood, and gives better system performances despite the wide variations of system parameters [7]. Operating points of the power system network are continuously changing due to sudden load perturbation (SLP); hence, selections of optimal values of the designed controller is a major issue in the study of LFC problem. Different population based optimization techniques such as differential evolution (DE) [7,21], genetic algorithm (GA) [22], particle swarm optimization (PSO) [23], artificial bee colony algorithm (ABCA) [24], bacteria foraging optimization algorithm (BFOA) [3], hybrid bacteria foraging optimization algorithm – particle swarm optimization (hBFOA-PSO) [2], craziness based particle swarm optimization (CRPSO) [4], gravitational search algorithm (GSA) [8], and firefly algorithm (FA) [9,13] were proposed in this area to select optimum gains of designed controller. However, recent research identifies some drawbacks of these methods. Nearly all the said algorithms depend on the proper initialization of input parameters and slow convergence rate toward the global solutions. Moreover, they sometimes produce local solution instead of the global ones. Among the well popular optimization techniques, DE has a very simple algorithmic structure that can be effortlessly applied to LFC problem. The DE adopts mutation, crossover and selection strategies like GA. Though the mutation process involved in DE is stronger than that of GA, the search ability of DE is highly affected by the choice of mutation factor and crossover rate. PSO is another popularly used optimization algorithm in the optimization field, but it is highly susceptible to the initial values of weighting factor of the cognitive and social components and weighting strategy of the velocity vector. The success of ABCA is highly dependent on the limit value, number of employed bees. In the line of "no free lunch" algorithm, there is no meta-heuristic optimization scheme which is well suited for all optimization problems, i.e., a particular evolutionary algorithm gives better results on a set of problems, but same algorithm may also show poor performance on a different

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Table 1 Nominal values of system parameters.

Parameters	Values	Parameters	Values	Parameters	Values
Test system-1: Two-area non-reheat thermal–thermal power system (without GDB)					
f	60 Hz	$T_{t1} = T_{t2}$	0.3 s	$R_1 = R_2$	2.4 Hz/p.u MW
$P_{r1} = P_{r2}$	2000 MW	$T_{sg1} = T_{sg2}$	0.03 s	T_{12}	0.545 p.u
$K_{ps1} = K_{ps2}$	120 Hz/pu MW	$T_{ps1} = T_{ps2}$	20 s	$B_1 = B_2$	0.425 pu MW/Hz
Test system-1: Two-area non-reheat thermal–thermal power system (with GDB)					
f	60 Hz	$T_{t1} = T_{t2}$	0.3 s	$R_1 = R_2$	2.4 Hz/p.u MW
$P_{r1} = P_{r2}$	2000 MW	$T_{sg1} = T_{sg2}$	0.2 s	T_{12}	0.0707 p.u
$K_{ps1} = K_{ps2}$	120 Hz/pu MW	$T_{ps1} = T_{ps2}$	20 s	$B_1 = B_2$	0.425 pu MW/Hz
Test system-2: Three-area thermal–thermal-hydro power system					
f	60	$T_{t1} = T_{t2}$	0.3 s	$B_1 = B_2 = B_3$	0.425 pu MW/Hz
$P_{r1} = P_{r2} = P_{r3}$	2000 MW	$T_{sg1} = T_{sg2}$	0.08 s	$R_1 = R_2 = R_3$	2.4 Hz/p.u MW
$T_{12} = T_{23} = T_{31}$	0.086 pu	T_w	1 s	$T_{r1} = T_{r2}$	10 s
$K_{r1} = K_{r2}$	0.5	$T_{p1} = T_{p2} = T_{p3}$	20 s	$K_{p1} = K_{p2} = K_{p3}$	120 Hz/pu MW
Nominal values of coal fired, well tuned boiler					
T_d	40	T_F	25	K_{IB}	0.020
T_{IB}	90	T_{RB}	69	K_1	0.85
K_2	0.095	K_3	0.92	C_B	200
Test system-3: four-area hydro-thermal power plant [32]					
Thermal unit					
f	60 Hz	R_i	2.4 Hz/p.u	T_{ti}	0.3 s
B_i	0.425 p.u. MW/Hz	T_{gi}	0.08 s	T_{pi}	20 s
K_{pi}	120 Hz/p.u. MW	$T_{12} = T_{13} = T_{23}$	0.707 p.u	i	1, 2, 3
Hydro unit					
K_p	80 Hz/p.u. MW	T_w	1 s	B_4	0.425 p.u. MW/Hz
T_p	13 s	R	2.4 Hz/p.u	T_{14}	0.0707 p.u

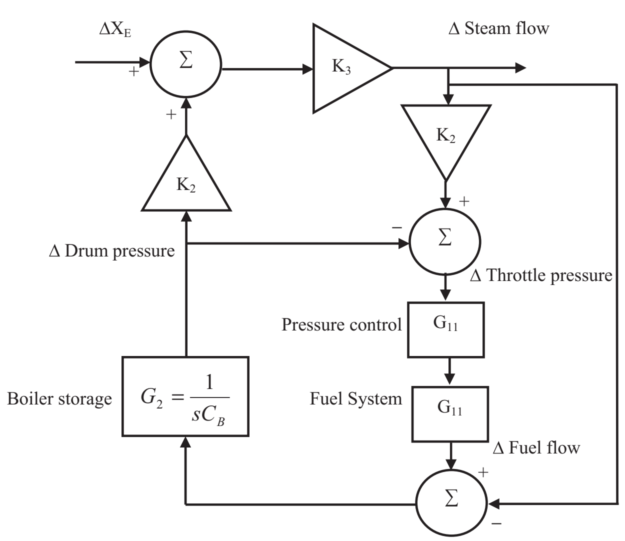

Figure 2 Block diagram of drum type coal fired well tuned boiler.

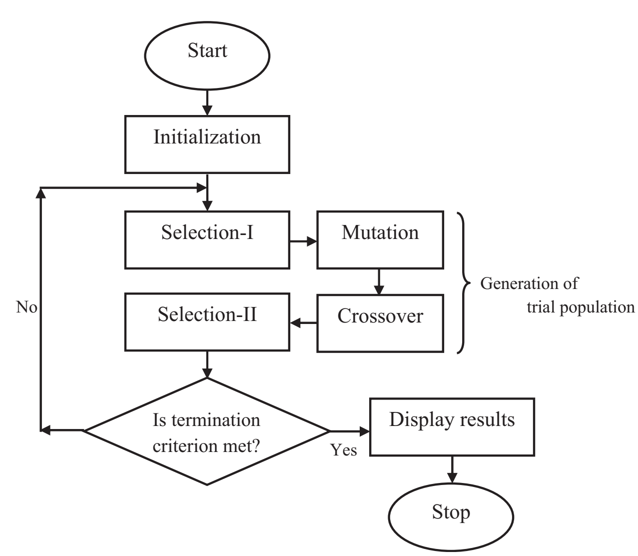

Figure 3 General flowchart of BSA.

set of problems. Thus, there remains a need for efficient and effective optimization technique to solve nonlinear optimization problems. Apart from the aforesaid optimization techniques, other evolutionary algorithms (EA) namely biogeography based optimization (BBO) [25], krill herd algorithm (KHA) [26], chemical reaction optimization (CRO) [27], teaching learning based optimization (TLBO) [28], and differential search algorithm (DSA) [29] were successfully designed and implemented in the other fields of power system.

Having knowledge of all the aforesaid, an attempt has been made in this paper to design and implement a relatively new optimization technique called backtracking search algorithm

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Table 2 Optimum gains of controller parameters for test system-1.

Controller gains	Evolutionary Algorithms							
	Proposed Controllers		Ref. [2]					Ref. [8]
	BSA: PI	BSA: PID	hBFOA-PSO	PSO	GA	BFOA	Conventional	GSA with PI
K_{i1}	1.1996	1.9657	0.4741	0.4756	0.2662	0.4741	0.4741	0.6179
K_{i2}	0.1851	0.0164	0.4741	0.4756	0.2662	0.4741	0.4741	0.6179
K_{p1}	0.3873	1.0663	−0.3317	−0.3597	−0.2346	−0.3317	−0.3317	−0.1880
K_{p2}	1.9909	1.5606	−0.3317	−0.3597	−0.2346	−0.3317	−0.3317	−0.1880
K_{d1}	–	0.3462	–	–	–	–	–	–
K_{d2}	–	0.4259	–	–	–	–	–	–
Objective function	0.3510	**0.1288**	1.1865	1.2142	2.7475	1.8379	3.5795	0.6659
Damping ratio	0.0971	**0.0269**	0.1795	0.1887	0.2359	0.174	0.0206	0.1144

Bold values shows the best results.

Table 3 Comparative performance between different algorithms in terms of settling time of transient responses for test system-1.

Parameters	Proposed controllers		Ref. [2]					Ref. [7]	Ref. [8]
	BSA: PI	BSA: PID	hBFOA-PSO	PSO	GA	BFOA	Conventional	DE	GSA
Area-1	5.11	**1.39**	7.39	7.37	10.59	5.52	45	8.96	12
Area-2	6.31	**3.30**	7.65	7.82	11.39	7.09	45.01	8.16	11.90
Tie-line power	4.58	**3.48**	5.73	5	9.37	6.35	28.27	5.75	8.90

Bold signifies best results.

(BSA) to solve real-time LFC problem of an interconnected power system. Unlike other EA's, BSA is the most effective algorithm in terms of CPU running times and has a single control parameter. The design problem can be treated as an optimization problem and BSA is used to tune the settings of classical controllers. The dynamic responses are studied with step load perturbation (SLP) in area-1 considering overshoot, settling time of frequency and tie-line power deviations as performance indices. By minimizing time multiplied integral absolute error fitness function, stability of the interconnected system is improved. To present the test system be more realistic and to verify the algorithm's effectiveness in nonlinear environment, power system nonlinearities such as reheater, governor dead band, boiler dynamics and generation rate constraint are considered during system modeling. Dynamic performances of BSA optimized PI/PID controller are compared with other algorithms available in the literature to prove its superiority. Finally, a realistic random load pattern is considered to demonstrate the robustness of the proposed method.

The rest of the paper is organized as follows: Section 2 describes mathematical model of test system. Nonlinearities of power system networks are explained in Section 3. The proposed BSA optimization algorithm is briefly explained in Section 4. The controllers' structure with objective function is illustrated in Section 5, followed by the implementation of BSA in LFC problem in Section 6. Transient analysis of the test systems with simulation results are presented in Section 7 and finally, Section 8 gives conclusion.

2. Mathematical modeling of test system

Before designing a controller structure, it must be ensured that mathematical model of test system must be valid for time domain simulation. The power system under investigation consists of an interconnected two-area non-reheat thermal–thermal power system network, which is widely used in the literature for design and analysis of LFC problem [2]. Each area has a rating of 2000 MW with nominal loading of 1000 MW. The linearized model of governor, turbine used for simulation and LFC study of the power system are shown in Fig. 1. The different parameters used in Fig. 1 are as follows: T_g is the time constant of speed governor, T_t is the time constant of steam turbine, K_{ps} is the gain of power system unit, T_{ps} is the time constant of power system unit, R_1 and R_2 are the speed regulation parameter of speed governor in area-1 and area-2, respectively. T_{12} is the synchronizing time constant of tie-line, B_1 and B_2 are the frequency bias parameter of the respective areas, ΔP_{D1} and ΔP_{D2} are the load disturbances in area-1 and area-2, respectively, Δf_1 and Δf_2 are deviation of frequency in area-1 and area-2, respectively. Nominal values of system parameters are taken from [2] and illustrated in Table 1.

3. Nonlinearities of power system networks

A physical system is a collection of several physical components connected together to serve a specific task. In practice, no physical system can be identified by all its components. But to make the system be realistic, we need to consider all the possible nonlinearities of the system during the modeling of same. To get an accurate imminent of LFC problem, it is essential to include the important inherent requirements and include them into modeling. The basic sources of nonlinearities in power system network such as governor dead band (GDB), boiler dynamics (BD) and generation rate constraints (GRC) are considered in this paper to study the effect of the same

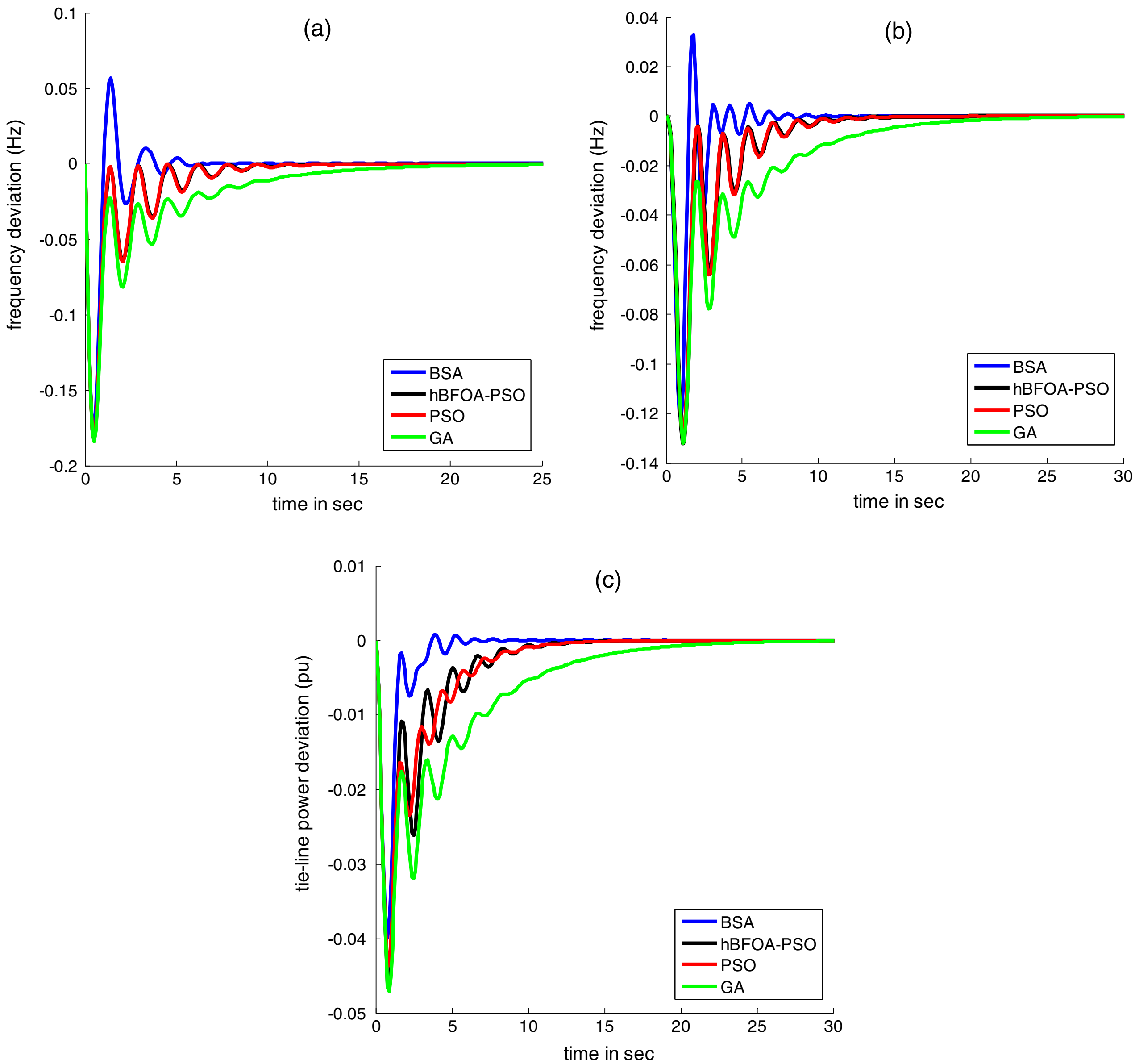

Figure 4 Comparative analysis between different EA's for test system-1 equipped with PI-controller (a) changes of frequency in area 1, (b) changes of frequency in area 2, (c) changes of tie-line power.

on the power system dynamics. This section describes the basic sources of nonlinearities in power system.

3.1. Governor dead band (GDB)

The speed governor is a device that varies the governor controlled valves to adjust energy input levels to maintain a uniform speed of a rotating machine. Governor dead band (GBD) [6] is defined as the total magnitude of sustained speed changes within which there are no resulting changes in valve positions. The hysteresis type of nonlinearity is used to define GDB and its maximum value is 0.06% [6]. Describing function approach is used to find the linear model of GDB and is defined as follows:

$$G_{DB}(s) = 0.8 - \frac{0.2}{\pi}s \tag{1}$$

3.2. Boiler dynamics (BD)

The boiler is meant for producing steam under pressure. Fig. 2 shows the block diagram of coal fired well-tuned drum type boiler [6]. This includes the long-term dynamics of fuel and steam flow on boiler drum pressure. Nominal values of all parameters are taken from [6] and given in Table 1. The T.F models of pressure control unit and fuel system are defined in (2) and (3), respectively.

$$G_{11}(s) = \frac{K_{IB}(1 + sT_{IB})(1 + sT_{RB})}{s(1 + 0.1sT_{RB})} \tag{2}$$

Table 4 Optimum controller settings, minimum damping ratio, fitness function value, settling time for test system-1 with GDB.

Parameter		BSA: PI (ISE)	BSA: PI (ITAE)	BSA: PID (ISE)	BSA: PID (ITAE)	hBFOA-PSO:PI (ISE) [2]	hBFOA-PSO:PI (ITAE) [2]	CRPSO (ISE) [4]
Optimum values of controller gains	K_{i1}	0.4068	0.4774	1.9702	1.9979	0.3673	0.3260	0.2491
	K_{i2}	0.0069	0.2072	1.0279	0.3420	0.3673	0.3260	0.2491
	K_{p1}	0.4233	0.1423	1.6838	1.5838	0.2186	0.4253	0.2514
	K_{p2}	0.6985	0.5534	0.5401	0.5912	0.2186	0.4253	0.2514
	K_{d1}	–	–	1.6212	1.4212	–	–	–
	K_{d2}	–	–	0.2904	0.3904	–	–	–
Objective function		2.64×10^{-4}	0.0586	2.39×10^{-5}	0.0122	20.51×10^{-4}	0.3948	22.41×10^{-4}
Minimum damping ratio		0.0171	0.0364	0.0992	0.0939	0.0434	0.1084	0.0612
Settling time (s)	Δf_1	12.5	11.5	5.91	**5.49**	37.02	14.22	23.84
	Δf_2	20.7	16.7	6.11	**6.12**	37.02	15.32	23.83
	ΔP_{tie}	20.8	16.3	7.01	**4.31**	25.35	11.05	17.57

Bold signifies best results.

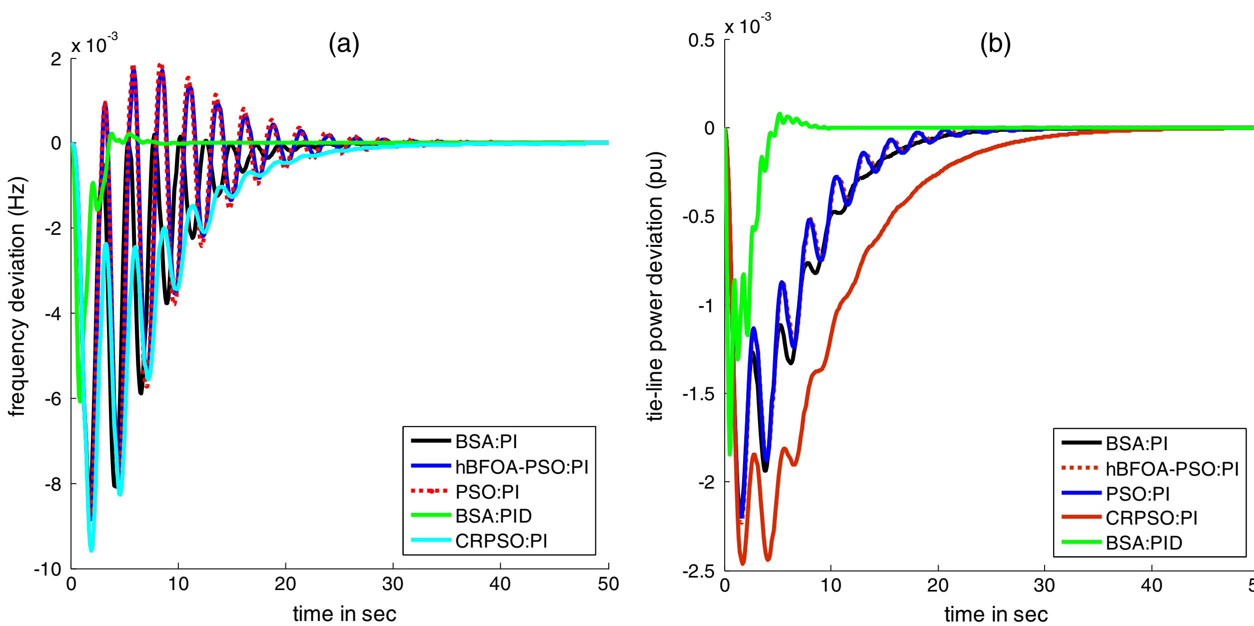

Figure 5 Comparative analysis between different EA's for test system-1 with GDB (a) changes of frequency, (b) changes of tie-line power.

Table 5 Optimum values of controller parameters using BSA.

Mode of operation	Optimum values						Objective function (J)
	K_{i1}	K_{i2}	K_{p1}	K_{p2}	K_{d1}	K_{d2}	
PID-controller with reheat turbine	1.9872	1.8916	1.8942	0.8362	0.3462	0.7436	0.3350
PID-controller with reheat turbine and GDB	1.9852	1.9960	1.7658	0.7926	0.4967	1.2413	0.4539
PID-controller with reheat turbine, GDB and BD	1.9984	1.9978	1.8873	0.8543	0.4633	1.5844	0.4732
PID-controller with reheat turbine, GDB, BD and GRC	1.9688	1.7968	1.5778	0.9841	0.3824	1.3728	0.5020

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Table 6 Transient specifications of test system in terms of overshoot, undershoot and settling time.

Mode of operation	Area-1			Area-2			Tie-line power		
	OS	US	ST	OS	US	ST	OS	US	ST
PID-controller with reheat turbine	0.0158	−0.1380	7.01	0.0081	−0.0926	10.8	0.0017	−0.0305	13.7
PID-controller with reheat turbine plus GDB	0.0197	−0.1665	6.29	0.0177	−0.1209	11.2	0.0024	−0.0372	14.2
PID with reheat turbine, GDB and BD	0.0184	−0.1738	6.64	0.0176	−0.1248	11.1	0.0022	−0.0390	13.5
PID with reheat turbine, GDB, BD and GRC	0.4103	−0.6451	19.6	0.4621	−0.6276	19.8	0.0107	−0.0875	26.7

OS = overshoot, US = undershoot, ST = settling time (s).

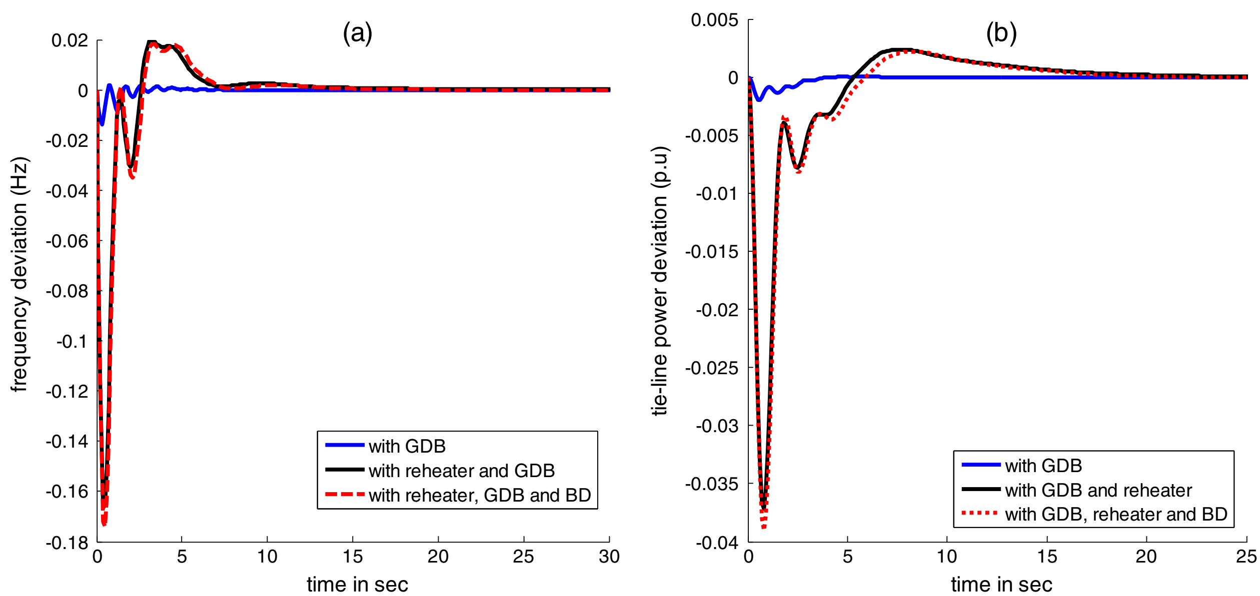

Figure 6 Effect of nonlinearities to the dynamics of test system-1 (a) changes of frequency, (b) changes of tie-line power.

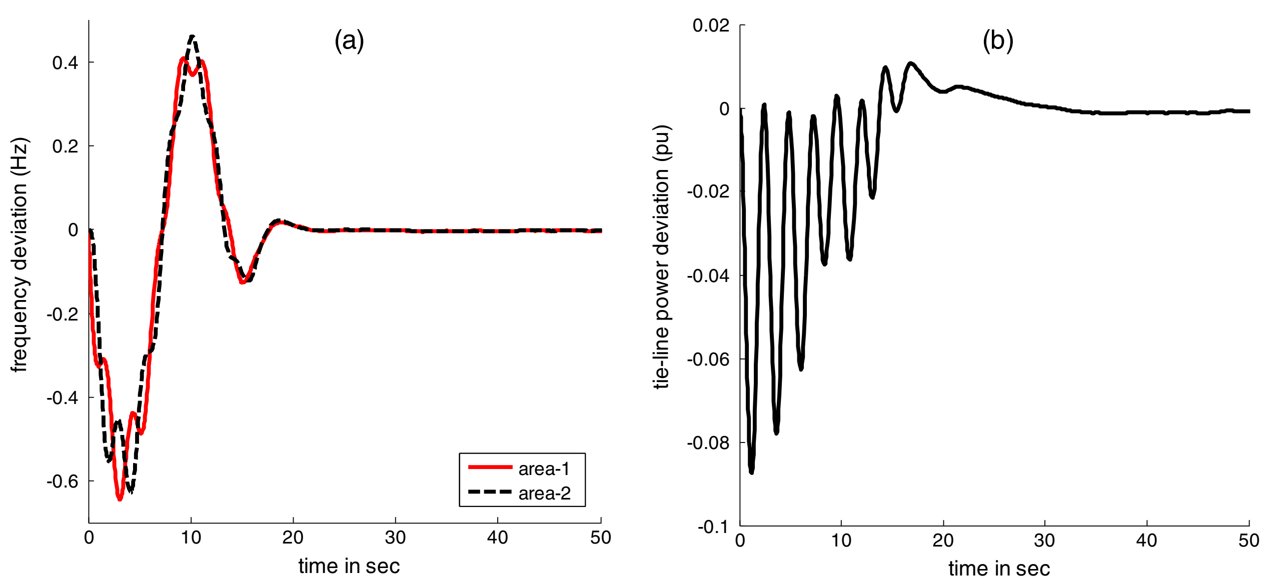

Figure 7 Transient performances of test system-1 considering GRC (a) changes of frequency, (b) changes of tie-line power.

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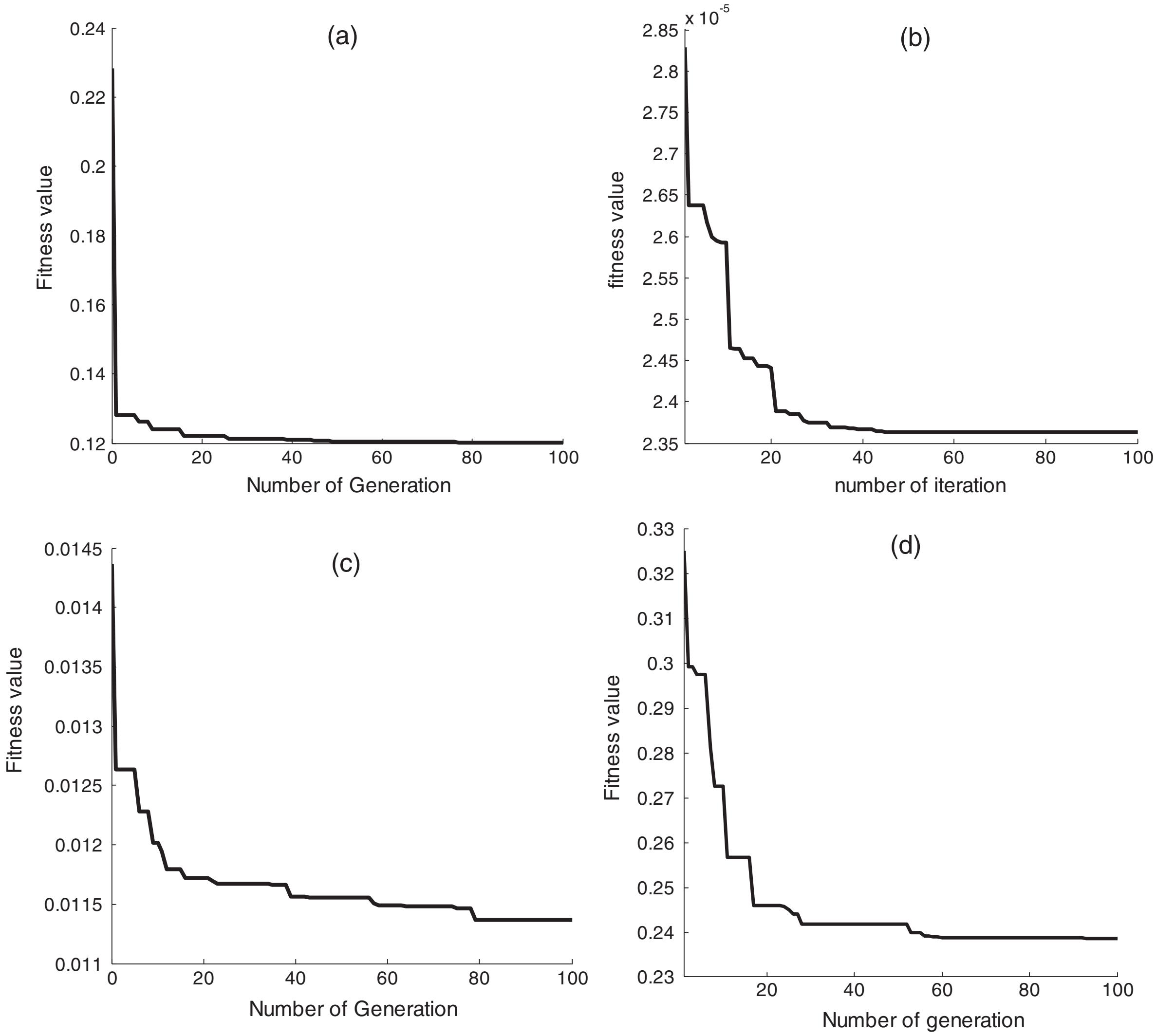

Figure 8 Convergence behavior of proposed BSA (a) PI-controller (ITAE) with GDB, (b) PI-controller (ISE) with GDB, (c) PID-controller (ITAE) with GDB, (d) 10% SLP in all areas of test system-1.

Table 7 Optimum values of controller parameters, ITAE value, maximum overshoot, settling time under different loading conditions.

Parameters	Optimum values of controller parameters						ITAE value	Maximum overshoot			Settling time		
	K_{i1}	K_{i2}	K_{p1}	K_{p2}	K_{d1}	K_{d2}		Δf_1	Δf_2	ΔP_{tie}	Δf_1	Δf_2	ΔP_{tie}
10% SLP in both areas	1.9867	1.9570	1.8362	1.8238	0.8950	0.8833	0.2386	8.76×10^{-6}	1.82×10^{-5}	1.05×10^{-4}	3.93	3.90	7.35
20% SLP in area-1	1.9905	0.0109	1.3475	0.1037	0.4057	1.4925	0.2965	5.15×10^{-5}	0	0	2.18	3.99	3.93
20% SLP in both areas	1.9632	1.9570	1.9274	1.9116	0.9127	0.9026	0.4784	0	0	0	4.19	4.19	5.04

$$G_{12}(s) = \frac{e^{-T_D s}}{1 + sT_F} \quad (3)$$

where $e^{-T_D s}$ can be approximated as in (4) using 2nd order Pade approximation technique. The signal flow graph (SFG) method is used to find the linear model of BD and its T.F model is defined in (5).

$$e^{-sT_D} = \frac{1 - \frac{sT}{2} + \frac{s^2T^2}{2}}{1 + \frac{sT}{2} + \frac{s^2T^2}{2}} \quad (4)$$

$$G(s) = \frac{K_3(1 + G_1G_2)}{1 - K_1K_2K_3G_1G_2 + G_1G_2 + K_1K_3G_2} \quad (5)$$

where $G_1 = G_{11} * G_{12}$.

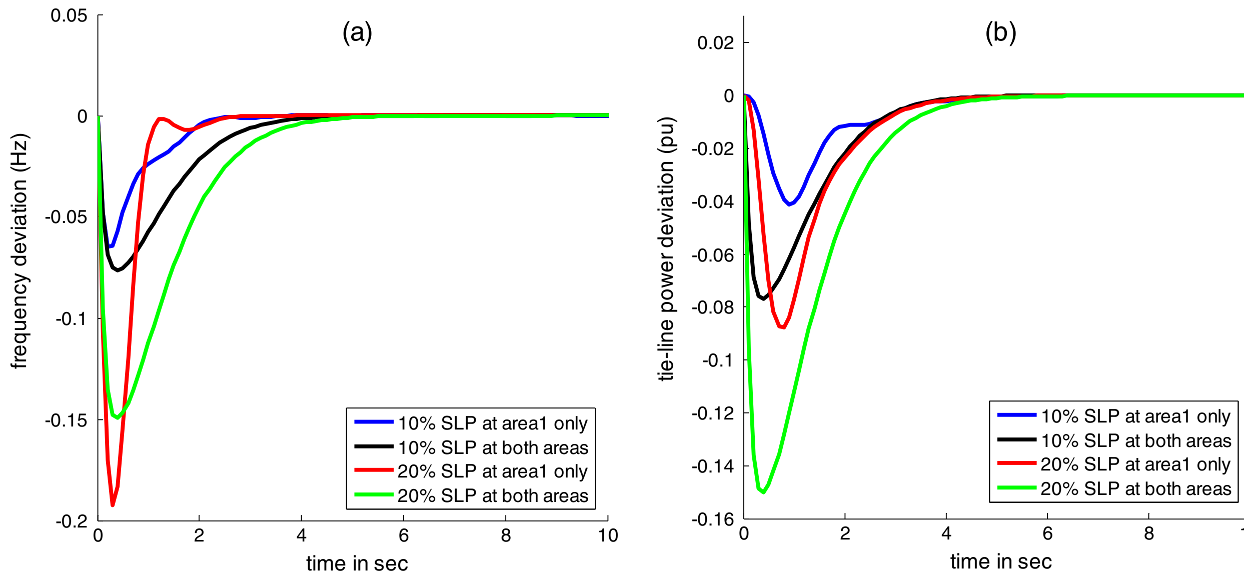

Figure 9 Transient responses of test system-1 under different loading conditions with PID-controller (a) changes of frequency, (b) changes of tie-line power.

Table 8 Optimum values of controller parameters of test system-1 using BSA with 10% SLP in area-1 under wide variation of system parameters.

Parameter variation	% of change	Controller parameters tuned by ITAE						Controller parameters tuned by ISE					
		K_{i1}	K_{i2}	K_{p1}	K_{p2}	K_{d1}	K_{d2}	K_{i1}	K_{i2}	K_{p1}	K_{p2}	K_{d1}	K_{d2}
Nominal	No change	1.9657	0.0164	1.0663	1.5606	0.3462	0.4259	1.9528	0.7063	1.7938	0.6093	1.8656	1.4221
T_G	+50%	1.9846	0.5474	1.1300	1.5317	0.3657	0.2714	1.9574	0.1504	1.5407	0.0219	1.7650	1.3702
	+25%	1.9857	0.0313	1.0351	1.4739	0.3258	0.2179	1.9784	0.2759	1.5397	0.7348	1.7833	1.8713
	−25%	1.9765	1.8741	1.2290	1.9093	0.3505	0.7880	1.9829	0.4535	1.7399	0.3656	1.9419	1.9828
	−50%	1.9749	0.0129	1.2272	0.9430	0.3828	1.6243	1.8246	0.0230	1.5118	0.2296	1.6966	1.5718
T_t	+50%	1.9621	0.8706	1.0811	1.9537	0.3813	0.8389	1.8673	0.6525	1.7203	1.6982	1.5987	1.0196
	+25%	1.9682	0.0862	1.2109	1.9758	0.4510	0.7183	1.9150	0.7279	1.2926	0.4569	1.8150	1.9816
	−25%	1.9852	0.0310	0.9703	1.4020	0.2650	0.0764	1.9590	0.3168	1.9712	0.3724	1.7738	1.0796
	−50%	1.8795	1.7737	0.6259	1.2365	0.0716	0.0691	1.9122	0.0287	1.9923	0.0899	1.8205	0.9909
T_{12}	+50%	1.9785	1.5618	0.8991	1.8902	0.2929	0.8745	1.9723	0.3218	1.8217	0.1343	1.8976	1.4334
	+25%	1.9759	0.0438	0.9650	1.8679	1.3349	1.0249	1.9723	0.3218	1.8217	0.1343	1.8976	1.4334
	−25%	1.9478	1.5474	1.7945	1.7687	0.5222	0.1558	1.8957	0.0033	1.5372	0.1679	1.8157	1.6913
	−50%	1.9657	0.2154	1.9719	0.0112	0.3398	0.9870	1.8990	0.0659	1.9052	0.9574	1.7893	1.4903
Parameter variation	% of change	Controller parameters tuned by ITSE						Controller parameters tuned by IAE					
		K_{i1}	K_{i2}	K_{p1}	K_{p2}	K_{d1}	K_{d2}	K_{i1}	K_{i2}	K_{p1}	K_{p2}	K_{d1}	K_{d2}
Nominal	No change	1.9081	0.3076	1.8653	1.4879	0.6591	1.5743	1.9869	0.0921	1.9750	1.7348	0.3957	1.8652
T_G	+50%	1.9684	0.0227	1.8792	0.7064	0.6404	1.9768	1.8942	1.6943	1.9088	0.3503	0.6923	0.1733
	+25%	1.8908	0.0375	1.8086	1.4987	0.6143	0.6908	1.9938	1.4094	1.5755	1.2917	0.6840	0.4296
	−25%	1.9978	0.3311	1.8594	1.4817	0.5405	1.7802	1.9666	1.1842	1.9712	1.3527	0.7443	0.6168
	−50%	1.9847	0.1972	1.9414	1.7578	0.4725	1.0403	1.9281	1.7555	1.8632	1.6305	0.8132	0.7210
T_t	+50%	1.9725	0.2618	1.8349	1.4632	0.8718	1.4592	1.9784	1.9792	1.8062	1.6729	0.6374	0.8377
	+25%	1.8819	0.4024	1.7529	1.9055	0.5807	1.6708	1.9814	0.5031	1.8674	1.9271	0.8601	1.9893
	−25%	1.9607	0.0772	1.8680	1.9724	0.3654	1.2398	1.8839	0.8720	1.8367	0.0268	0.8914	0.0535
	−50%	1.9810	0.0898	1.9862	1.3523	0.2016	1.3527	1.9591	1.9458	1.5623	1.0445	0.4358	1.1210
T_{12}	+50%	1.8951	0.5432	1.6704	1.2541	0.4061	1.6688	1.9565	1.5953	1.8472	1.7753	0.8696	0.2063
	+25%	1.9527	0.0427	1.9941	1.3135	0.5780	1.2936	1.9474	1.9171	1.7768	1.7653	0.8209	0.8360
	−25%	1.9834	0.0801	1.9642	0.2943	0.5122	1.8325	1.9646	0.0543	1.2635	1.8952	0.3314	0.0629
	−50%	1.8921	0.5087	1.8105	1.8639	0.5549	1.0555	1.9856	0.0237	1.5706	0.2646	0.3836	0.8863

Table 9 Performance indices, settling time of test system 1 with 10% SLP in area-1 under wide variation of system parameters.

Evolutionary algorithm	% of change	Performances indices				Settling time in s (ITAE)		
		ITAE	ISE	ITSE	IAE	Δf_1	Δf_2	ΔP_{tie}
BSA	No change	0.1288	0.0034	0.0029	0.1431	1.39	3.30	3.48
hBFOA-PSO [2]		1.4933	0.1324	0.1650	0.9251	5.17	6.81	4.59
Change of turbine time constant, T_t in the range of ±50%								
BSA	+50%	0.1408	0.0043	0.0031	0.1438	2.95	3	3.12
	+25%	0.1309	0.0045	0.0032	0.1445	1.11	3.29	3.52
	−25%	0.1269	0.0030	0.0027	0.1518	1.13	3.57	3.48
	−50%	0.1391	0.0029	0.0025	0.1457	1.98	2.88	3.59
hBFOA-PSO [2]	+50%	2.2629	0.1634	0.222	1.112	9.17	10.04	7.55
	+25%	1.7288	0.1463	0.1875	0.988	7.84	7.09	7.35
	−25%	1.4075	0.1214	0.1515	0.8898	6.32	5.5	5.02
	−50%	1.4542	0.114	0.1448	0.8807	6.77	4.94	5.63
Change of speed governor time constant, T_G in the range of ±50%								
BSA	+50%	0.1286	0.0038	0.0028	0.1501	2.36	3.55	3.56
	+25%	0.1270	0.0037	0.0030	0.1448	2.43	2.87	3.47
	−25%	0.1326	0.0034	0.0027	0.1446	2	3.74	3.94
	−50%	0.1332	0.0040	0.0026	0.1475	1.17	3.77	3.78
hBFOA-PSO [2]	+50%	1.573	0.1398	0.1746	0.9509	7.6	6.85	4.46
	+25%	1.5251	0.1359	0.1694	0.9364	7.53	6.82	4.52
	−25%	1.4725	0.1293	0.1615	0.9159	5.32	6.77	4.68
	−50%	1.4614	0.1264	0.1588	0.9088	5.48	6.62	4.76
Change of synchronizing time constant of tie-line, T_{12} in the range of ±50%								
BSA	+50%	0.1073	0.0032	0.0029	0.1454	1.05	2.55	2.77
	+25%	0.1164	0.0032	0.0026	0.1461	1.39	2.86	2.96
	−25%	0.1462	0.0040	0.0028	0.1508	1.42	3.93	4.46
	−50%	0.1469	0.0037	0.0035	0.1940	1.17	5.65	5.71
hBFOA-PSO [2]	+50%	1.3702	0.126	0.1561	0.9254	6.61	7.19	5.13
	+25%	1.4946	0.1286	0.1595	0.9288	7.06	6.22	5.35
	−25%	1.5043	0.1386	0.1746	0.89209	5.51	7.37	5.02
	−50%	1.7231	0.1491	0.1935	0.9698	6.26	6.77	5.81

Table 10 Optimum values of controller variables for test system-2.

Parameters	Algorithms	K_{i1}	K_{i2}	K_{i3}	K_{p1}	K_{p2}	K_{p3}	K_{d1}	K_{d2}	K_{d3}	J
Without GRC	BSA: PI	1.6638	0.0831	0.0683	1.8898	0.0788	0.0673	–	–	–	0.0578
	BSA: PID	1.9667	0.8788	0.0116	1.8810	0.0265	0.0622	1.0067	1.9784	0.1919	0.0475
With GRC	BSA: PI	1.1131	0.3241	0.1227	1.9416	0.7227	0.0661	–	–	–	0.0674
	BSA: PID	0.3885	0.2405	0.2219	1.9106	0.3749	0.2658	1.3317	0.6157	0.0949	0.0853
	hBFOA-PSO	0.0952	0.1199	0.0210	0.1502	0.1202	0.0399	–	–	–	NA

3.3. Generation rate constraint (GRC)

It is mainly caused by mechanical and thermodynamics constraints of steam turbine. A typical GRC is represented by saturation type nonlinearity and considered as limiter with steam turbine, since power generation can only be changed at a maximum specified rate. If this constrain is not considered during modeling of power system, the system is likely to chase large turbulence thus resulting into wear and tear of controllers. In general GRC [5] of hydro unit is larger than that of thermal unit. In hydro unit, the value is 270%/min for raising generation and 360%/min for lowering generation, whereas the same for thermal unit is 3%/min.

4. Backtracking search algorithm (BSA)

Optimization is a very important and popular tool for the researchers over past few decades in the area of power system operation and control. Its aim is to find the best values of system parameters through the determination of objective function in order to extract maximum benefits from the system. BSA is one of the new population based EA's introduced by

Table 11 Output specifications of test system-2 in terms of settling time and overshoot without GRC.

Algorithms	Δf_1		Δf_2		Δf_3		ΔP_{tie1}		ΔP_{tie2}		ΔP_{tie3}	
	OS	ST	OS	ST	OS	ST	OS	ST	OS	ST	OS	ST
BSA: PI	0.0101	13.6	0.0025	23.4	0.0048	27.4	0	23.9	0.0013	20.1	0.0011	29.8
BSA: PID	0.0020	8.68	0.0021	25.8	0.0044	29.7	0	22.5	0.0010	27.5	0	33.9

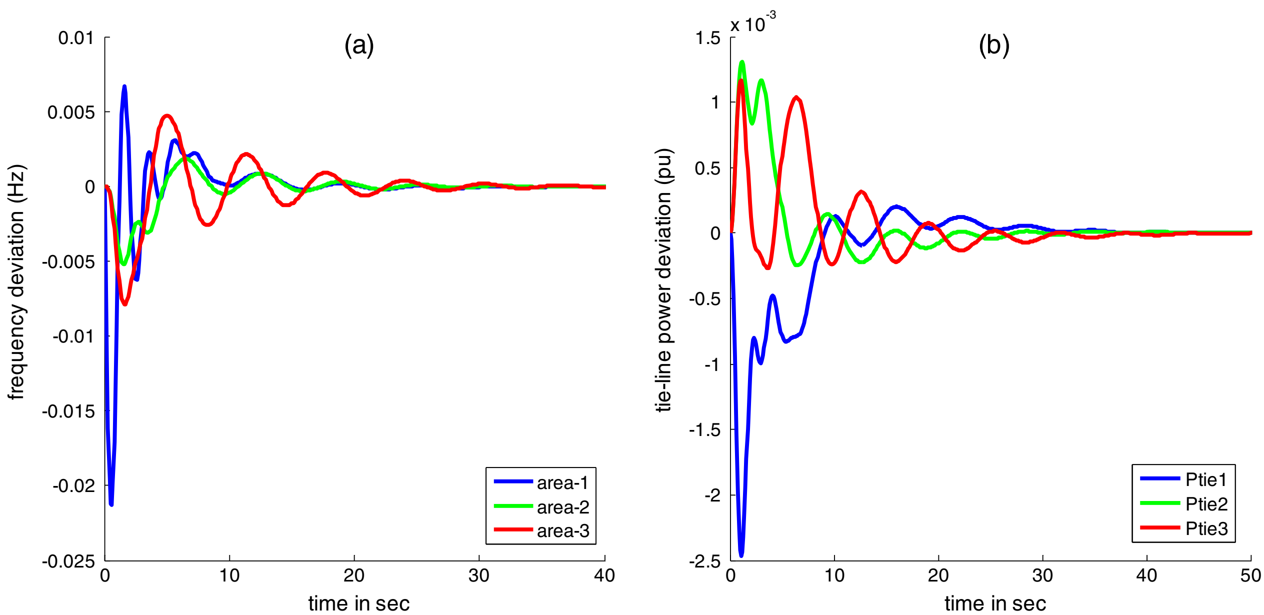

Figure 10 Transient performances of test system-2 without GRC equipped with BSA optimized PID-controller (a) changes of frequency, (b) changes of tie-line power.

Civicioglu. It is fast and capable of solving multimodal problems. It has simple structure and unique mechanism for generating trial individuals enables it to solve nonlinear, dynamic optimization problem successfully and rapidly. BSA can be explained by dividing its evolutionary mechanism into five parts as follows: initialization, selection-I, mutation, crossover and selection-II [30,31].

4.1. Initialization

BSA initially scatters the population (*pop*) in the solution space by using uniform random distribution as defined in (6).

$$pop_{i,j} \sim U(low_j, up_j) \quad (6)$$

where $i = 1, 2, 3, ----, N, j = 1, 2, 3, ----, D$, U is the uniform distribution function, *low* and *up* are defined as lower and upper bounds of the solution space, respectively. The pseudo code of defining initial population, according to (6), is as follows:

```
Input:N, D, low, up
Output: pop
fori = 1 : N
forj = 1 : D
pop(i,j) = rand * (up(j) − low(j)) + low(j);
end
end
```

where N and D are the population size and dimension of the problem (number of control variables), respectively.

4.2. Selection-I

Selection-I stage in BSA involves in determination of historical population (*old_pop*) for finding search direction.

Initially, historical population is defined randomly using (7)

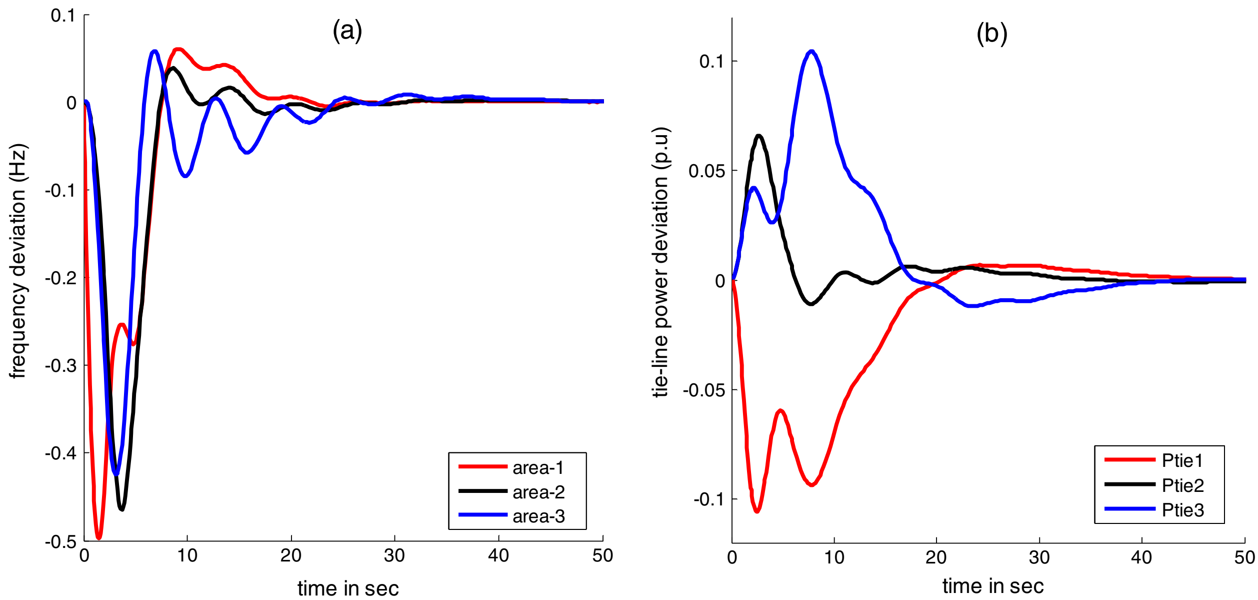

Figure 11 Transient performances of test system-2 with GRC equipped with BSA optimized PID-controller (a) changes of frequency, (b) changes of tie-line power.

$$old\_pop_{i,j} \sim U(low_j, up_j) \quad (7)$$

In BSA, *if* $a < b$, where a and b are two random numbers between $(0, 1)$, then historical population is updated using (8).

$for\ i = 1 : N$

$for\ j = 1 : D$

$$old\_pop(i,j) = pop(i,j); \quad (8)$$

end

end

It is evident from (8) that BSA randomly selects population from the previous generation and remembers until it is changed. Basically, historical population is the swarm memory of BSA. After having historical population, (9) is used for shuffling the order of individual population.

$$old\_pop := permuting(old\_pop) \quad (9)$$

where *permuting* is a random shuffling function and ':='is the update operation.

4.3. Mutation

The mutation process in BSA is generated by using (10)

$$Mutatnt = pop + F.(old\_pop - pop) \quad (10)$$

where F controls the amplitude of search direction and this paper considered $F = 4 * randg$ (Brownian-walk). *randg* represents random number chosen from gamma distribution with unit size and shape.

4.4. Crossover

The final form of the trial population (T) is generated by using crossover process of BSA. The initial value of the trial population is *mutatnt*, generated from mutation process. The pseudo code of crossover process in BSA is given below.

```
Input :mutatnt, mixrate, N, D
Output :Trialpopulation (T)
  map(1:N,1:D) = 1
  if rand < rand
    for i = 1 : N
      u = randperm(D)
      map(i, u(1 : ceil(mixrate * rand * D))) = 1
    end
    else
      for i = 1 : N
      map(i, randi(D)) = 1
      end
    end
    for i = 1 : N
      for j = 1 : D
        if map_i,j = 1
        T_i,j := pop_i,j
        end
      end
    end
```

where ceil is the ceiling function. It mainly involves two processes: first strategy includes *mixrate* (binary integer-valued matrix) that indicates the individual T to be manipulated using individual values of *pop*. The second strategy allows only one random number to select from *mutatnt* in each trial. Line 2–5 and line 7–9 in algorithm show first and second strategy of crossover process in BSA, respectively.

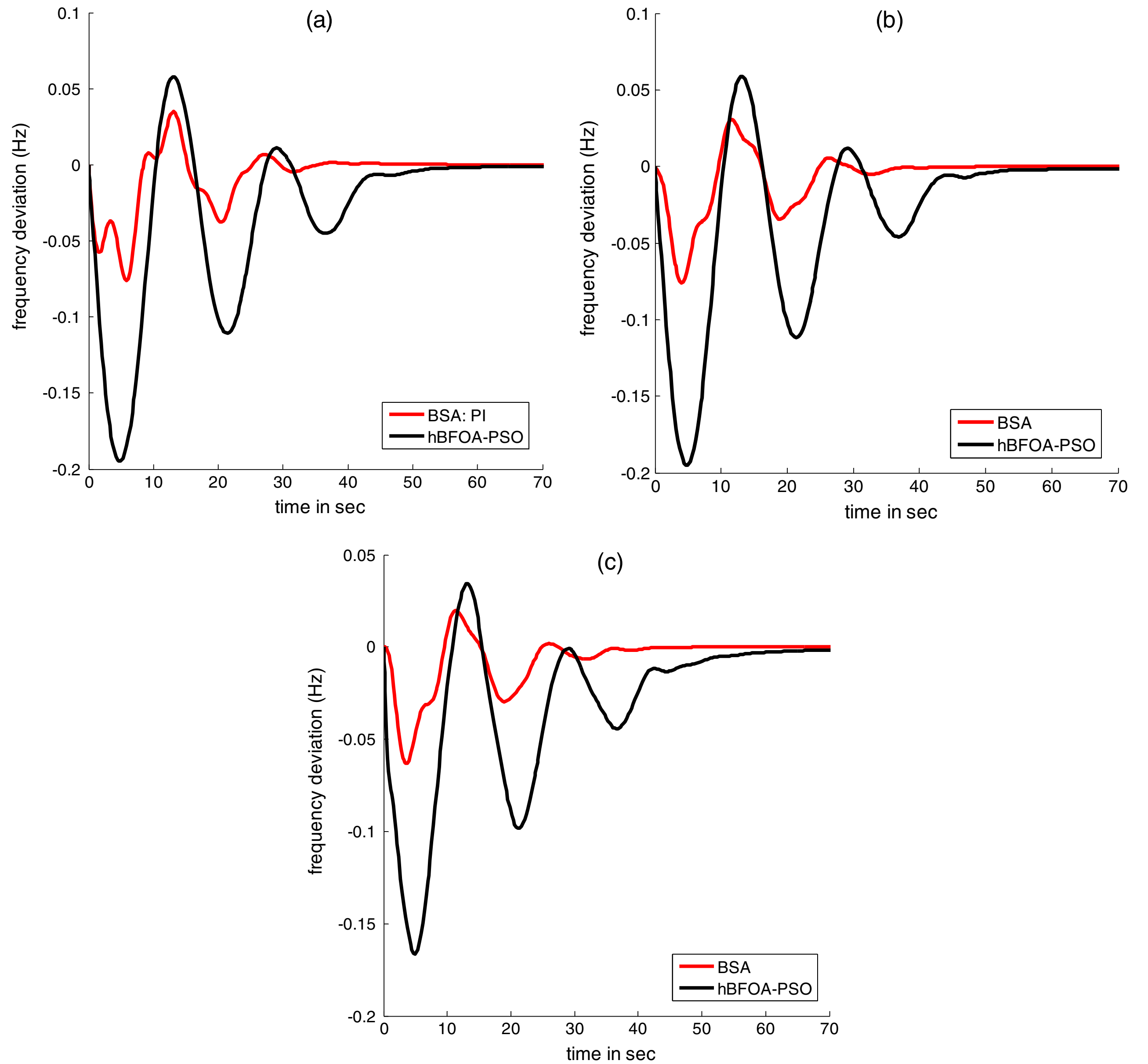

Figure 12 Transient performances of test system-2 with 1% SLP in all area (a) changes of frequency in area-1, (b) changes of frequency in area-2, (c) changes of frequency in area-3.

Table 12 Comparative analysis between performance indices obtained by different algorithms for test system-2 with 1% SLP in area-1 including GRC.

Optimization Algorithms	Δf_1		Δf_2		Δf_3		ΔP_{tie1}		ΔP_{tie2}		ΔP_{tie3}	
	OS	ST	OS	ST	OS	ST	OS	ST	OS	ST	OS	ST
BSA: PID	**0.0020**	**8.68**	**0.0021**	**25.8**	**0.0044**	**29.7**	$\mathbf{1.70 \times 10^{-6}}$	**22.6**	**0.0010**	**27.5**	$\mathbf{7.41 \times 10^{-6}}$	**33.9**
BSA: PI	0.0079	17.2	0.0028	29.6	0.0070	34.4	0	30.13	0.0016	26.5	0.0015	36.1
ISE [20]	3.5	68.2	3.266	61.3	3.225	69.4	0.018	96.1	0.715	106.7	0.625	113.4
ANFIS [20]	1.65	36.9	1.377	49.2	2.107	62.7	0	54.7	0.669	55.2	1.105	62.3

Bold signifies best results.

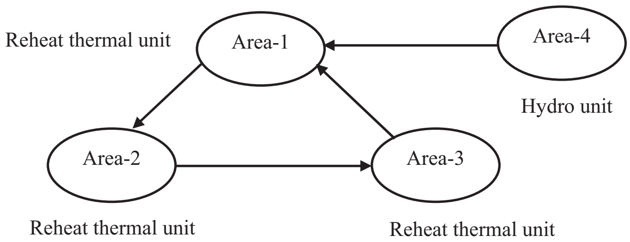

Figure 13 Schematic diagram of four-area hydro-thermal power system.

Some individual solution at the end of BSA crossover strategy may exceed the search space boundaries. In order to control the movement of the same, boundary control mechanism of BSA is employed and the pseudo-code of this strategy is as described below:

```
Input : T, low_j, up_j
Output : T
  for i = 1 : N
    for j = 1 : D
      if(T_i,j < low_j)or(T_i,j > up_j)
        T_i,j = randast(up_j − low_j) + low_j
      end
    end
  end
```

4.5. Selection-II

In selection-II process of BSA, individual values of trial population (T_i) has better fitness value than individual corresponding population (*pop*) are used to update individual population (*pop*) using greedy selection process. If the best individual of *pop* has better fitness value obtained so far, then global minimum value is replaced by the best individual of population (*pop*). The detailed BSA structure is available in [30].

The general flowchart of BSA is illustrated in Fig. 3.

5. Controller structure and objective function

The error input to the controllers is the ACE of the respective areas as defined in (11) and the controlled output from the controller is defined in (12).

$$\begin{aligned} e_1(t) &= ACE_1 = B_1\Delta f_1 + \Delta P_{tie} \\ e_2(t) &= ACE_2 = B_2\Delta f_2 - \Delta P_{tie} \end{aligned} \quad (11)$$

$$\begin{aligned} u_1(t) &= K_{P1}ACE_1 + K_{I1}\int ACE_1 dt + K_{D1}\tfrac{d(ACE_1)}{dt} \\ u_2(t) &= K_{P2}ACE_2 + K_{I2}\int ACE_2 dt + K_{D2}\tfrac{d(ACE_2)}{dt} \end{aligned} \quad (12)$$

The primary objective of LFC system is to restore system frequency to its schedule value as quickly as possible and reduces tie-line power oscillations between neighboring control areas under small perturbation of load. In order to satisfy above conditions, settings of PI-control $(K_{i1}, K_{i2}, K_{p1}, K_{p2})$ and PID-controller $(K_{i1}, K_{i2}, K_{p1}, K_{p2}, K_{d1}, K_{d2})$ are optimized using proposed BSA to have minimum overshoot, settling time in area frequencies and power exchange between different control areas. Effectiveness of proposed optimization algorithm is compared with other EA's available in the literature. In this paper, ITAE criterion is used to minimize the objective function as defined in (13).

$$J = \sum_{0}^{T_{sim}} (abs(\Delta f_1) + abs(\Delta f_2) + abs(\Delta P_{tie})) * t * \Delta T \quad (13)$$

where ΔT is small time interval in s, T_{sim} is the maximum simulation time in s. The design problem can be formulated as the following constrained optimization problem.

Minimize J

Subjected to:

$$\begin{aligned} K_{I,\min} &\leqslant K_I \leqslant K_{I,\max} \\ K_{P,\min} &\leqslant K_P \leqslant K_{P,\max} \\ K_{D,\min} &\leqslant K_D \leqslant K_{D,\max} \end{aligned} \quad (14)$$

where $K_{PID,\min}, K_{PID,\max}$ are the minimum and maximum gains of PI/PID-controller, respectively. The minimum and maximum values of the controller gains are chosen as 0 and 2, respectively.

6. Implementation of BSA in LFC problem

In this article, BSA is employed to solve LFC problem of an interconnected multi-area power system network and to find optimal solutions satisfying all operating constraints. The algorithmic steps of the proposed BSA method applied to LFC system are enumerated below.

Step 1. Randomly initialize population (*pop*) within search space using following pseudo code and evaluate fitness function using (13).

```
for i = 1 : popsize
  for j = 1 : dim
    pop(i,j) = rand * (up(j) − low(j)) + low(j);
  end
end
```

where *popsize* is the population size, dim is the number of control variables (4 for PI-controller and 6 for PID-controller), *up* and *low* are the upper and lower bounds of control variables.

Step 2. Randomly initialize historical population (*old_pop*) with in the search space.

```
Input : popsize, low, up
Output : old_pop
for i = 1 : popsize
  for j = 1 : dim
    old_pop(i,j) = rand * (up(j) − low(j)) + low(j);
  end
end
```

Step 3. Update historical population at the beginning of each iteration using following pseudo code.

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```
if rand < rand
  for i = 1 : popsize
    for j = 1 : dim
    old_pop(i,j) := pop(i,j);
    end
  end
```

where *old_pop*: indicates updating of historical population by current population.

Step 4. Perform mutation strategy using (10).

Step 5. Perform crossover strategy using following pseudo code.

```
if rand < rand
  for i = 1 : popsize
                    u = randperm(dim);
    map(i, u(1 : ceil(dim_rate * rand * dim)) = 1;
  end
else
  for i = 1 : popsize
    map(i, randi(dim)) = 1;
  end
end
for i = 1 : popsize
    for j = 1 : dim
    offsprings(i,j) = pop(i,j) + F * (old_pop(i,j) − pop(i,j));
    end
end
```

Step 6. Check, whether output solution (*offsprings*) goes beyond the search space or not using boundary conditions as described in Section 4.4.

Step 7. Select the fitter solution (*fitnessoff springs*) from the generated population as in step 7 and evaluate fitness value using (13).

Step 8. Check, whether *fitnessoff springs* gives better fitness value than that obtained so far using initial population or not. If *fitnessoff springs* gives better results, then update *offsprings* by *fitnessoff springs*, otherwise keep the previous one.

Step 9. Sort the current population from best to worst and use for the next generation.

Step 10. Go to step 3 until termination criterion is met.

7. Results and discussion

The main idea of performing the simulation study is to test the effectiveness of the proposed algorithm based PI/PID controller in multi-area power system networks. The model of test system under study has been developed in Matlab/Simulink environment and proposed BSA algorithm is written in (*.m file*). The objective function (time multiplied absolute value of ACE) as depicted in (13) is evaluated in (*.m file*) using BSA to optimize gains of controller parameters. The nominal values of system parameters are adopted from [2] and listed in Table 1.

For successful implementation of BSA, optimum gains of different parameters are required to be determined. Due to the uncertain behavior of BSA, several trials have been made to select optimum values of input parameters of the same for successful optimization of controller parameters and following are found to be best for LFC problem:

Population size = 40, elitism parameter = 4, iteration cycle = 100, dimension of problem, i.e. number of control variables = 6 (for PID structure) and 4 (for PI structure).

7.1. Transient analysis of test system 1

7.1.1. Linear model

Initially, two-area interconnected identical linear non-reheat thermal–thermal power system shown in Fig. 1 is considered for investigation, with 10% SLP in area-1. Two numbers of PI-controllers are designed using BSA and included in power system modeling. Table 2 gives optimum values of controller settings at the end of optimization. With the proposed BSA method using ITAE as an objective function defined in (13), the minimum ITAE value obtained by BSA is **0.3510** and that of using hBFOA-PSO is 1.1865, using PSO is 1.2142, using BFOA is 2.7475, using GA is 1.8379, using ZN is 3.7568, using DE is 0.9911 and using GSA is 0.6659 for the same test system with similar controller structure. Improvement of ITAE value by BSA is 70.4% (hBFOA-PSO), 71.09% (PSO), 87.2% (BFOA), 80.9% (GA), 90.65% (ZN), 64.58% (DE) and 47.3% (GSA) for the similar test system with PI-controller. Hence, it clearly noted from the above discussion that minimum ITAE value is obtained by BSA for the same test system with similar controller structure. The settling time taken by the area frequencies and tie-line power oscillations by BSA techniques is 5.11 s (Δf_1), 6.31 s (Δf_2), 4.58 s (ΔP_{tie}), whereas, settling time for the area frequencies and tie-line power is 7.39 s, 7.65 s, 5.73 s using hBFOA-PSO [2], 7.37 s, 7.82 s, 5 s using PSO [2], 10.59 s, 11.39 s, 9.37 s using BFOA [2], 5.52 s, 7.09 s, 6.37 s using GA [2], 45 s, 45 s, 28 s using ZN [2], 8.96 s, 8.16 s, 5.75 s using DE [7], 12 s, 11.90 s, 8.90 s using GSA [8]. Improvement of settling time using BSA is 7.43% (Δf_1), 11% (Δf_2), 20.1% (ΔP_{tie}) w.r.t other EA's. The comparative transient analysis between BSA and other EA's is given in Table 3 and Fig. 4. It is clearly observed from Fig. 4 and Table 3 that BSA gives better transient responses than other EA's. Further, it is noted from Table 3 that ITAE value by BSA tuned PID-controller is 0.1288 and settling time for the area frequencies and tie-line power oscillations is 1.39 s, 3.30 s and 3.48 s, respectively. Improvement of ITAE value and settling time by BSA optimized PID-controller are 63.3%, 72.79%, 47.7%, 24.02%, respectively, than those of BSA optimized PI-controller.

7.1.2. Nonlinear model

The study is further extended by incorporating GDB nonlinearity into the power system modeling. The nominal values of system parameters are taken from [2] and illustrated in Table 1. During this study, one more objective function based on ISE criterion, as defined in (15), is considered. 1% SLP in area 1 is considered to investigate the effect of GDB on the dynamics of power system.

$$J = \sum_{t=0}^{T_{sim}} ((\Delta f_1)^2 + (\Delta f_2)^2 + (\Delta P_{tie})^2) * \Delta T \quad (15)$$

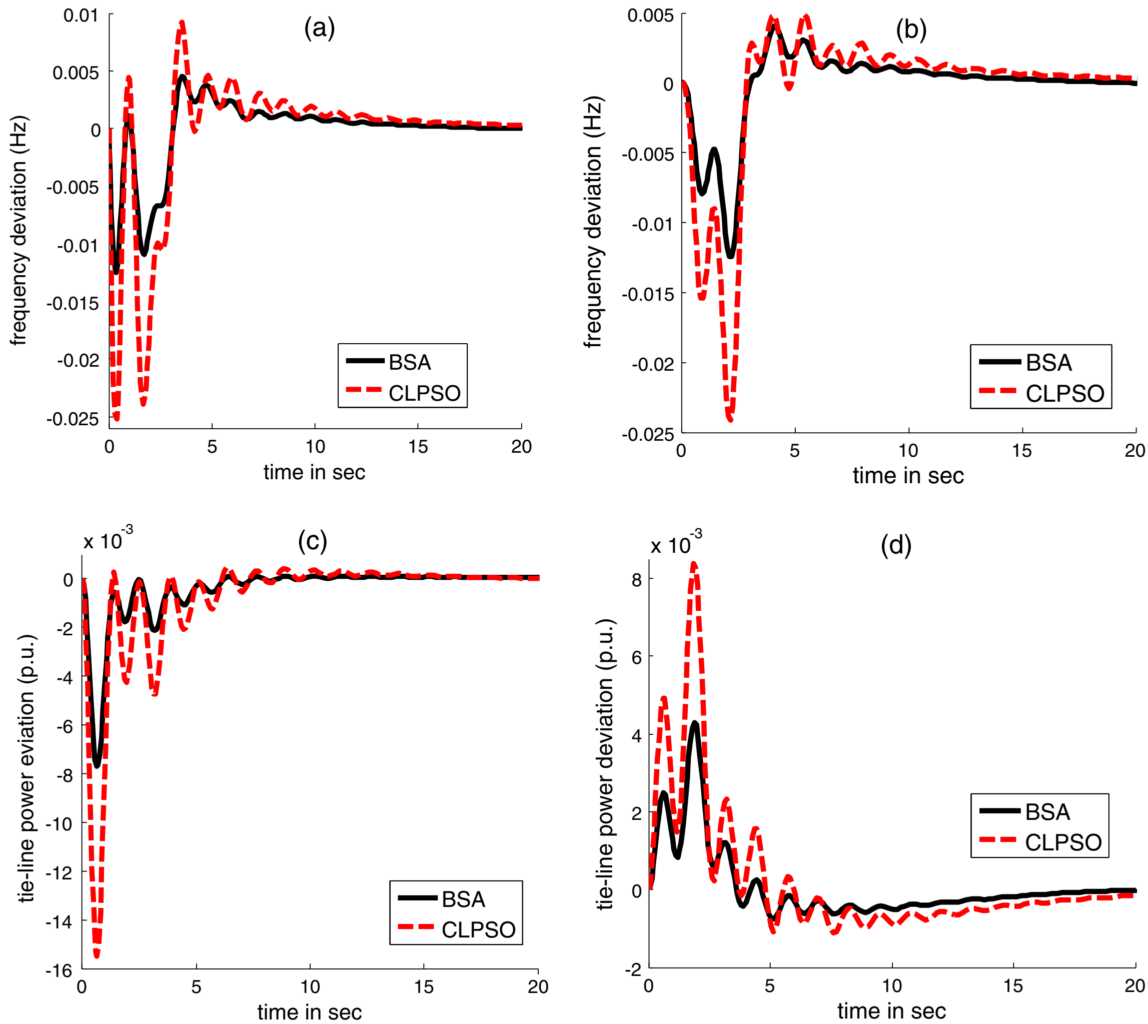

Figure 14 Transient performances of test system-3 with 1% SLP in area-1 (a) changes of frequency in area-1, (b) changes of frequency in area-2, (c) changes of tie-line power in area-1, (d) changes of tie-line power in area-2.

Table 13 Optimum values of PID-controller settings, fitness values and comparative system performances for test system-3 after 1% SLP in area-1.

Optimization techniques	Area-1			Area-2			Area-3			Area-4		
	k_{p1}	k_{i1}	k_{d1}	k_{p2}	k_{i2}	k_{d2}	k_{p3}	k_{i3}	k_{d3}	k_{p4}	k_{i4}	k_{d4}
CLPSO	0.9533	0.9790	0.3341	0.8919	0.9867	0.3114	0.7488	0.4464	0.6467	0.7589	0.1068	0.7082
BSA	0.7501	0.9950	0.3774	0.9721	0.9993	0.2847	0.7945	0.2329	0.7558	0.9680	0.3406	0.5066
Parameters	IMC [32]			QOHSA [32]			CLPSO			BSA		
	OS ($\times 10^{-3}$)	US	ST	OS ($\times 10^{-3}$)	US	ST	OS ($\times 10^{-3}$)	US	ST	OS ($\times 10^{-3}$)	US	ST
Δf_1	16	–	11.14	9.5	–	10.86	9.2	0.0252	16.37	4.5	0.0125	15
Δf_2	3.20	–	24.82	0.87	–	29.45	4.9	0.0241	17.03	4	0.0124	**14.76**
Δf_3	3.20	–	24.82	1.1	–	28.73	5.3	0.0213	17.77	3.33	0.0105	**15.37**
Δf_4	3.20	–	24.32	0.974	–	26.65	3.4	0.0246	16.07	3.2	0.0125	**14.42**
$\Delta P_{tie,12}$	0.88	–	29.35	0.317	–	30.41	4.45	0.0155	11.49	1.09	0.0077	**7.19**
$\Delta P_{tie,23}$	0.88	–	29.35	0.311	–	45.77	8.4	0.0011	20.05	4.3	7.52×10^{-4}	**16.99**
$\Delta P_{tie,14}$	1.10	–	24.04	0.357	–	55.29	5.4	0.0022	18.50	2.7	0.0010	**13.33**
ISE	5.26×10^{-4}			4.26×10^{-5}			2.1721×10^{-5}			2.1952×10^{-5}		
ITSE	3.8×10^{-4}			6.80×10^{-5}			1.7133×10^{-5}			1.7255×10^{-5}		
ITAE	0.5924			0.5098			0.1181			**0.1168**		

Bold signifies best results (for entry "–" means not applicable).

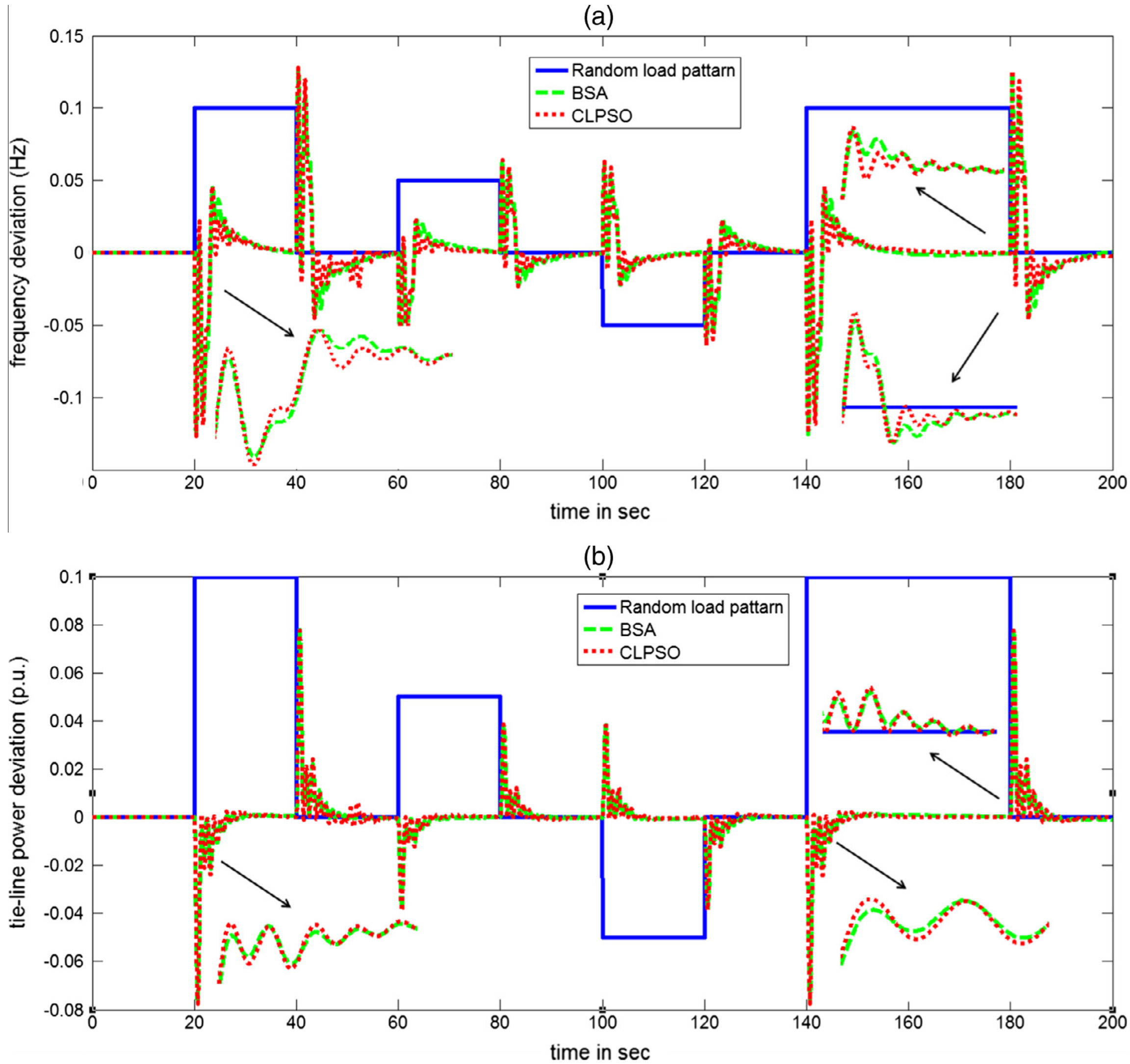

Figure 15 Robustness analysis of test system-3 with random load pattern, (a) changes of frequency in area-1, (b) changes of tie-line power in area-1.

Optimum values of PI-controller, ITAE and ISE value, settling time of area frequencies and tie-line power, and minimum damping ration by BSA are given in Table 4. The ISE value using BSA based PI-controller is 2.64×10^{-4} and that of using hBFOA-PSO and CRPSO is 20.51×10^{-4} and 22.41×10^{-4}, respectively. Improvement of ISE value by BSA is 87.1% as compared to hBFOA-PSO and 88.22% as compared to CRPSO. Similarly, ITAE value by BSA based PI-controller is 0.0586 and that of using hBFOA-PSO is 0.3948. Improvement of ITAE value by BSA is 85.16% than that of hBFOA-PSO. Comparative performances of transient behavior with GDB nonlinearity are depicted in Fig. 5. Additionally, the system is also investigated with PID-controller and at the end of optimization, controller gains are given in Table 4. The ISE and ITAE value with BSA based PID-controller are 2.39×10^{-5} and 0.0122, respectively. Improvement of fitness value with BSA optimized PID-controller is 90.9% (ISE) and 79.2% (ITAE). It is evident from Fig. 5 and Table 4 that BSA optimized PID-controller gives better results than other; thus, it may be accepted as better controller structure optimized by BSA and consequent studies in this article are based on BSA based PID-controller.

Additionally, reheater, BD and GRC types of nonlinearities are taken into consideration to investigate their effects on the power system dynamics. Optimum settings of PID-controller using BSA are tabulated in Table 5 and output specifications in terms of overshoot, undershoot and settling time are given in Table 6. Fig. 6 shows the transient behavior of concerned power system network with GDB, BD and reheater. In addition to that, GRC is also incorporated into the system modeling and its effect with other nonlinearities is shown in Fig. 7. It is clearly evident from Figs. 6 and 7 that nonlinearities have prominent effect on the transient behavior of power system network.

7.1.3. Convergence behavior of proposed BSA

The convergence curves of proposed algorithm for PI-controller structure with GBD using ITAE criterion, PI-controller structure with GBD using ISE criterion, PID-controller structure with GBD using ITAE criterion and

PI-controller with sudden load variation are shown in Fig. 8 (a)–(d) respectively. From the convergence graphs, it may be observed that the objective function value converges smoothly with the optimum value without any unexpected oscillations, thus ensuring convergence consistency of the proposed BSA.

7.1.4. Sensitivity analysis

Sensitivity analysis is performed to investigate robustness of proposed BSA based PID-controller with changing of loads and time constant of different system parameters such as speed governor, steam turbine, and synchronizing time constant of tie-line in the range of $\pm 50\%$. Obtained results in terms of ITAE value, optimum values of controller parameters, maximum overshoot and settling time of area frequencies and tie-line power under different loading conditions are given in Table 7.The dynamic responses under sudden load variation are depicted in Fig. 9. In addition to the objective functions as defined in (13) and (15), two more objective functions based on ITSE and IAE criterion are considered in this article to test robustness of proposed controller structure and they are defined in (16) and (17).

$$IAE = \sum_{t=0}^{T_{sim}} (abs(\Delta f_1) + abs(\Delta f_2) + abs(\Delta P_{tie})) \tag{16}$$

$$ITSE = \sum((\Delta f_1)^2 + (\Delta f_2)^2 + (\Delta P_{tie})^2) * t * \Delta T \tag{17}$$

Table 8 gives the optimum settings of PID-controller parameter during system parameter variation and it is done by taking 10% SLP in area-1. Comparative analysis between proposed BSA and hBFOA-PSO in terms of different cost functions (ITAE, ISE, IAE, ITSE) and settling times of area frequency and tie-line power oscillations under system parameter variations are illustrated in Table 9. It is seen from Table 9 that all variations of area frequencies and tie-line power to different values of time constant of system parameters are in the vicinity of the results obtained by nominal settings.

7.2. Transient analysis of test system 2

One more test system having three area hydro-thermal interconnected power system network equipped with PI/PID controller is considered to test effectiveness and further validation of proposed optimization technique. The T.F model of same is given in [18] and nominal values of system parameters are illustrated in Table 1. Thermal area is studied with single stage reheat turbine and hydro unit is equipped with electrical governor. The internal characteristics of hydro unit differ significantly from thermal area and for details readers are referred to [5].

7.2.1. Linear model

Initially, the system is studied with linear mode without any physical constraints and at the end of optimization through BSA, the controller parameters are given in Table 10. The ITAE value with BSA tuned PI-controller is 0.0578 and that of using BSA tuned PID-controller is 0.0475. Improvement of ITAE value with PID-controller is 17.82%. Output transient specifications in terms of overshoot and settling time are given in Table 11. The changes of frequency and tie-line power with 1% SLP in area-1 using PID-controller are shown in Fig. 10.

7.2.2. Nonlinear model

GRC of steam turbine is incorporated into system modeling to make the system be realistic one. The optimum gains of BSA based PI/PID controllers with GRC are tabulated in Table 10 and transient responses in terms of changes of frequency and tie-line power are shown in Fig. 11. To investigate superiority of proposed BSA based controller, the performance of the same is compared with hBFOA-PSO and ANFIS techniques. Fig. 12 show comparative performances of BSA controller with hBFOA-PSO and Table 12 gives comparative transient performances between ANFIS and results obtained using ISE criterion. It is further observed form Table 12 and Fig. 12 that BSA tuned PID-controller gives better results than others.

7.3. Test system-3

To appraise the applicability and efficacy of the proposed BSA tuned PID-controller, the study is forwarded to another test system, namely four-area hydro-thermal power plant [32]. The schematic diagram of the concerned test system is shown in Fig. 13; however, for detail of transfer function model of the same, the readers are referred to [32]. It is viewed from Fig. 13 that areas 1, 2 and 3 are reheat type thermal unit while area 4 is a hydro power plant. The nominal values of system parameters are taken from [32] and listed in Table 1. In this phase of analysis, BSA is used to identify the optimal settings of PID-controller between [0, 1] employing (13), (16) and (17). The optimal controller gains and minimum fitness values (ITAE, ISE, and ITSE) are presented in Table 13. To show the advantage of the proposed algorithm, the controller is further designed by comprehensive learning particle swarm optimization (CLPSO) and the controller gains are specified in Table 13. For details of CLPSO, the readers are referred to [33]. The comparative dynamic behavior after 1% SLP in area-1 at $t = 0\,s$ is depicted in Fig. 14. Typical transient specifications such as peak overshoot, undershoot and settling time are noted down from Fig. 14 and displayed in Table 13. The system performances of the proposed method are compared with CLPSO, internal model control (IMC) [5], and quasi-oppositional harmony search (QOHS) [5] techniques to judge its superiority. Critical observation of Fig. 14 and Table 13 reveals that the proposed BSA-tuned PID-controller improves system dynamics remarkably as compared to others as listed in Table 13.

Furthermore, to affirm the robustness of proposed method, a random load pattern is considered and applied to area-1 of test system-3. In this phase of analysis, a real-time random load perturbation is considered for simulation. The profile of continuous load perturbation is depicted in Fig. 15 (blue color, solid line). The dynamic behavior of the concerned power system after load perturbation is depicted in Fig. 15. To demonstrate the superiority of proposed method, the dynamic responses are compared with those of CLPSO and the comparative responses are displayed in Fig. 15. It may be inferred from Fig. 15 that the proposed BSA tuned PID-controller yields robust and stable performance under the said disturbed condition.

8. Conclusion

This article presents the usage of BSA as new optimization algorithm to solve LFC problem for an interconnected power system network and gives a broad analysis of its tuning performances with its robustness. Initially, two-area interconnected non-reheat power system is considered and parameters of PI/PID controller are optimized by the proposed algorithm. Standard time domain error criteria such as ITAE, ISE, IAE and ITSE are considered to minimize fitness function using proposed method. To reveal superiority of BSA, the performances of same are compared with other optimization techniques available in the literature for the similar test system with same controller structure and analysis shows good results in terms of fitness value, peak overshoot, settling time of frequency and tie-line power deviations. On the other hand, robustness of designed PI/PID controller is also proved by the applied method. Accordingly, the designed controller is not affected by the variation of loads and system parameters. Furthermore, the study is extended to test the effectiveness of proposed algorithm considering power system nonlinearities such as reheater, GDB, BD and GRC of steam turbine and analysis shows that proposed algorithm ensures satisfactory results in the presence of all nonlinearities. Furthermore, a four-area hydro-thermal power plant is included in the simulation study to show the novelty of the proposed technique and a comparative study is made to appraise the acceptability and efficacy of the proposed BSA technique. Finally, it is concluded that proposed controllers tuned by BSA may effectively be applied in practical nonlinear system.

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