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Heuristic based binary grasshopper optimization algorithm to solve unit commitment problem

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Abstract: The unit commitment problem in power system is a highly nonlinear, nonconvex, multiconstrained, complex, highly dimensional, mixed integer and combinatorial generation selection problem. The phenomenon of committing and decommitting represents a discrete problem that requires binary/discrete optimization techniques to tackle with unit commitment optimization problem. The key functions of the unit commitment optimization problem involve deciding which units to commit and then to decide their optimum power (economic dispatch). This paper confers a binary grasshopper optimization algorithm to solve the unit commitment optimization problem under multiple constraints. The grasshopper optimization algorithm is a metaheuristic, multiple solutions-based algorithm inspired by the natural swarming behavior of grasshopper towards food. For solving the binary unit commitment optimization problem, the real/continues value grasshopper optimization algorithm is mapped into binary/discrete search-space by using an S-shaped sigmoid function. The proposed algorithm is tested on IEEE benchmark systems of 4, 5, 6, 10, 20, 26, 40, 60, 80, and 100 generating units including the IEEE 118-bus system and the results are compared with different classical, heuristics, metaheuristics, quantum, and hybrid approaches. The results confer better performance of binary grasshopper optimization algorithm to solve the unit commitment optimization problem.

Key words: Heuristic, unit commitment, optimal scheduling, constraints handling, power operation, grasshopper optimization algorithm

1. Introduction

In a smart power system network, the increasing demand for energy is fulfilled by different conventional (hydro, thermal and nuclear) and nonconventional (solar, tidal and wind) energy resources. Also, the load demand curve is not constant but changes with time along different peaks. Thus, it is an essential requirement of the power system operation to optimally decide which unit (generator) to turn on (committed) and which unit to turn off (decommitted). This whole optimal decision-making process of on/off, committed/decommitted and selection/not selection of units under system, unit, network, security, environmental and cost constraints is termed as unit commitment optimization problem. Unit commitment (UC) is important to thermal power plants only, not for hydro and nuclear (base load) power plants. So due to boiler operational constraints, thermal units cannot be turned on immediately to fulfill the power demand. The proper generator selection is an essential feature to fulfill the load demand with ample reverse generating capacity in order to avoid malfunctions and failures under severe conditions. The earliest techniques to solve the UC optimization problem include classical, conventional, traditional and gradient-based optimizer such as dynamic programming (DP)

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[1], Lagrangian relaxation (LR), extended Lagrangian relaxation (ELR), dynamic programming Lagrangian relaxation [2], mixed-integer linear programming (MILP) [3], Priority list approach (PL) [4], branch and bound (BB).These techniques suffer from numerous iterations, local optima stagnation, premature convergence, larger execution time and parameter sensitivity. The heuristic and evolutionary techniques are based on mimicking natural phenomena. These natures inspired algorithms are also adopted to optimize the UC problem under different constraints. These heuristic techniques include genetic algorithm (GA) which is based on the principle of biological evolution and natural selection of genes for the survival of the fittest [5].

Ant colony optimization (ACO) [6] and particle swarm optimization (PSO) [7] mimics the social interaction, behavior, and coordination among the swarms. There is an extended list of nature inspired algorithms such as binary grey wolf optimization algorithm (BGWO) [8], ring crossover genetic algorithm (GA) [9], firefly algorithm (FF) [10], evolutionary algorithms (EA) [11] and improve binary cuckoo search (IBCS) [12] etc. to solve the UC optimization problem. Some hybrid approaches compromising of the benefits of both heuristic and classical techniques such as Lagrangian relaxation PSO [13] and Lagrangian relaxation GA [14] are developed to improve the solution quality of UC optimization problem. With low population size evolutionary quantum approaches improve the exploitation and exploration of the evolutionary techniques as compared to the others evolutionary techniques. Hybridization of two natured inspired algorithms such as PSO-GWO [15] is also investigated to UC optimization problem for better solution quality.

Recently Saremi et al. [22] proposed multisolutions based metaheuristic approach named as grasshopper optimization algorithm (GOA) which mimics swarming behavior of grasshopper in nature to solve the optimization problems. This is used to solve the multiple real value and binary optimization problems such as optimal reconfiguration for partial shaded photo voltaic array [16], frequency control of the load for interconnected multiarea micro grid power system by tuning the gains of fuzzy proportional integral derivative (fuzzy PID) controller through GOA [17], economic load dispatch (ED) with renewable energy (wind mill) integration [18], optimal selection of conductor for radial distribution system [19], optimal control of voltage and frequency for an islanded micro grid [20], feature selection problem and short term load forecasting specific to the region [21] etc. Inspired by the successful applications of GOA and BGOA (binary grasshopper optimization algorithm) to research and industrial problems, this paper proposes BGOA to solve the combinatorial generation selection problem with a better solution quality as compared to the traditional GOA.

The paper is organized as follows: Sections 2 and 3 explain UC formulation including constraints. The principles of grasshopper optimizer and binary grasshopper optimizer are described in Section 4. Section 5 describes the BGOA-UC approach. Section 6 presents the IEEE test systems, computational results, performance, statistical significance and parametric analysis. Conclusion and contributions are demonstrated in Section 7.

2. Unit commitment

The power system includes hydro thermal coordination, load forecasting, unit commitment, and economic dispatch. UC optimization problem is defined as the optimal turn off and turn on the schedule of a set of generators to obtain a minimum production cost for given power demand satisfying the physical and system operational constraints. Production cost consists of fuel cost, shut-down cost, and start-up cost. Constraints that must be handled are: (a) Total power of generated units should be equal to the power demand for the given hour, (b) In case of any shortfall of generated power, there should be a sufficient amount of spinning reserve, (c) Power for each generator should be within its minimum and maximum rating for a given hour, (d) Every generating unit must satisfy the minimum uptime and minimum downtime.

3. Problem formulation

The formulation of the UC binary minimization problem consists of a single objective function and multiple constraints. The main objective of the problem is to find out the optimal on/off schedule of the generating units to obtain minimum operating cost including fuel cost, shut-down cost and start-up cost subject to the power demand, generation limit, spinning reserve and minimum up and downtime constraints within a specific time period. Electricity generation cost is an essential index in the power sector. The highest contribution to the operational cost for the power plant consists of fuel costs. In order to minimize the tariff, the fuel cost should be minimized by allocating the optimal power to the given generators. All the thermal committed units include the cost in order to satisfy the minimum power limits and these on units are economically dispatched to minimize the overall cost of the fuel. The calculation of fuel cost is done on the basis of data given by the characteristics of generating units. Price of fuel, heat rates, initial status, turn-on and turn-off time are the characteristics, which are mathematically represented by a nonconvex and nonsmooth quadratic equation with power output and without losses using economic dispatch (ED) of the load as Equation (1).

$$F_i(P_{ih}) = a_i P_i^2 + b_i P_i + c_i, \tag{1}$$

where i is thermal unit index, $F_i =$fuel cost function, $P_i =$ power of unit i, $a_i, b_i, c_i =$fuel cost coefficients.

Start-up cost represents the cost to restart a decommitted unit depending on the committed and decommitted states of the unit. It varies with the temperature of the boiler as a hot start, cold start and warm start (banking). when going back to the committed state from the decommitted state, the start-up cost also depends on the decommitted hours of the unit. If decommitted hours of the unit are greater than or equal to the cold start-up hours after the minimum decommitted time, cold start-up cost is related to the committed event. However, if the decommitted hours of the unit are less than cold start-up hours, the hot start cost is related to the committed event. The mathematical equation for the start-up cost is given by the following equation.

$$SUC_{ih} = \begin{cases} HSC_i; & for\, MDT_i \leq MDT_i^{ON} \leq (MDT_i + CSH_i) \\ CSC_i; & for\, MDT_i^{ON} > (MDT_i + CSH_i), \end{cases} \tag{2}$$

where h is scheduling hour index, SUC_{ih} is start-up cost, CSH_i and CSC_i are hot start and cold start cost, MDT_i and MDT_i^{ON} are minimum down time and continuously on time, respectively.

In the proposed methodology to solve the UC optimization problem shut-down cost is neglected, which is often given as a constant value for the decommitted status of the corresponding unit. The total cost of fuel (TC) for the specific interval h and on/off status of the unit i unit U_{ih} include shut-down cost, start-up cost and fuel cost is given by Equation (3).

$$TC = \sum_{h=1}^{H} \sum_{i=1}^{N} F_i(P_{ih}) * U_{ih} + SUC_{ih}(1 - U_{i(h-1)}) * U_{ih}, \tag{3}$$

where N and H are total number of units and scheduling hours, respectively.

3.1. Constraints

The maximum power of each generator is limited due to the corresponding thermal consideration and cannot produce power more than its rated value. The minimum power of each unit is limited due to the stability issue of the machine. For an optimal operation of the given system, if the generated power of the unit is less than its rated value P_{min} then this unit cannot be put on the related bus bar. Thus actual generated power of each unit should satisfy the generation limit as by Equation (4).

$$P_{imin} < P_i < P_{imax}, \tag{4}$$

where P_{imin} and P_{imax} are minimum and maximum generation limits, respectively. Power balance or load balance constraint satisfaction requires the sum of generated power of all the committing units at specific hour h should be greater than or equal to the power demand at that specific hour h.

$$\sum_{i=1}^{N} P_{ih} U_{ih} \geq P_d, \tag{5}$$

where P_d is the system load. Spinning reserve SR_t requirement is implemented to satisfy the adequate online capacity of a generation which is needed in case of running unit failure or sudden increase of the load demand. This generated adequate power capacity is termed as spinning reserve and mathematically represented by the following equation:

$$\sum_{i=1}^{N} P_{ih} U_{ih} \geq P_d + SR_t. \tag{6}$$

The switching states i.e. committed and decommitted for the thermal generating units in the total time range are constrained by considering the operating features of the generating units. Due to the boiler operating characteristics, there must be a predefined time horizon between committed and decommitted state. A generating unit must remain committed for this specific time horizon when it is ON termed as a minimum uptime.

$$T_{(i,h)}^{ON} \geq MUT_i \tag{7}$$

A generating unit must remain decommitted (OFF) for the specific time horizon when it is OFF termed as a minimum downtime.

$$T_{(i,h)}^{OFF} \geq MDT_i, \tag{8}$$

where $T_{(i,h)}^{ON}$ and $T_{(i,h)}^{OFF}$ are continuously on and off time for unit i, respectively. MUT_i is the minimum up time.

At the start of organizing the time horizon UC optimization problem parameters like uptime and downtime constraint, start-up cost, etc. are affected by the committed and decommitted status of the generating thermal units. Thus initial status for every operating unit must take the previous day's prior scheduling time horizon into account in order to satisfy the minimum uptime and downtime.

4. Grasshopper optimizer (GO)

4.1. Overview of GO

Grasshoppers are basically insects. Due to their severe damaging effect on agriculture and crop production, they are often considered a pest. Their life cycle consists of three stages as egg, nymph, and adult. There is no caterpillar stage in their two-month whole life cycle due to incomplete metamorphosis. The nymph stage is different from adults due to smaller size, no wings, and no reproductive organs. They join to make the largest swarm in nature as compared to other creatures. The swarming size of grasshoppers may be as large as the continental scale. Nymph and adult both show the swarming behavior is the interesting aspect of their swarm in nature. Billions of Nymph move just like spinning cylinders and jump with a short distance. In their way, they eat all agriculture and crop production.

Grasshoppers in their adult form make a huge swarm to travel a long distance. In the nymph phase, small steps and slow movement is the main feature of the swarming behavior (exploitation). In contrast, in the adult phase abrupt and long range movement is the main property of the swarming behavior (exploration). For nature-inspired optimization algorithms; the searching process consists of two steps: exploitation and exploration. Grasshoppers performed these two steps and target seeking naturally. Their natural behavior to tackle optimization problems is mathematically modeled by Saremi et al. [22]. He proposed a model in order to simulate the attraction (exploitation) and repulsion (exploration) forces among the grasshoppers. Exploitation takes place during the attraction forces towards a local solution while repulsion forces cause to explore the search space to a global optimum. In order to make a balance between exploitation and exploration, grasshopper optimizer (GO) is provided with an adaptive coefficient to change the comfort zone for the grasshoppers.

4.2. Continues values grasshopper optimization (GOA)

The continuous-valued mathematical model of the swarming behavior of the grasshoppers in nature to simulate the social interaction forces is given by Equation 9.

$$X_k = r_1 S_k + r_2 G_k + r_3 A_k, \tag{9}$$

where k is the grasshopper index X_k is the position, S_k is the force of social interaction (attraction or repulsion), G_k is the force of gravity and A_k is the wind propagation of grasshopper k, r_1, r_2 and r_3 are random numbers between [0, 1] where the strength of social forces is given by the function S_k.

$$S_k = \sum_{l}^{N_{gs}} S_f(d_{kl})(\hat{d}_{kl}) \tag{10}$$

d_{kl} is the distance between grasshopper l and k which is calculated as $d_{kl} = |X_l - X_k|$, N_{gs} is the total number of the grasshoppers (search agents) and $\hat{d}_{kl}$ is the unit vector between grasshopper l and k.

$$\hat{d}_{kl} = \frac{X_l - X_k}{d_{kl}} \tag{11}$$

Social forces are defined by S_f function, calculated by Equation (12).

$$S_f = f e^{\frac{r}{l}} - e^{-r} \tag{12}$$

f is the intensity of attraction=0.5, l is the length scale of attraction=1.5, f and l change the social behavior (force of repulsion and attraction) of the grasshoppers to a large extent. Comfort zone, repulsion region and attraction region of the grasshoppers are significantly changed by f and l. G_k is calculated by the following equation.

$$G_k = -g\hat{e}_g, \tag{13}$$

where g represents the gravitational constant and $\hat{e}_g$ indicates a unity vector towards the center of the earth. The A_k component of the Equation (7) is calculated by the following equation.

$$A_k = \mu \hat{e}_k \tag{14}$$

Where μ represents drift/flow constant and $\hat{e}_k$ is the unit vector towards the wind flow direction. Substituting the value of S_k, G_k and A_k in Equation (9), Equation (15) is obtained.

$$X_k = \sum_{l}^{N_{gs}} S_f(X_l - X_k) * \frac{X_l - X_k}{d_{kl}} - g\hat{e}_g + \mu \hat{e}_k \tag{15}$$

The above equation is used to simulate the interaction between grasshoppers in the swarm. However, the above model cannot be used directly to simulation purposes due to improper convergence. So the modified equation used for optimization is (16).

$$X_k^d = \alpha_1 \left[\sum_{j=l}^{N_{gs}} \alpha_2 \frac{u_b - l_b}{2} * S_f(|X_l^d - X_k^d|) * \frac{X_l - X_k}{d_{kl}} \right] * \hat{T}_d \tag{16}$$

Where u_b represents upper bound, l_b is the lower bound, $\hat{T}_d$represents the best solution obtained so far α_1 is just like an inertial weight in particle swarm optimization (PSO) in order to make a balance between exploitation and exploration around the optimum target and α_2 causes to decrease the comfort zone, repulsion zone, and attraction zone. It reduces the comfort zone with proportional to iterations as below equation.

$$\alpha = \alpha_{max} - 1 \frac{\alpha_{max} - \alpha_{min}}{L}, \tag{17}$$

where L is maximum number of iterations, α_{max} and α_{min} are set as 1 and 0.00001, respectively.

4.3. Binary values GO (BGOA)

UC is a binary problem consisting of 1 and 0 states at each interval of time and iteration. Therefore, in order to optimize this problem real value to binary value mapping has to be done. In this BGOA the position vector of search agents/grasshopper, search space and food location is mapped into the binary value by an s-shaped sigmoid function. Due to easy computation and the ability to differentiate across the entire domain, the sigmoid function is quite useful for binary conversion. A simple s-shaped sigmoid function is given by:

$$T(\Delta X_t) = \frac{1}{1 + e^{-X_t}} \tag{18}$$

ΔX_t is velocity of a grasshopper for a specific iteration. The position of each search agent will be updated according to Equation (19) depending on the probability value of ΔX_t.

$$X_{k+1}^d = \begin{cases} 1 & if\, r_1 < T(X_{k+1}^d) \\ 0 & if\, r_1 \geq T(X_{k+1}^d) \end{cases}, \tag{19}$$

where X_{k+1}^d is the d^{kh} dimension of the search agent in the next iteration and r_1 is a random number [0, 1].

5. BGOA implementation to UC optimization problem

In this paper, the BGOA is used to obtain optimal feasible commitment scheduling of thermal units. The power allocation among the committed thermal units through economic dispatch (ED) is observed using the quadratic programming technique. The generalized form for the UC optimization problem is shown by a flow chart in Figure 1.

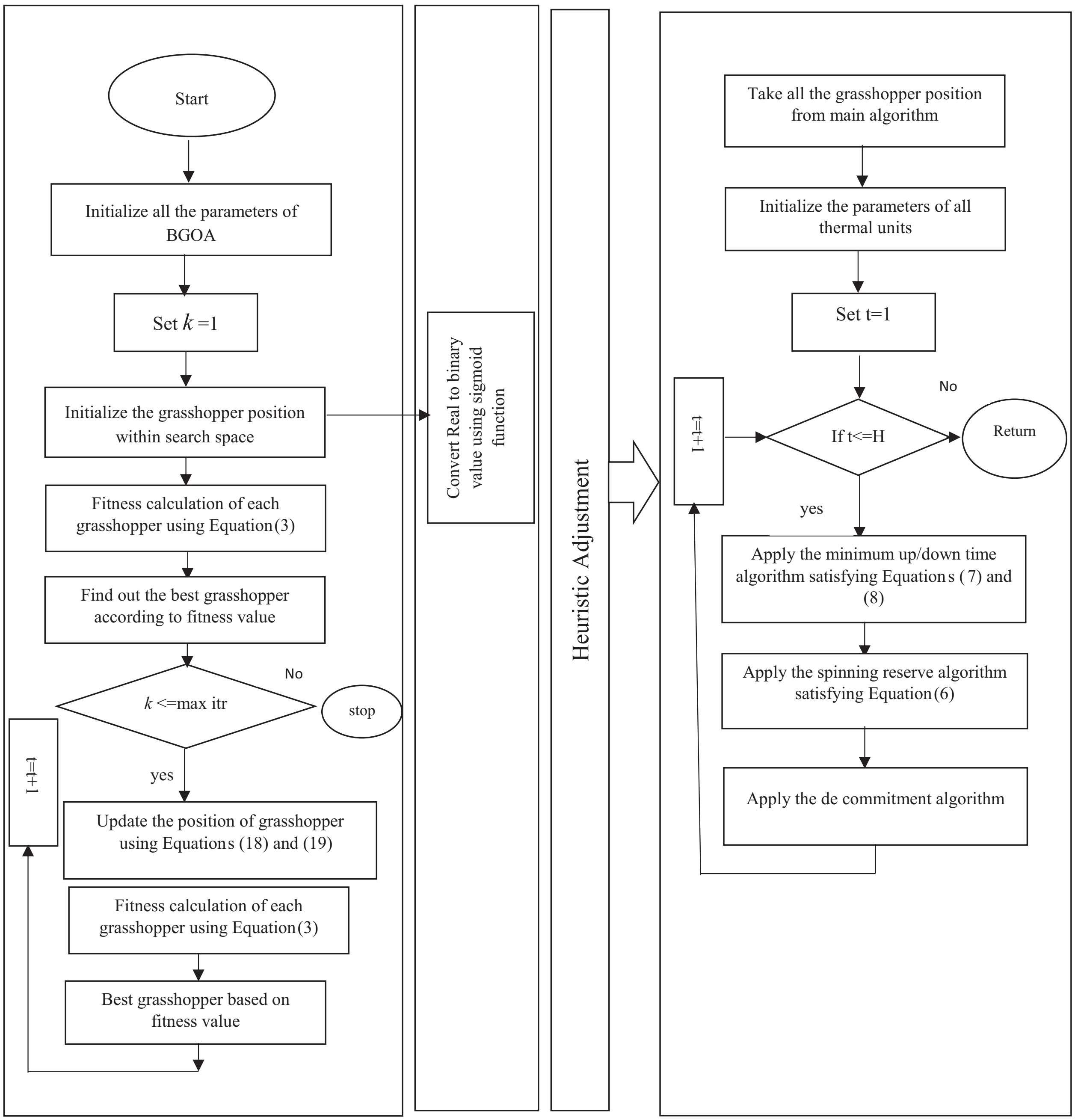


Figure 1. Flow chart of UC optimization problem by BGOA.

A search agent represents a commitment schedule of a unit within a given time horizon. Mathematically it is described in the form of integer matrix U with $N * H$ matrix, where u_i^t represents on/off status of ith unit at a time interval of t. A random set of search agents is formed in this initial process. The element u_i^t is generated either 1 or 0 by a random function.

$$U = \begin{bmatrix} u_1^1 & u_1^2 & u_1^3 & & u_1^H \\ u_2^1 & u_2^2 & u_2^3 & & u_2^H \\ u_3^1 & u_3^2 & u_3^3 & & u_3^H \\ & & . & . & \\ & & . & . & \\ u_N^1 & u_N^2 & u_N^3 & & u_N^H \end{bmatrix} \tag{20}$$

The priority list for the UC optimization problem is based on fuel cost acquired from full-load average production cost. The unit having the lowest cost value will be at the highest priority. This unit scheduling may not be satisfied with the minimum up and minimum downtime constraints. In order to determine the violation of these constraints, on and off times of the given units should be computed by Equation (21). In order to repair these types of constraints, heuristic adjustment is used.

$$T_{i,on}^t = \begin{cases} T_{i,on}^{t-1} + 1 & if\, u_i^t = 1 \\ 0 & if\, u_i^t = 0 \end{cases} \tag{21}$$

$$T_{i,off}^t = \begin{cases} T_{i,off}^{t-1} + 1 & if\, u_i^t = 1 \\ 0 & if\, u_i^t = 0 \end{cases}$$

The reliability of the system depends upon the spinning reserve and load demand satisfaction. For all the tested system spinning reserve is 10% and 5%. Modification of the search agents in order to repair the minimum up and downtime constraints may extend the spinning reserves of corresponding units. Power is allocated to each committed unit through economic dispatch using quadratic programming. The fitness of each search agent is calculated by Equation (3). After the fitness calculation, each search agent is sorted according to fitness values. BGOA is used to update the position of each search agent. Termination criteria are the number of iterations. Upon reaching the maximum number of iterations optimal scheduling of the units with optimal power allocation is obtained.

6. Numerical results, comparison, and discussion

The proposed BGOA is modeled to find the solution of UC optimization problem with IEEE benchmark systems of 4 [23], 5 [24], 6 [24], 10 [24], 20 [23], 26 [24],40 [23], 60 [23], 80 [23] and 100 [23] generating units including IEEE 118-bus system. Twenty-four-h time horizon is utilized for the 5 to 100-units while for 4-unit system 8-h time horizon is used. MATLAB R2016a software is used to implement unit commitment problem by grasshopper optimization with Intel(R) Core(TM) i3-4030 CPU @ 1.90 GHz processor. By observing the effect of changing population size on the total cost, 30 is chosen as the best population size. By observing optimality, the controlling parameters l, f and interval are set to 1.5, 0.5 and [0 2.079], respectively.

6.1. Performance of BGOA for small test systems

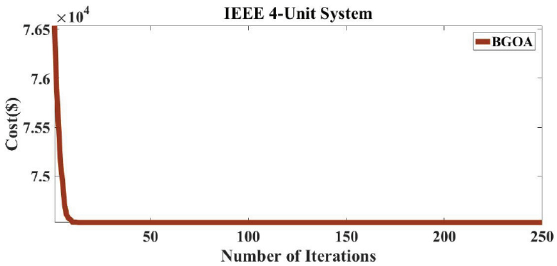
The small test system includes 4, 5, 6, and 10-unit systems. The best optimal solution for IEEE 4, 5, and 6-unit system for 8-h and 12-h is obtained using BGOA and its comparison with different approaches is analyzed. Table 1 shows the simulation results for the IEEE 10-unit system. Their convergence characteristics and cost variation with respect to different trials are shown in Figures 2 and 3, respectively.

Table 1. Unit commitment of IEEE 10-unit system by BGOA.

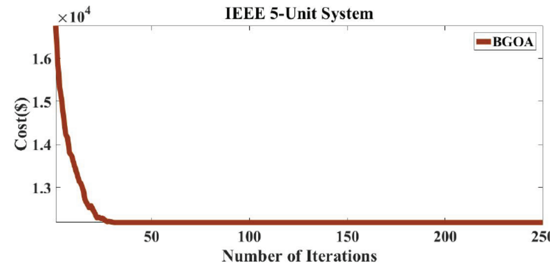
Hour	Unit 1-10			
	Commitment	Power allocation by DP	Fuel cost ($)	Startup cost ($)
1	1100000000	455 245 0 0 0 0 0 0 0 0	13683	0
2	1100000000	455 295 0 0 0 0 0 0 0 0	14554	0
3	1101000000	455 265 0 130 0 0 0 0 0 0	16892	560
4	1101000000	455 365 0 130 0 0 0 0 0 0	18638	0
5	1111000000	455 285 130 130 0 0 0 0 0 0	20133	550
6	1111100000	455 360 130 130 25 0 0 0 0 0	22387	900
7	1111100000	455 410 130 130 25 0 0 0 0 0	23262	0
8	1111100000	455 455 130 130 30 0 0 0 0 0	24150	0
9	1111110000	455 455 130 130 110 20 0 0 0 0	26589	340
10	1111111100	455 455 130 130 162 33 25 10 0 0	30058	580
11	1111111110	455 455 130 130 162 73 25 10 10 0	31916	60
12	1111111111	455 455 130 130 162 80 25 43 10 10	33890	60
13	1111111100	455 455 130 130 162 33 25 10 0 0	30058	0
14	1111110000	455 455 130 130 110 20 0 0 0 0	26589	0
15	1111100000	455 455 130 130 30 0 0 0 0 0	24150	0
16	1111100000	455 310 130 130 25 0 0 0 0 0	21514	0
17	1111100000	455 260 130 130 25 0 0 0 0 0	20642	0
18	1111100000	455 360 130 130 25 0 0 0 0 0	22387	0
19	1111100000	455 455 130 130 30 0 0 0 0 0	24150	0
20	1111111100	455 455 130 130 162 33 25 10 0 0	30058	750
21	1111111000	455 455 130 130 85 20 25 0 0 0	27251	0
22	1111011000	455 340 130 130 0 20 25 0 0 0	23085	0
23	1101000000	455 315 0 130 0 0 0 0 0 0	17764	0
24	1100000000	455 345 0 0 0 0 0 0 0 0	15427	0
Total cost ($) = 559226.576292 + 3800.00= 563026.576292 Elapsed time 30.73 s				

6.2. Performance of BGOA for medium test systems

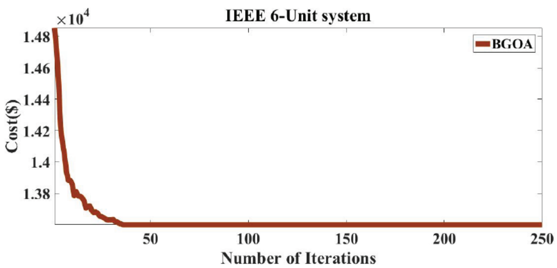
The unit systems (20, 26, 40, and 60) are simulated and the results of 40 and 60-unit systems are shown in the Tables 2 and 3, respectively. The simulation results show feasible commitment and optimal power allocation as well. The comparison for different approaches is also observed for IEEE 20, 26, 40, and 60-unit system. The results obtained and their comparison shows the best quality of the purposed algorithm to tackle with the binary optimization problem.



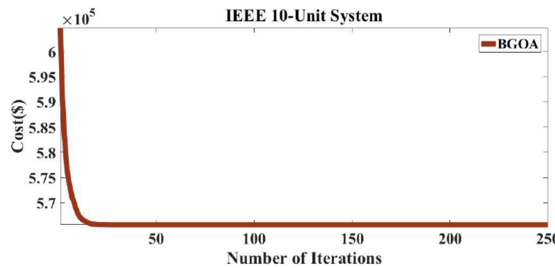
(a) Convergence curve of IEEE 4-unit system.



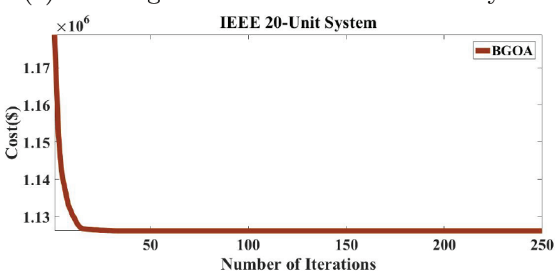
(b) Convergence curve of IEEE 5 -unit system.



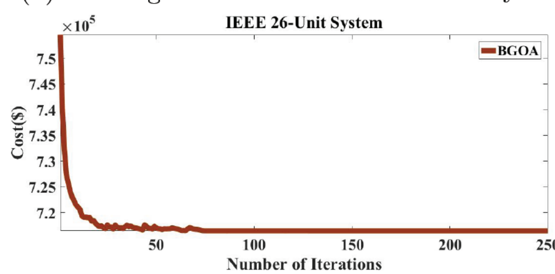
(c) Convergence curve of IEEE 6 -unit system.



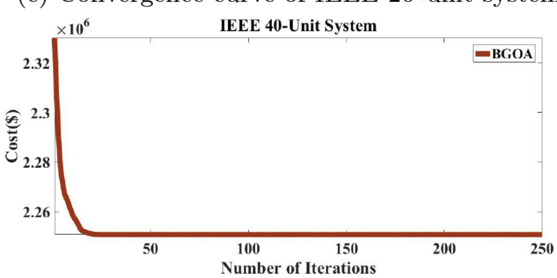
(d) Convergence curve of IEEE 10 -unit system.



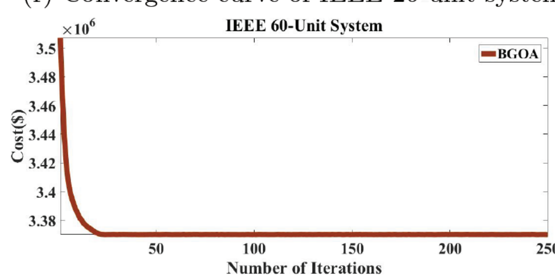
(e) Convergence curve of IEEE 20 -unit system.



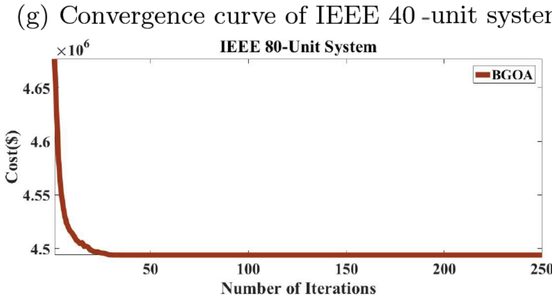
(f) Convergence curve of IEEE 26-unit system.



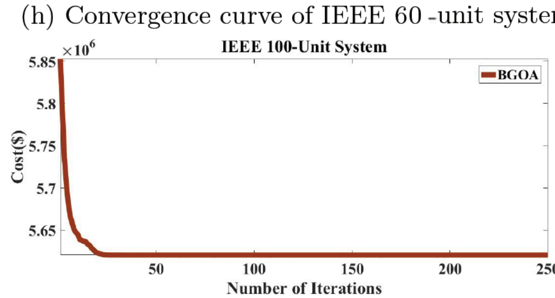
(g) Convergence curve of IEEE 40 -unit system.



(h) Convergence curve of IEEE 60 -unit system.



(i) Convergence curve of IEEE 80 -unit system.



(j) Convergence curve of IEEE 100 -unit system.

Figure 2. Convergence curves of IEEE unit systems.

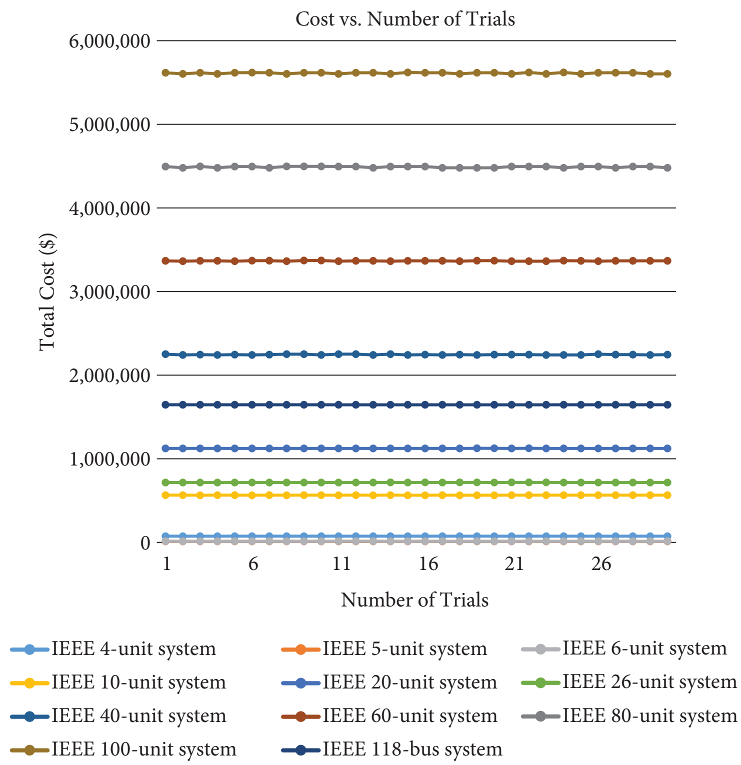


Figure 3. Variations of total cost of different units with different trials.

Table 2. Unit commitment of IEEE 40 unit systems by BGOA.

Hour	Unit commitment of 1-40 units by BGOA	Fuel cost ($)	Startup cost ($)
1	1100000000110000000011000000001000000000	53787	0
2	1100000000110000000011000000001100000000	58218	5000
3	1101000000110000000011000000001100000000	65794	560
4	1101000000110100000011010000001101000000	74551	1680
5	1111000000111100000011010000001101000000	79285	1100
6	1111100000111110000011111000001111100000	88025	2000
7	1111100000111111000011111000001111100000	92034	900
8	1111100000111111000011111100001111110000	96601	1800
9	1111110000111111000011111100001111110000	1.0636e+05	1360
10	1111111001111111100111111100011111111000	1.1885e+05	2200
11	1111111101111111110111111110011111111100	1.2626e+05	240
12	1111111111111111111111111111101111111110	1.3419e+05	240
13	1111111100111111110011111110001111111000	1.1885e+05	0
14	1111110000111111000011111100001111110000	1.0636e+05	0
15	1111100000111111000001111110000011111100000	96601	0
16	1111100000111111000001111110000011111100000	86055	0
17	1111100000111111000001111110000011111100000	82567	0
18	1111100000111111000001111110000011111100000	89548	0
19	1111100000111111000001111110000011111100000	96601	0
20	1111111001111111100111111100011111111000	1.1885e+05	2880
21	1111011000111111100011111110001111111000	1.0859e+05	0
22	1101011000110111100011010110001100011000	90342	0
23	1101000000110010000011000000001100000000	69801	0
24	1100000000110010000011000000001100000000	62218	0
Total cost ($) = 2220317.766613 + 19960.00 = 2240277.7666 Elapsed time 116.925396 s			

Table 3. Unit commitment of IEEE 60 unit systems by BGOA.

Hour	Unit commitment of 1-60 units by BGOA	Fuel cost ($)	Startup cost ($)
1	110000000011000000001100000000110000000011000000001000000000	81151	0
2	110000000011000000001100000000110000000011000000001000000000	86389	0
3	110100000011000000001100000000110000000011000000001100000000	98397	5560
4	110100000011010000001101000000110100000011010000001101000000	1.1183e+05	2800
5	111100000011110000001111000000110100000011010000001101000000	1.1893e+05	1650
6	111110000011111000001111100000111110000011111000001111000000	1.3178e+05	2550
7	111110000011111000001111100000111100000011110000001111000000	1.3805e+05	1800
8	111110000011111000001111100000111100000011110100001111110000	1.4485e+05	1580
9	111111000011111100001111110000111111000011111100101111110000	1.6027e+05	3220
10	111111110011111111001111111100111111100011111110001111111000	1.7827e+05	3300
11	111111111011111111101111111110111111110011111111001111111100	1.8938e+05	360
12	111111111111111111111111111111111111111011111111101111111110	2.0129e+05	360
13	111111110011111111001111111100111111100011111110001111111000	1.7827e+05	0
14	111111000011111100001111110000111111000011111100001111110000	1.5953e+05	0
15	111110000011111000001111100000111110000011111000001111100000	1.449e+05	0
16	111110000011111000001111100000111110000011111000001111100000	1.2908e+05	0
17	111110000011111000001111100000111110000011111000001111100000	1.2385e+05	0
18	111110000011111000001111100000111110000011111000001111100000	1.3432e+05	0
19	111110000011111000001111100000111110000011111000001111100000	1.449e+05	0
20	111111110011111111001111111100111111100011111110001111111000	1.7827e+05	4320
21	111111100011111110001111111000111011000111101100011011110000	1.6251e+05	0
22	110111100011011110001100011000110001100011010110001100011000	1.3569e+05	0
23	110010000011001000001100000000110000000011000100001100000000	1.0455e+05	0
24	110010000011000000001100000000110000000011000100001000000000	92614	0
Total cost ($) = 3329074.112433 + 27500.00 = 3356574.112433 Elapsed time 201.706896 s			

6.3. Performance of BGOA for large test systems

For the 80-unit system, the optimal cost and convergence quality results show as the number of units increasing the ability of BGOA to obtain the best optimal solution enhances as shown in the Table 4. Table 5 and Table 6 show the comparison of proposed method with different algorithms for the IEEE unit systems with respect to cost ($) and time elapsed (s) respectively. Cost reduction ability of BGOA is most effective and reliable as shown in the table 7 for IEEE 100-unit system. In order to observe the proposed algorithm IEEE 118-bus system is also observed with better results as compared to other techniques. Fast and the best convergence curves are obtained for each IEEE unit system due to better tradeoff between the exploitation and exploration quality of the proposed BGOA by controlling parameters as shown in the Figure 2. The improved convergence characteristics show the better reliability and fitness of the solution as compared to the others algorithms. Total cost obtained and execution time by the proposed methodology is drastically less than many other algorithms found in the literature. The ability of BGOA approach to reduce total cost with less execution time goes on increasing from small to large IEEE unit system, which makes this approach to have robustness in finding results, most efficient searching ability and real-time practical based UC problem solving ability.

Table 4. Unit commitment of IEEE 80 unit systems by BGOA.

Hour	Unit commitment of 1-80 units by BGOA	Fuel cost ($)	Startup cost ($)
1	11000000001100000000110000000011000000001100000000110000000010000000001000000000	1.0757e+05	0
2	11000000001100000000110000000011000000001100000000110000000011000000001000000000	1.155e+05	5000
3	11000000001100000000110000000011000000001100000000110000000011000000001101000000	1.31e+05	5560
4	11010000001101000000110100000011010000001101000000110100000011010000001101000000	1.491e+05	3920
5	11110000001111000000111100000011010000001101000000110100000011010000001101000000	1.5795e+05	1650
6	11111000001111100000111100000011110000001111000000111100000011110000001101000000	1.7543e+05	4000
7	11111000001111100000111110000011110000001111000000111100000011100000001111100000	1.8407e+05	2350
8	11111000001111100000111110000011111000001111100000111110000011100000001111100000	1.9276e+05	2700
9	11111100001111110000111111000011111100001111110000111111000011111100001111110000	2.1271e+05	3620
10	11111111001111111100111111110011111111001111111000111111100011111110001111111000	2.3769e+05	4400
11	11111111101111111110111111111011111111101111111100111111110011111111001111111100	2.5251e+05	480
12	11111111111111111111111111111111111111111111111110111111111011111111101111111110	2.677e+05	420
13	11111111001111111100111111110011111111001111111000111111100011111110001111111000	2.3769e+05	0
14	11111100001111110000111111000011111100001111110000111111000011111100001111110000	2.1271e+05	0
15	11111000001111100000111110000011111000001011000000111110000011111000001111100000	1.9333e+05	0
16	11111000001111100000111110000011111000001011000000111110000011111000001111100000	1.7149e+05	0
17	11111000001111100000111110000011111000001011000000111110000011111000001111100000	1.6451e+05	0
18	11111000001111100000111110000011111000001011000000111110000011111000001111100000	1.7848e+05	0
19	11111000001111100000111110000011111000001011000000111110000011111000001111100000	1.9291e+05	0
20	11111111001111111100111111110011111111001111111000111111100011111110001111111000	2.3769e+05	6310
21	11111110001111111000111111100011110110001111011000111111100011110110001111011000	2.1649e+05	0
22	11010110001101011000110101100011010110001111011000110111100011000110001100011000	1.8056e+05	0
23	11010000001100000000110000000011000000001110000000110010100011000000001100010000	1.4033e+05	0
24	11000000001100000000110000000011000000001110000000110010100011000000001000010000	1.2482e+05	0
Total cost ($) = 4434997.754713 + 40410.00 = 4475407.754713 Elapsed time 246.984534 s			

Table 5. Comparison of unit commitment best cost ($) of IEEE test systems.

Method	Best cost ($) of IEEE unit systems									
	4-unit	5-unit	6-unit	10-unit	20-unit	26-unit	40-unit	60-unit	80-unit	100-unit
A.SMP [25]	74812	nr	nr	563937.26	1124490	nr	nr	nr	nr	nr
LRPSO [26]	74808	nr	nr	566297	1128281	nr	2252330	3377718	4499347	5623607
GA [27]	74675	nr	nr	565825	1126243	nr	2251911	3376625	4504933	5627437
BWOA [23]	74644.07	nr	nr	565771	1126625	nr	2235113	nr	4490172	5614038
ILR [28]	75231	nr	nr	563977	1123297	nr	2244237	3363491	4485633	5605678
BDE [29]	nr	nr	nr	563997	112399	nr	2245700	3367066	4489022	5609341
PSO-GWO [15]	nr	12281	13600	565210	nr	nr	nr	nr	nr	nr
iDA-PSO [24]	nr	11830	13292.28	565807	nr	741587.7	nr	nr	4498479	5623885
EP [30]	nr	Nr	nr	564551	1126494	nr	2249093	3371611	4526022	5657277
BPSO [31]	nr	nr	nr	563977	1128192	nr	2243210	nr	4498943	5630838
SDP [32]	nr	nr	nr	563777	1122622	nr	2242178	3363491	4485633	5605189
IBPSO [33]	nr	nr	nr	563977	1125216	nr	2248581	3367865	4491083	5610293
ESA [34]	nr	nr	nr	565828	1126254	nr	2250063	nr	4489022	5,609,341
BFWA [35]	nr	nr	nr	563977	1124858	nr	2248228	3367445	4491284	5610954
BGWO1 [8]	73933.1	nr	nr	563976.64	1125546	nr	2252475	3368934	4483381	5604146
BGWO2 [8]	73933.1	nr	nr	563937.31	1123297	nr	2244701	3362515	4498479	5623885
BGOA (proposed)	74370.32	11648.49	12945	563026	1120470	709354	2240277	3356574	4475407	5596414
Parameters	Number of iterations = 30, number of populations = 30, intensity of attraction f = 1.5, attractive length scale l= 0.5, repulsion interval = [0 2.079].									

Table 6. Comparison of elapsed time for IEEE test system.

Method	Elapsed time (s) of IEEE unit systems									
	4-unit	5-unit	6-unit	10-unit	20-unit	26-unit	40-unit	60-unit	80-unit	100-unit
A.SMP [25]	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
LRPSO [26]	nr	nr	nr	45	96	nr	218	384	595	856
GA [27]	nr	nr	nr	221	733	nr	2697	5840	10036	15733
BWOA [23]	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
ILR [28]	nr	nr	nr	4.0	16	nr	52	113	209	345
BDE [29]	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
PSO-GWO [15]	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
iDA-PSO [24]	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
EP [30]	nr	nr	nr	100	340	nr	1176	2267	3584	6120
BPSO [31]	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
SDP [32]	nr	nr	nr	25.41	63.94	nr	157.73	260.76	353.84	392.56
IBPSO [33]	nr	nr	nr	27	55	nr	110	172	235	295
ESA [34]	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
BFWA [35]	nr	nr	nr	65.42	106.03	nr	238.02	422.29	676.53	1043.47
BGWO1 [8]	nr	nr	nr	64.19	80.47	nr	169.24	281.2	473.4	836.5
BGWO2 [8]	nr	nr	nr	66.15	87.533	nr	153.5	268.2	469.6	822.23
BGOA	9.98	17.22	20.32	30.73	57.55	86.43	116.93	201.70	246.98	337.04

Table 7. Unit commitment of IEEE 100 unit systems by BGOA.

Hour	Unit commitment of 1-100 units by BGOA	Fuel cost ($)
1	1100000000110000000011000000001100000000110000000011000000001100000000100000000010000000001000000000	1.34e+05
2	1100000000110000000011000000001100000000110000000011000000001100000000110000000010000000001000000000	1.4367e+05
3	1101000000110000000011000000001100000000110000000011000000001100000000110000000011000000001100000000	1.636e+05
4	1101000000110000000011110000001101000000110100000011010000001101000000110100000011010000001101000000	1.8641e+05
5	1111000000111100000011110000001111000000110100000011010000001101000000110100000011010000001101000000	1.9759e+05
6	1111100000111110000011110000001111000000111100000011110000001111000000111100000011110000001111000000	2.1981e+05
7	1111100000111110000011111000001111100000111110000011110000001111000000111100000011110000001111000000	2.3008e+05
8	1111100000111110000011111000001111100000111110000011111000001111100000111110000011110000001111000000	2.4103e+05
9	1111110000111111000011111100001111110000111111000011111100001111110000111111000011111100001111110000	2.6589e+05
10	1111111100111111110011111111001111111100111111100011111110001111111000111111100011111110001111111000	2.9642e+05
11	1111111110111111111011111111101111111110111111110011111111001111111100111111110011111111001111111100	3.1493e+05
12	1111111111111111111111111111111111111111111111111011111111101111111110111111111011111111101111111110	3.3479e+05
13	1111111100111111110011111111001111111100111111100011111110001111111000111111100011111110001111111000	2.9642e+05
14	1111110000111111000011111100001111110000111111000011111100001111110000111111000011111100001111110000	2.6589e+05
15	1111100000111110000011111000001111100000111110000011111000001111100000111110000011111000001111100000	2.4192e+05
16	1111100000111110000011111000001111100000111110000011111000001111100000111110000011111000001111100000	2.1561e+05
17	1111100000111110000011111000001111100000111110000011111000001111100000111110000011111000001111100000	2.0689e+05
18	1111100000111110000011111000001111100000111110000011111000001111100000111110000011111000001111100000	2.2434e+05
19	1111100000111110000011111000001111100000111110000011111000001111100000111110000011111000001111100000	2.4192e+05
20	1111111100111111110011111111001111111100111111100011111110001111111000111111100011111110001111111000	2.9642e+05
21	1111111000111111100011111110001111011000111101100011111110001111011000111101100011111110001111011000	2.7061e+05
22	1101011000110101100011011110001101011000110101100011011110001101011000110101100011000010001100011000	2.2541e+05
23	1101001000110001000011001100001100010000110000000011001000001100000000110000000011000000001100000000	1.7551e+05
24	1100001000110001000011001100001100000000110000000011001000001100000000110000000010000000001000000000	1.5511e+05
Total cost ($) = 5544304.094150 + 52110.00 = 5596414.094150 Elapsed time 337.043674 s		

7. Conclusion

This study presents binary grasshopper optimization algorithm models to obtain an optimal solution of UC optimization problem. The objective function of the UC optimization problem is formulated as the cost function under the load balance, generation limit, spinning reserve (10% and 5%), minimum up time & minimum down time and de commitment constraints. Sigmoid function is used for binary mapping. The simulation results of the small, medium and large unit systems show the superiority and searching efficiency of the proposed algorithm as compared to the other modern techniques. This approach can also be used to tackle profit based unit commitment and multiobjective such as reliability maximization, emission reduction and many other constraints optimization problem. The proposed algorithm also has ability to better results of UC optimization problem with the integration of renewable energy resources, security, ramp rate and many other constraints.

References

[1] Su CC, Hsu YY. Fuzzy dynamic programming: an application to unit commitment. IEEE Transactions on Power Systems 1991; 6 (3): 1231-1237.

[2] Ongsakul W, Petcharaks N. Unit commitment by enhanced adaptive Lagrangian relaxation. IEEE Transactions on Power Systems 2004; 19 (1): 620-628.

[3] Venkatesh B, Jamtsho T, Gooi HB. Unit commitment–a fuzzy mixed integer linear programming solution. IET Generation, Transmission & Distribution 2007; 1 (5): 836-846.

[4] Senjyu T, Shimabukuro K, Uezato K, Funabashi T. A fast technique for unit commitment problem by extended priority list. IEEE Transactions on Power Systems 2003 ; 18 (2): 882-888.

[5] Kazarlis SA, Bakirtzis AG, Petridis V. A genetic algorithm solution to the unit commitment problem. IEEE Transactions on Power Systems 1996; 11 (1): 83-92.

[6] Vaisakh K, Srinivas LR. Evolving ant colony optimization based unit commitment. Applied Soft Computing 2011; 11 (2): 2863-2870.

[7] Saber AY, Senjyu T, Yona A, Funabashi T. Unit commitment computation by fuzzy adaptive particle swarm optimisation. IET Generation, Transmission & Distribution 2007; 1 (3): 456-465.

[8] Panwar LK, Reddy S, Verma A, Panigrahi BK, Kumar R. Binary grey wolf optimizer for large scale unit commitment problem. Swarm and Evolutionary Computation 2018; 38: 251-266.

[9] Bukhari SB, Ahmad A, Raza SA, Siddique MN. A ring crossover genetic algorithm for the unit commitment problem. Turkish Journal of Electrical Engineering & Computer Sciences 2016; 24 (5): 3862-3876.

[10] Koodalsamy B, Veerayan MB, Koodalsamy C, Simon SP. Firefly algorithm with multiple workers for the power system unit commitment problem. Turkish Journal of Electrical Engineering & Computer Sciences 2016; 24 (6): 4773-4789.

[11] Uyar AŞ, Türkay B. Evolutionary algorithms for the unit commitment problem. Turkish Journal of Electrical Engineering & Computer Sciences 2008; 16 (3): 239-255.

[12] Zhao J, Liu S, Zhou M, Guo X, Qi L. An improved binary cuckoo search algorithm for solving unit commitment problems: methodological description. IEEE Access 2018; 6: 43535-43545.

[13] Balci HH, Valenzuela JF. Scheduling electric power generators using particle swarm optimization combined with the Lagrangian relaxation method. International Journal of Applied Mathematics and Computer Science 2004; 14: 411-421.

[14] Cheng CP, Liu CW, Liu CC. Unit commitment by Lagrangian relaxation and genetic algorithms. IEEE Transactions on Power Systems 2000; 15 (2):707-714.

[15] Kamboj VK. A novel hybrid PSO–GWO approach for unit commitment problem. Neural Computing and Applications 2016; 27 (6): 1643-1655.

[16] Fathy A. Recent meta-heuristic grasshopper optimization algorithm for optimal reconfiguration of partially shaded PV array. Solar Energy 2018; 171: 638-651.

[17] Lal DK, Barisal AK, Tripathy M. Load frequency control of multi area interconnected microgrid power system using grasshopper optimization algorithm optimized fuzzy PID controller. In: IEEE Recent Advances on Engineering, Technology and Computational Sciences (RAETCS); Allahabad, India; 2018. pp. 1-6.

[18] Hazra S, Pal T, Roy PK. Renewable energy based economic emission load dispatch using grasshopper optimization algorithm. International Journal of Swarm Intelligence Research (IJSIR) 2019; 10 (1): 38-57.

[19] Ismael SM, Aleem SH, Abdelaziz AY, Zobaa AF. Optimal conductor selection of radial distribution feeders: an overview and new application using grasshopper optimization algorithm. In: Zobaa AF, Aleem SH, Abdelaziz AY (editors). Classical and Recent Aspects of Power System Optimization. Cambridge, MA, USA: Academic Press, 2018, pp. 185-217.

[20] Jumani TA, Mustafa MW, Md Rasid M, Mirjat NH, Leghari ZH et al. Optimal voltage and frequency control of an islanded microgrid using grasshopper optimization algorithm. Energies 2018; 11 (11): 3191.

[21] Barman M, Choudhury ND, Sutradhar S. A regional hybrid GOA-SVM model based on similar day approach for short-term load forecasting in Assam, India. Energy 2018; 145: 710-720.

[22] Saremi S, Mirjalili S, Lewis A. Grasshopper optimisation algorithm: theory and application. Advances in Engineering Software 2017; 105: 30-47.

[23] Kumar V, Kumar D. Binary whale optimization algorithm and its application to unit commitment problem. Neural Computing and Applications 2020; 32 (7): 2095-2123.

[24] Khunkitti S, Watson NR, Chatthaworn R, Premrudeepreechacharn S, Siritaratiwat A. An improved DA-PSO optimization approach for unit commitment problem. Energies 2019; 12 (12): 2335.

[25] Khanmohammadi S, Amiri M, Haque MT. A new three-stage method for solving unit commitment problem. Energy 2010; 35 (7): 3072-3080.

[26] Balci HH, Valenzuela JF. Scheduling electric power generators using particle swarm optimization combined with the Lagrangian relaxation method. International Journal of Applied Mathematics and Computer Science 2004; 14: 411-421.

[27] Kazarlis SA, Bakirtzis AG, Petridis V. A genetic algorithm solution to the unit commitment problem. IEEE Transactions on Power Systems 1996; 11 (1): 83-92.

[28] Ongsakul W, Petcharaks N. Unit commitment by enhanced adaptive Lagrangian relaxation. IEEE Transactions on Power Systems 2004; 19 (1):620-628.

[29] Jeong YW, Lee WN, Kim HH, Park JB, Shin JR. Thermal unit commitment using binary differential evolution. Journal of Electrical Engineering & Technology 2009; 4 (3): 323-329.

[30] Juste KA, Kita H, Tanaka E, Hasegawa J. An evolutionary programming solution to the unit commitment problem. IEEE Transactions on Power Systems 1999; 14 (4): 1452-1459.

[31] Jeong YW, Park JB, Jang SH, Lee KY. A new quantum-inspired binary PSO for thermal unit commitment problems. In: 15th IEEE International Conference on Intelligent System Applications to Power Systems; Curitiba, Brazil; 2009. pp. 1-6.

[32] Jabr RA. Rank-constrained semidefinite program for unit commitment. International Journal of Electrical Power & Energy Systems 2013; 47: 13-20.

[33] Yuan X, Nie H, Su A, Wang L, Yuan Y. An improved binary particle swarm optimization for unit commitment problem. Expert Systems with applications 2009; 36 (4): 8049-8055.

[34] Simopoulos DN, Kavatza SD, Vournas CD. Unit commitment by an enhanced simulated annealing algorithm. IEEE Transactions on Power Systems 2006; 21 (1): 68-76.

[35] Panwar LK, Reddy S, Kumar R. Binary fireworks algorithm based thermal unit commitment. International Journal of Swarm Intelligence Research (IJSIR) 2015; 6 (2): 87-101.