International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8 Issue-4, November 2019

Optimization of Unit Commitment Problem with Third Order Polynomials using Grasshopper Optimization Algorithm

Karthikeyan. R, Subramanian. S, Elanchezhian. E. B

Abstract*: *This paper deals with a Unit Commitment (UC) problem of a power plant aimed to find the optimal scheduling of the generating units involving cubic cost functions. The problem has non convex generator characteristics, which makes it very hard to handle the corresponding mathematical models. However, grasshopper optimization algorithm (GOA) has reached a high efficiency, in terms of solution accuracy and computing time for such non convex problems. Hence, GOA is applied for scheduling of generators with higher order cost characteristics, and turns out to be computationally solvable. In particular, we represent a model that takes into account the accurate higher order generator cost functions along with ramp limits, and turns to be more general and efficient than those available in the literature. The behavior of the model is analyzed through proposed technique on modified IEEE-24 bus system and IEEE-30 bus system.

Keywords*: *Cubic Cost Functions, Ramp Rate, Grasshopper Optimization Algorithm, Unit Commitment.

I. INTRODUCTION

Electrical systems are interconnected to provide the benefits of minimum generation costs, maximum reliability, and improved operational conditions, such as power reserve sharing, stability enhancement and emergency operation. In this context, the problem of optimization of the economic dispatch of electric energy is relevant to meet the requirements of quality and efficiency in the generation of electric energy.

The basic objective of the unit commitment (UC) of the electric power generation is the scheduling of the outputs of the agreed generation units to satisfy the demand of the consuming load for the given period at a minimum cost of operation, satisfying to all units and the restrictions of equality and inequality imposed by the problem [1]. When the problem of economic dispatch (ED) deals with a simple time interval, it is referred to as a static economic dispatch problem. The dynamic economical dispatch problem considers a finite number of dispatch intervals coupled with the load forecast to provide an "optimal" generation trajectory following a variable load demand [2].

Many of the optimization problems in power systems including ED and UC have complex and non-linear characteristics with the presence of constraints of equality and inequality. Since the problem of UC has been introduced, several methods have been used to solve this problem.

Conventional approaches to solving UC problems include iterative method [3], gradient-based techniques [4], piecewise linear approximation [5], UC problem has been described as a function of the quadratic functions [6], mixed integer linear programming [7]. However, many of the conventional approaches used in UC problems may not be able to provide an optimal solution.

The literature has described some studies relating to the use of methods of classic artificial intelligence to UC problems, such as tabu search [8], simulated annealing [9] and expert systems [10]. In this context, the applications of artificial intelligence techniques using mainly the sub-area of computational intelligence, to cite the applications of neural networks [11], evolutionary algorithms [12], fuzzy systems [13], grasshopper optimization algorithm (GOA) [14] and intelligent hybrid systems have been successfully addressed due to their ability to seek solutions close to the optimal global solution [15].

In the specific context of GOA, several recent studies have been presented aiming at the design of efficient stochastic optimization algorithms based on GOA such as, binary grasshopper optimization algorithm [16] and hybrid grasshopper optimization algorithm [17].

Nature with its gradual process of evolution changes the environment continuously. Nature is one of the biggest sources of inspiration and human develops many technical theories by inspired the nature. The life cycle of grasshopper has inspired the researchers to solve the optimization problem. The grasshopper optimization algorithm (GOA) is one such nature inspiring problem and was developed by Seyedali Mirijalili in 2017 [14].

The contribution of this paper is to describe and evaluate the GOA to solve the UC problem of electric power generating units considering the system constraints.

Manuscript published on November 30, 2019.
* Correspondence Author

Karthikeyan. R*, Lecturer (Assistant professor on deputation from Annamalai University), Department of EEE, Alagappa Government Polytechnic College, Karaikudi, Tamilnadu, India. Email:mrrknila@gmail.com

Subramanian. S**, Professor, Department of EEE at Annamalai University, Chidambaram, Tamilnadu, India. Email: dr_smani@yahoo.co.in.

Elanchezhian. E. B***, Lecturer (Assistant professor on deputation from Annamalai University), Department of EEE, Government PolytechnicCollege, Srirangam, Tamilnadu, India. Email: elanchezhian.eb@gmail.com

© The Authors. Published by Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP). This is an open access article under the CC-BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)

The advantage of using GOA method is to improve the convergence speed of the optimization algorithm as a whole in relation to the search in the vicinity of a promising point. The final solution obtained by the GOA method tends to be closer to the optimum solution, on average, than that obtained by other existing methods.

The proposed GOA methodology is validated for two case studies known in the literature for twenty six and six thermal generating units [18], [19]. The results obtained are analyzed and compared with others presented in the literature, which highlight the efficiency of the GOA approach proposed in this paper.

The paper is organized as follows. The formulation of the problem of unit commitment of electric energy is detailed in section 2. In addition, comments on the handling of constraints are presented. Section 3 presents the fundamentals of GOA in the forms of unit commitment problem design. The description of the two unit commitment problems tested and an analysis of the optimization results obtained are presented in section 4. At the end of this paper, the conclusion and the perspectives of future works are presented in section 5, respectively.

II. PROBLEM FORMULATIONS

The type of unit commitment problem, discussed in this paper, can be described mathematically with an objective function and constraints. The objective function of UC problem is the minimization of the total operating cost F_T (in \$/h) which is the sum of the fuel cost F and the start up cost SUC of individual units (N) for the given period T subject to various constraints. The total operating cost F_T should be minimized as represented in equation (1),

$$\min F_T = \sum_{t=1}^{T} \sum_{i=1}^{N} U_{it} \left[F_i\left(P_i\left(t\right)\right) + SUC_i\left(1 - U_{i(t-1)}\right)\right] \quad (1)$$

where $F_i(P_i(t))$ is the fuel cost of generator i at hour t, $P_i(t)$ is the output power of i^{th} generator at hour t, U_{it} is the on/off status of i^{th} generator at hour t.

The fuel cost function $F_i(P_i(t))$ for the generating unit i (in \$/h) [18],[19], which is defined by cubic polynomial can be mathematically formulated as,

$$F_i\left(P_i\right) = a_i P_i^3 + b_i P_i^2 + c_i P_i + d_i \quad (2)$$

where a_i, b_i, c_i and d_i are cost coefficients value of the generator i.

The constraints represented by equations (3) to (7) must be satisfied. Equation (3) represents the equality constraints, while expression (4) to (7) represents the inequality constraints.

2.1 Power Balance Constraints

Equation (3) represents the power balance equality constraints i.e., balance between supply and demand.

$$\sum_{i=1}^{N} U_{it} P_i\left(t\right) = P_d\left(t\right), \qquad t = 1,2,...,T \qquad (3)$$

where $P_d(t)$ is the total load demand (in MW) at t^{th} interval.

2.2 Spinning Reserve Constraints

The sum of the maximum power generating capacities of all the committed units at a time instant should be at least equal to the sum of the known power demand and minimum spinning reserve requirement at that time instant.

$$\sum_{i=1}^{N} U_{it} P_{i(max)} \geq P_d\left(t\right) + R_t, \qquad t = 1,2,...,T \qquad (4)$$

where $P_{i(max)}$ is the known maximum power that can be generated by unit i at any time instant and R_t is the minimum spinning reserve requirement at time t.

2.3 Generator Operational Constraints

Equation (5) represents the inequality constraints relative to the limits of the power generation capacity of each generating unit.

$$\begin{gathered} P_{i,min} \leq P_i\left(t\right) \leq P_{i,max,}\ when\ U_{it} = 1 \\ P_i\left(t\right) = 0, when\ U_{it} = 0 \end{gathered} \qquad (5)$$

$P_{i,min}$ and $P_{i,max}$ are the minimum and maximum operating outputs of the generating unit i (in MW) respectively.

2.4 Unit Minimum up/down Time Constraints

$$\begin{gathered} \left[X_{i(t-1)}^{on} - T_i^{on}\right]\left[U_{i(t-1)} - U_{i(t)}\right] \geq 0 \\ \left[X_{i(t-1)}^{off} - T_i^{off}\right]\left[U_{i(t)} - U_{i(t-1)}\right] \geq 0 \end{gathered} \qquad (6)$$

where $X_{i(t)}^{off}$ and $X_{i(t)}^{off}$ is the time duration for which unit i has been on and off respectively at hour t.

2.5 Ramp Rate Limits

$$\begin{gathered} P_i\left(t\right) - P_i\left(t-1\right) \leq UR_i \quad As\ \ generation\ \ increases \\ P_i\left(t-1\right) - P_i\left(t\right) \leq DR_i \quad As\ \ generation\ \ decreases \end{gathered} \qquad (7)$$

where UR_i and DR_i are the ramp up and ramp down limits of the i^{th} generator unit respectively.

2.6 Emission dispatch

The NO_X emission (in kg/h) function of economic load dispatch problem, produced from the generating unit i, is accurately formulated as a cubic function of the generator power output and that can be expressed as follows [19],

$$E_i\left(P_i\right) = \alpha_i P_i^3 + \beta_i P_i^2 + \gamma_i P_i + \eta_i \qquad (8)$$

where α_i, β_i, λ_i and η_i are NO_X emission coefficients value of the generator i.

2.7 Objective Function

In this paper, a single and multi objective functions are considered separately to validity the efficiency and superiority of the GOA to solve the UC problem of electric power generating units.

Single Objective

In single objective problem, equation (1) is taken as the fitness function for the GOA.

Multi-Objective

In multi-objective problem, equation (9) is taken as the fitness function of the GOA. A multi-objective optimization is converted into a single objective optimization problem by introducing price penalty factor h to NO_X pollutant.

$$\min F_T = \sum_{i=1}^{N} \left(F_i\left(P_i\right) + h_i * E_i\left(P_i\right)\right) \qquad (9)$$

As described in most of the existing literature the price penalty factor h_i is the ratio between minimum fuel cost and maximum NO_X emission of corresponding generator.

$$h_i = \frac{\left(a_i P_{min}^3 + b_i P_{min}^2 + c_i P_{min} + d_i\right)}{\left(\alpha_i P_{max}^3 + \beta_i P_{max}^2 + \eta_i P_{max} + \gamma_i\right)} \qquad (10)$$

III. GRASSHOPPER OPTIMIZATION ALGORITHM (GOA)

Optimization methods have two forms of configuration: deterministic methods and stochastic methods. The deterministic techniques tend to look for a minimum point (when the problem is minimization) in the search space based on the information given by the objective function (cost function) gradient. The efficiency of these techniques depends on several factors, such as: the initial solution, the accuracy of the downward direction evaluation, the method used to perform the online search and the adopted stopping criterion. The solution obtained is usually a local minimum point, which may be global minimum if the function is only a fashion. The two main disadvantages of deterministic methods, of which quadratic programming is part.

Stochastic methods, of which GOA is a part, do not require the gradient calculation and are apt to find the global solution. However, the number of evaluations of the objective function required to find the solution is generally greater than the number required by deterministic methods [14], [16], [17].

The GOA is a promising tool for search, optimization, machine learning and for solving design problems. The algorithm uses simulated evolution seeking solutions to complex problems [14]. The GOA is based on a population of individuals, where each represents a point of search in the space of potential solutions of a given problem. The GOA has some selection procedures based on fitness of individuals.

Some of the potentialities of the GOA are: (i) the speed of convergence of the optimization and (ii) the ease of implementation. The following are the fundamentals and potentialities of GOA.

The unit commitment problem is comprehended by applying GOA and it is executed in this paper. GOA is displayed by copying the social conduct of the grasshopper. The grasshopper swarm regularly both in nymph and adult stage and it scans for is prey. The grasshopper voyages and discovers its prey by investigating the prey and afterward exploits the prey at long last. The GOA method is planned with the model activity of investigating and exploiting conduct of grasshopper. In GOA the speed of convergence is engaged by utilizing this grasshopper investigation model. GOA is moderately financial to different methods. GOA evens out the investigation and exploitation. GOA serves to take care of numerous most noteworthy potential problems in science and industry.

The mathematical expression of GOA can be expressed as [14],

$$X_i = S_i + G_i + A_i \qquad (11)$$

where X_i = Position of the i^{th} grasshopper, G_i = Gravity force, S_i = Social interaction and A_i = Wind advection.

The equation (11) is considering about the fundamentally three parts of social interaction, gravitational force outcome and wind advection [16]. The above all perspectives are taking care through grasshopper movement. The principle perspectives is started from grasshoppers and the social interaction can be discussed as follows

$$S_i = \sum_{\substack{j=1 \\ j \neq i}}^{N} s\left(d_{ij}\right) \hat{d}_{ij} \qquad (12)$$

where $\hat{d}_{ij}$ = distance between the i^{th} and j^{th} grasshopper and S = social forces.

The social forces s(r), can be expressed as follows,

$$s(r) = f_i e^{\frac{-r}{l}} - e^{-r} \qquad (13)$$

where *f* = attraction intensity and *l* = attractive length scale.

One progressively critical trademark in swarming conduct is the social attraction which includes attractive and repulsive forces of grasshopper, when they move together and separated in the looking through space. The parameters *l* and *f* adjust the comfort zone, attraction area, and repulsion area apparently. The function S will expressly isolate the space between repulsion area, comfort zone and attraction area. This S function outcome a number closer to zero with distances more than 10. The gravity force (G_i), can be estimated by using equation (14),

$$G_i = -g\hat{e}_g \qquad (14)$$

where g = gravitational constant, $\hat{e}_g$ = unity vector towards the centre of earth.

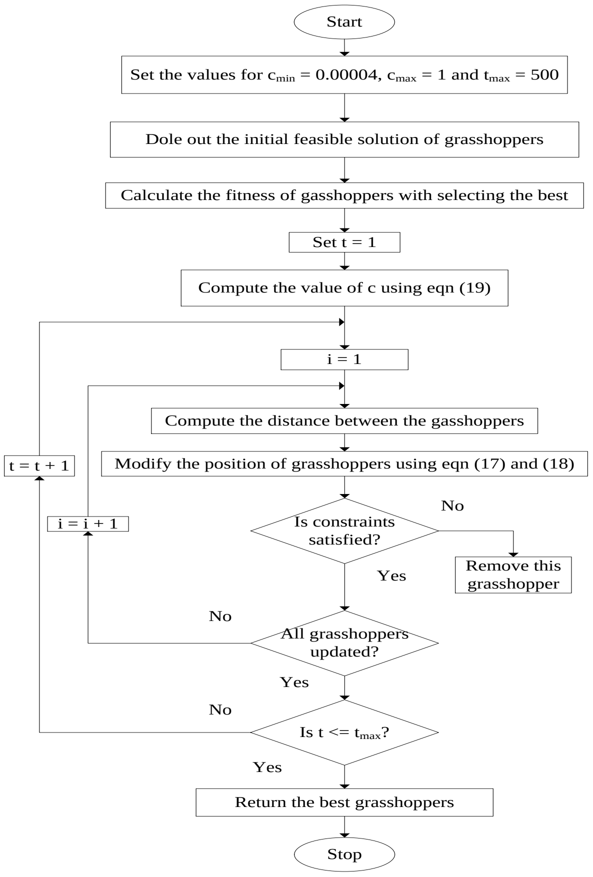


Fig. 1 Flowchart of the grasshopper optimization algorithm

The wind advection (A_i), can be estimated as follows,

$$A_i = u\hat{e}_w \qquad (15)$$

where u = constant drift, $\hat{e}_w$ = unity vector in the direction of wind.

$$X_i = \sum_{\substack{j=1 \\ j \neq i}}^{N} s\left(\left|x_j - x_i\right|\right) \frac{x_j - x_i}{d_{ij}} - g\hat{e}_g + u\hat{e}_w \qquad (16)$$

Numerically the model can't be utilized straightforwardly in light of the fact that either the grasshoppers quickly achieve the comfort zone or the swarm not moves towards the predetermined point. Further an altered form of this expression is suggested as pursues to take care of the optimization problem.

$$X_i^d = c\left(\sum_{\substack{j=1 \\ j \neq i}}^{N} c\frac{ub_d - lb_d}{2} s\left(\left|x_j^d - x_i^d\right|\right) \frac{x_j - x_i}{di_j}\right) + \hat{T}_d \qquad (17)$$

where u_{bd} = upper limit in the D^th^ dimension, l_{bd} = lower limit in the D^th^ dimension, $s(r) = f_i e^{\frac{-r}{l}} - e^{-r}, \overset{\wedge}{T_d}$ = value of the D^th^ dimension in the target, c = decreasing coefficient to shrink the comfort zone, repulsion zone and attraction zone.

The coefficient c lessens the comfort zone proportional to the iteration count and can be computed by using equation (19),

$$c = c_{\max} - l\,\frac{c_{\max} - c_{\min}}{L} \qquad (18)$$

where $c_{\max}$ = coefficient c maximum limit, $c_{\min}$ = coefficient c minimum limit, l = current iteration, L = maximum iteration count.

In GOA it is accepted that the best grasshopper during optimization is the primary objective. This will help GOA to spare the most encouraging objective for all solutions in the search dimension. This is finished with the expectation of finding a superior and increasingly precise objective as the best result. The above discourses make clear the effectiveness of the GOA method in finding the global optimum solution in a given pursuit space. The flowchart of the proposed GOA techniques is given in Fig. 1.

IV. NUMERICAL SIMULATION RESULTS AND DISCUSSIONS

To show the relative performance of GOA, two scenarios are simulated. Scenario I is validated for 26 thermal generating unit test systems and Scenario II is validated for 6 thermal generating unit test systems.

The algorithms for solving the examples were implemented in Math Works 2010 computing environment, using the 2.65 GHz Intel Core i5 processor with 4 GB RAM. The obtained solutions were compared in tables that show the characteristics of convergence and computational time with each approach. At the end of this section, the results obtained are also compared with other methods presented in the literature.

Scenario I: Single Objective

In this scenario, GOA is employed to minimize the total operating cost F_T of the committed generating units for a given period of time without considering emission dispatch. Hence, the objective function F_T in equation (1) is alone considered as the fitness function for the GOA. This case study comprises of modified IEEE-24 bus test system with twenty six generating units [18]. The test system information including cost coefficient, power demand, ramp rate and power generation limits of the units are taken from the literatures [20]-[23].

Simulations are done for a period of 24 hours. The fuel cost, spinning reserve and start-up cost for 24 hours is depicted in Table-I. The optimum generator schedule and corresponding output found from the proposed method with cubic objective function is given in Table-II for a period of 24 hours.

A comparative study is presented in Table-III in relation to others reported in the literature. Table-III depicts the comparison of the total fuel cost, total operating cost and execution time accomplished from the GOA technique with the other existing techniques, such as dynamic programming sequential and truncated combination (DP-STC) [22], piecewise linear iterative (PLI) [22] and teaching learning based optimization (TLBO) algorithm [18]. The total fuel cost got from the GOA technique is 793815.30 $, whereas the fuel cost obtained from the techniques PLI, DP-STC and TLBO are 795698.33 $, 795489.09 $ and 795488.869 $ respectively.

The total operation cost considering start-up cost estimated from the GOA technique is 798485.3000 $ which is much lesser than the total operation cost achieved from the TLBO method and it the value is 800158.8690 $.

For the 26 unit test system, the number of generators committed over a period of 24 hours is depicted in Fig. 1. The Fig. 2 outlines the power demand for 24 hour horizon and the sum of the maximum power limit of all committed generators for every hour.

Fig. 3 optimized all generators ON/OFF status for a period of 24 hour. Execution time of each algorithm is significant for its application in practical implementation. Table-III also demonstrates the execution time of proposed GOA technique and it is 0.31 seconds which is slightly less than the other existing techniques.

The best, average and worst total fuel cost achieved from the proposed GOA technique for unit commitment problem are given in Table-IV. The success rate of getting the best results for the proposed technique is 75%. From the results, it is clear that the proposed method is robust and it is applicable to practical system. Like other evolutionary algorithms, GOA uses the stochastic techniques, thus randomness is an intrinsic feature of these techniques. The convergence characteristic of the GOA technique for UC problem with single objective is depicted in Fig. 4. The Fig. 5 represents the robustness characteristics of 100 times by running the generating cost and average value of generating cost of 26 unit system.

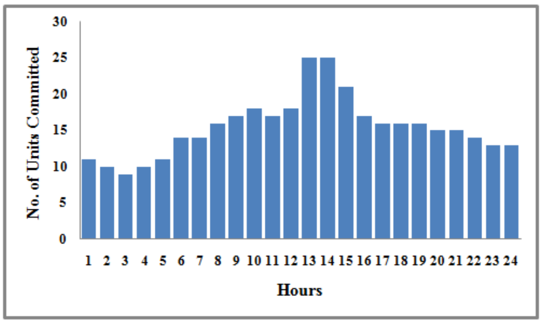


Fig. 1 Committed units for a period of 24 hours – 26 unit system

Table - I Fuel cost, spinning reserve and start-up cost for 24 hours

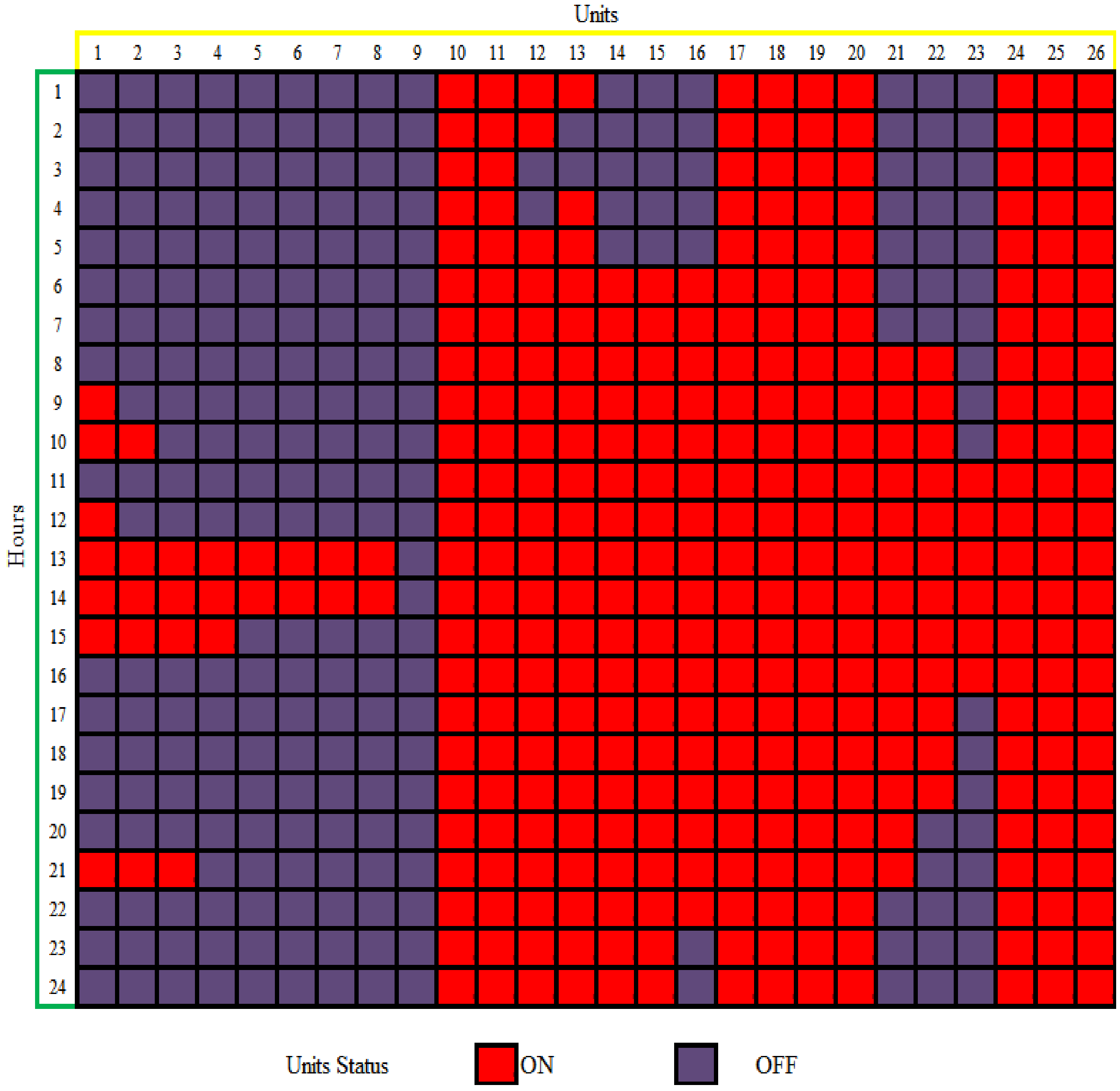
Hour (h)	Demand (MW)	% Reserve	Fuel cost ($)	Start-up cost ($)
1	2070	0.1932	23176.98	3220
2	1980	0.9091	21892.05	0
3	1920	0.1042	20907.07	0
4	1870	6.8449	20526.92	80
5	1990	4.2211	22132.31	80
6	2120	11.9811	25737.84	300
7	2260	5.0442	27842.61	0
8	2510	10.2789	33954.61	600
9	2620	6.1069	36329.52	0
10	2740	1.8978	39002.6	0
11	2800	5.8929	40418.88	300
12	2830	5.1943	41404.75	0
13	2980	3.5235	46027.06	90
14	3080	0.1623	48402.8	0
15	3010	0.0997	45452.41	0
16	2940	0.8503	43549.8	0
17	2720	1.7647	38148.07	0
18	2540	8.9764	35744.34	0
19	2580	7.2868	35159.22	0
20	2460	4.5122	32416.76	0
21	2520	3.4524	33774.94	0
22	2310	2.7706	28711.83	0
23	2230	1.9731	26841.09	0
24	2190	3.8356	26260.86	0

Table - II Optimal scheduling of modified IEEE-24 bus system

	Units								
Hours	1	2	3	4	5	6	7	8	9
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	11.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	11.35	11.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	12.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	11.81	11.74	11.74	11.74	11.76	19.69	19.72	19.72	0.00
14	12.00	12.00	12.00	12.00	12.00	20.00	20.00	20.00	0.00
15	12.00	12.00	12.00	12.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	11.79	11.82	11.82	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	Units								
Hours	10	11	12	13	14	15	16	17	18
1	76.00	75.86	75.86	75.86	0.00	0.00	0.00	154.11	154.11
2	76.00	76.00	76.00	0.00	0.00	0.00	0.00	152.76	152.76
3	76.00	76.00	0.00	0.00	0.00	0.00	0.00	155.00	155.00
4	69.71	69.71	0.00	69.71	0.00	0.00	0.00	154.67	130.12
5	63.79	63.79	73.65	63.79	0.00	0.00	0.00	143.86	132.17
6	66.65	66.65	66.65	66.65	71.15	89.45	43.09	154.50	150.66
7	72.06	72.06	72.06	72.06	72.43	100.00	93.54	142.23	132.77
8	73.25	73.25	73.25	73.25	90.52	80.13	86.72	142.77	142.18
9	70.97	70.97	70.97	70.97	83.64	95.55	83.64	150.60	149.20
10	70.37	70.37	70.37	70.37	98.86	97.59	98.86	149.49	154.67
11	74.89	74.89	74.89	74.89	99.00	100.00	98.66	155.00	153.96
12	76.00	76.00	76.00	76.00	97.29	78.45	86.80	155.00	135.27
13	75.95	75.95	75.95	75.95	95.63	99.74	95.63	154.92	154.92
14	76.00	76.00	76.00	76.00	100.00	100.00	100.00	155.00	155.00
15	75.56	75.56	75.56	75.56	100.00	99.97	100.00	155.00	155.00
16	75.99	75.99	75.99	75.99	99.63	99.97	99.63	155.00	155.00
17	75.68	75.68	75.68	75.68	99.30	99.63	99.30	154.81	154.37
18	74.38	74.38	74.38	74.38	77.48	98.80	77.48	134.92	154.37
19	76.00	76.00	76.00	76.00	73.44	82.98	82.74	148.25	155.00
20	75.71	75.71	75.71	75.71	92.71	95.04	71.51	117.28	154.60
21	70.11	70.11	70.11	70.11	88.81	87.43	88.81	154.37	154.37
22	75.65	75.65	75.65	75.65	98.91	99.23	98.91	153.87	153.87
23	75.57	75.57	75.57	75.57	97.70	98.81	0.00	143.71	150.18
24	67.30	67.30	67.30	76.00	92.90	91.40	0.00	153.50	154.96

	Units							
Hours	19	20	21	22	23	24	25	26
1	154.11	154.11	0.00	0.00	0.00	350.00	400.00	400.00
2	152.76	152.76	0.00	0.00	0.00	350.00	391.73	399.23
3	155.00	155.00	0.00	0.00	0.00	350.00	400.00	398.00
4	130.12	130.12	0.00	0.00	0.00	318.92	397.32	399.59
5	154.05	154.70	0.00	0.00	0.00	341.49	398.90	399.82
6	103.86	138.15	0.00	0.00	0.00	314.43	394.69	393.42
7	153.89	141.83	0.00	0.00	0.00	335.09	400.00	400.00
8	139.24	154.59	112.87	122.06	0.00	345.93	400.00	400.00
9	153.61	149.20	171.97	137.02	0.00	350.00	400.00	400.00
10	152.46	154.67	189.80	189.80	0.00	349.69	400.00	399.89
11	155.00	154.40	125.12	125.12	193.69	340.48	400.00	400.00
12	155.00	155.00	137.15	183.47	181.47	349.10	400.00	400.00
13	154.92	154.92	195.06	166.91	138.61	346.98	400.00	400.00
14	155.00	155.00	196.80	196.80	197.00	346.22	399.17	400.00
15	155.00	155.00	197.00	197.00	197.00	348.79	400.00	400.00
16	155.00	155.00	195.96	192.37	178.50	350.00	400.00	400.00
17	154.37	153.48	193.15	158.89	0.00	350.00	400.00	400.00
18	154.37	155.00	177.07	172.80	0.00	255.22	399.43	385.50
19	155.00	155.00	125.47	149.76	0.00	348.45	400.00	399.91
20	154.60	154.60	170.04	0.00	0.00	346.80	400.00	400.00
21	154.37	153.73	176.96	0.00	0.00	350.00	395.59	399.68
22	153.87	142.52	0.00	0.00	0.00	307.10	400.00	399.13
23	143.71	155.00	0.00	0.00	0.00	338.60	400.00	400.00
24	153.50	135.89	0.00	0.00	0.00	344.14	400.00	385.81



Units

Hours

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥
2	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥
3	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥
4	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟪	🟥	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥
5	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥
6	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥
7	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥
8	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟥	🟥	🟥
9	🟥	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟥	🟥	🟥
10	🟥	🟥	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟥	🟥	🟥
11	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
12	🟥	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
13	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
14	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
15	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
16	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
17	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟥	🟥	🟥
18	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟥	🟥	🟥
19	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟥	🟥	🟥
20	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟥	🟥	🟥
21	🟥	🟥	🟥	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟥	🟥	🟥
22	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥
23	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥
24	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟥	🟥	🟥

Units Status 🟥 ON 🟪 OFF

Fig. 3 Generators ON/OFF status for modified IEEE-24 bus system

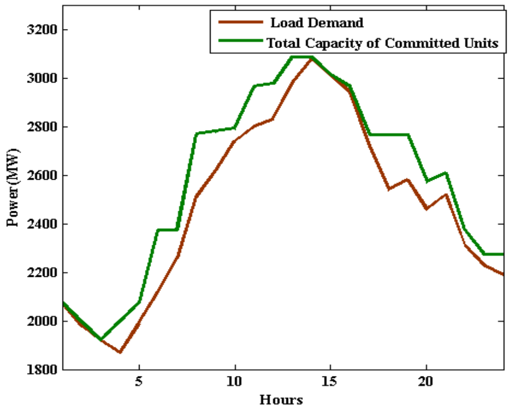


Fig. 2 Power demand and sum of maximum limit of committed units-26 unit system

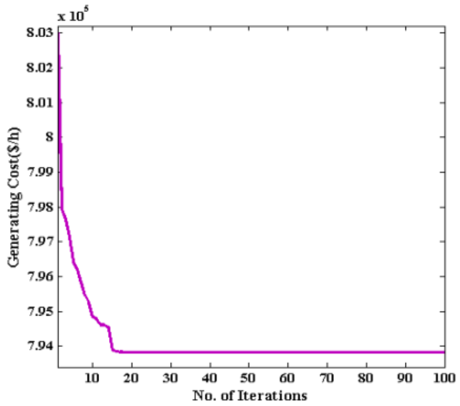


Fig. 4 Convergence characteristics of GOA- Modified IEEE-24 bus system

Table - III Comparison of best results obtained by different methods

Method	Total start-up cost ($)	Total fuel cost ($)	Total operation cost ($)
PLI [22]	-	795698.330	-
DP-STC [22]	-	795489.090	-
TLBO [18]	4670	795488.869	800158.869
GOA	4670	793815.300	798485.300

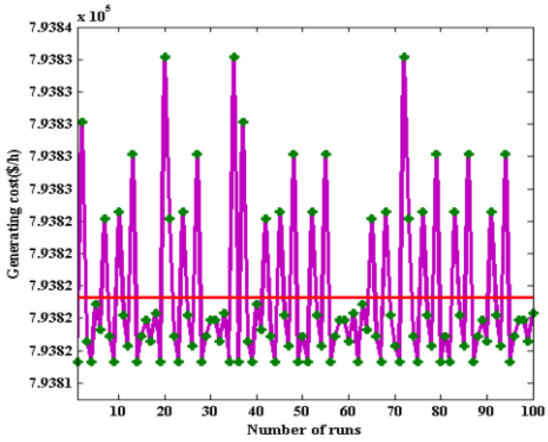


Fig. 5 Robustness characteristics of GOA- 26unit system

Table - IV Performance analysis of GOA

Test system	26-unit system
Population size	30
Best cost ($)	793815.300
Average cost ($)	793819.341
Worst cost ($)	793834.235
Computation time(s)	0.31
Success rate	75

Scenario II: Multi-Objective

In relation to Scenario I, the complexity and non-linearity of the problem are increased in multi-objective problem. In this case, GOA is employed to minimize the multi-objective that comprises of total operating cost F_T and the emission E_T released from the committed units for 24 hour horizon. Therefore, the objective function F in equation (9) is considered as the fitness function for the grasshopper. This problem consists of IEEE-30 bus system with six generating units, and its corresponding generator and load data are taken from the literatures [19]. The results obtained for this case are presented in Table-V and Table-VI.

For IEEE-30 bus system, the number of generators committed over a period of 24 hours is depicted in Fig. 6. The Fig. 7 outlines the power demand for 24 hour horizon and the sum of the maximum power limit of all committed generators for every hour. In this Fig. 8 represents the optimize all generators ON/OFF status for a period of 24 hour. Execution time of each algorithm is significant for its application in practical implementation. The convergence characteristic of the GOA technique for UC problem with multi-objective is depicted in Fig. 9.

Table - V Fuel cost, NO_X emission and CEED fuel cost

Hour (h)	Demand (MW)	Fuel cost ($)	NO_X emission cost (Kg)	CEED fuel cost ($)
1	166	3453.6	3322.1	4033.86
2	196	3828.9	3373.3	4427.67
3	229	4916.7	3917.9	5630.00
4	267	5969.5	4864.2	6939.10
5	283.4	6496.6	5381.7	74965.00
6	272	6153.7	5081.7	7102.00
7	246	5281.2	4314.9	6074.00
8	213	4320.6	3666.9	4932.10
9	192	4273.5	3627.7	4989.40
10	161	3769.5	3073.2	4408.86
11	147	3714.7	3311.5	4247.00
12	160	4246.1	3819	4843.40
13	170	4766	4354.9	5395.80
14	185	5679.7	5296.7	6367.90
15	208	7445.8	7128.4	8246.60
16	232	6814.2	6053.3	7772.75
17	246	6130.2	5263.1	7235.57
18	241	5903.6	5029.9	6996.27
19	236	5748.5	4905.6	6793.78
20	225	5294.2	4413.5	6334.67
21	204	4677.8	3938.5	5537.15
22	182	4167.7	3423.2	4892.10
23	161	3448.8	2888.1	4048.49
24	131	2925.4	2526	3337.60

Table - VI Optimal scheduling of IEEE-30 bus system

Units

Hour	1	2	3	4	5	6
1	54.81	0.00	48.228	33.20	0.00	29.762
2	50.00	0.00	41.386	37.102	39.104	28.408
3	57.999	61.154	31.179	31.431	47.237	0.00
4	53.43	76.375	47.041	45.333	44.821	0.00
5	63.743	71.068	48.589	50.00	50.00	0.00
6	63.002	73.108	44.461	45.445	45.984	0.00
7	50.114	56.149	39.769	49.999	49.969	0.00
8	50.00	43.787	29.228	48.489	41.496	0.00
9	50.00	68.534	42.144	31.322	0.00	0.00
10	52.228	69.616	39.156	0.00	0.00	0.00
11	72.061	74.939	0.00	0.00	0.00	0.00
12	80.00	80.00	0.00	0.00	0.00	0.00
13	90.07	79.93	0.00	0.00	0.00	0.00
14	105.00	80.00	0.00	0.00	0.00	0.00
15	128.00	80.00	0.00	0.00	0.00	0.00
16	102.00	80.00	50.00	0.00	0.00	0.00
17	76.225	79.99	49.998	0.00	0.00	39.787
18	71.00	80.00	50.00	0.00	0.00	40.00
19	71.822	77.68	47.09	0.00	0.00	39.408
20	57.079	79.388	48.533	0.00	0.00	40.00
21	60.11	60.422	46.762	0.00	0.00	36.706
22	55.821	55.406	48.158	0.00	0.00	22.615
23	52.005	42.404	37.317	0.00	0.00	29.274
24	58.743	43.948	28.309	0.00	0.00	0.00

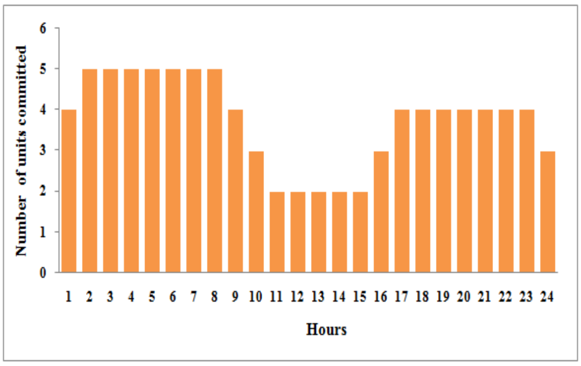


Fig. 6 Committed units for a period of 24 hours – 6 unit system

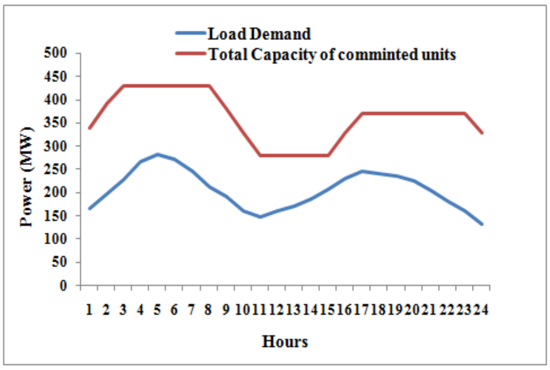


Fig. 7 Power demand and sum of maximum limit of committed units for 24 hours-6 unit system

Hours

		1	2	3	4	5	6	7	8	9	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
U	1	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	2	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
t	3	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
s	4	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
	5	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
	6	🟥	🟥	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪

Unit status ON 🟥 OFF 🟪

Fig. 8 Generators ON/OFF statuses for IEEE-30 bus system

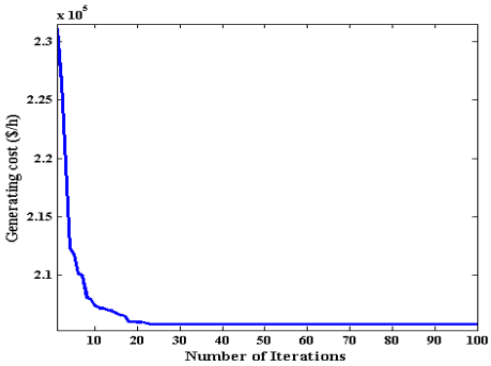


Fig. 9 Convergence characteristics of GOA-IEEE-30 bus system

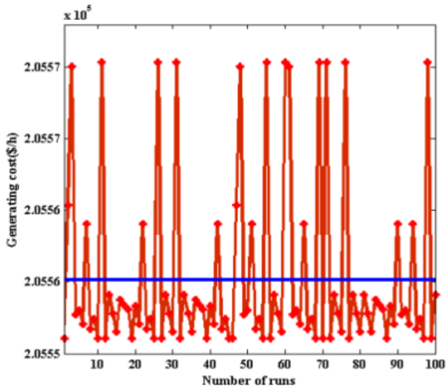


Fig. 10 Robustness characteristics of GOA-IEEE-30 bus system

Table-VII Performance analysis of GOA

Test system	6-unit system
Population size	30
Best cost ($)	205551.072
Average cost ($)	205555.127
Worst cost ($)	205570.379
Computation time(s)	0.14
Success rate	79

The Fig. 10 represents robustness characteristics of 100 time runs the generating cost and average generating cost clearly indicated. The best, average and worst total fuel costs achieved from the proposed GOA technique for unit commitment problem are given in Table-VII. The success rate of getting the best results for the proposed technique between the average fuel cost and the best fuel cost is about 79% for 6 unit system which demonstrates that GOA has satisfactory success rate. The computation time of the proposed method is very less for 6 unit systems which is about 0.14s. It is shows that the proposed method can give the optimal solutions within a fraction of second. From the above result, it is clear that the proposed method is robust and it is applicable to practical systems. Like other evolutionary algorithms, GOA uses the stochastic techniques, thus randomness is an intrinsic feature of these techniques.

V. CONCLUSION

In this paper, a GOA method has been presented to solve the problem of unit commitment in power system. The GOA algorithm is used to perform the global search and fine tune the feasible solution. The GOA when applied in isolation explores the search space quickly with the direction of the wind and ensures a good global solution. The performance of the GOA approach tested in the two scenarios is encouraging, as the approach found a high quality global solution in acceptable computational time. The presented GOA technique outstandingly minimizes the operating cost, controls the emission and lessens the computational time, and grants best unit scheduling, which demonstrates its capability to solve any higher order polynomial equations.

The search for a better compromise between exploitation (convergence speed) and exploration (diversity of population) is a relevant topic of research with UC, and will be the subject of future research, mainly to the conception of hybrid approaches with GOA for problems of UC that include time-varying nonlinear behavior and the presence of multiple conflicting objectives and inequality constraints.

ACKNOWLEDGMENT

The authors acknowledge with gratitude for the support and facilities provided by the authorities of Annamalai University, India to carry out this research work.

REFERENCES

1. A. J. Wood, B. F. Woollenberg and G. B. Shele, Power generation operation and control, John Wiley & Sons, 2013.
2. B. H. Chowdhury and S. Rahman, “A review of recent advances in economic dispatch”, IEEE Transactions on Power Systems, vol. 5, no. 4, Nov., 1990. pp. 1248-1259.
3. I. Cohen and S. Wan, “ A method for solving the fuel constrained unit commitment problem”, IEEE Transactions on Power Systems, vol. 2, no. 3, Aug., 1987, pp. 608-614,
4. R. Azizipanah-Abarghooee, T.Niknam, F. Bavafa and M. Zare, “ Short-term scheduling of thermal power systems using hybrid gradient based modified teaching-learning optimizer with black hole algorithm”, Electric Power Systems Research, vol. 108, Oct., 2014, pp. 16-34.
5. L. Wu, “A tighter piecewise linear approximation of quadratic cost curves for unit commitment problems”, IEEE Transactions on Power Systems, vol. 26, no. 4, Nov., 2011, pp.2581-2583.
6. E. C. Finardi and E. L. da Silva, “ Solving the hydro unit commitment problem via dual decomposition and sequential quadratic programming”, IEEE Transactions on Power Systems, vol. 21, no. 2, May, 2006,pp. 835-844.
7. M. Carrion and J. M. Arroyo, “ A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem”, IEEE Transactions on Power Systems, vol. 21, no. 3, Aug., 2006, pp. 1371-1378,
8. A. H. Mantawy, Y. L. Abdel-Magid and S. Z. Selim, “ Unit commitment by tabu search”, IEE Proceedings-Generation, Transmission and Distribution, vol. 145, no. 1, Jan., 1998, pp. 56-64.
9. F. Zhuang and F. Galiana, “ Unit commitment by simulated annealing”, IEEE Transactions on Power Systems, vol. 5, no. 1, Feb., 1990, pp. 311-318.
10. S. Mokhtari, J. Sing and B. Wollenberg, “A unit commitment expert system”, IEEE Transactions on Power Systems, vol. 3, no. 1, Feb., 1988, pp. 272-277.
11. H. Sasaki, M. Watanable, J. Kubokawa, N. Yorino and R. Yokoyama, “ A solution method of unit commitment by artificial neural networks”, IEEE Transactions on Power Systems, vol. 7, no. 3, Aug., 1992, pp. 974-981.
12. K. A. Juste, H. Kita, E. Tanaka and J. Hasegawa, “ An evolutionary programming solution to the unit commitment problem”, IEEE Transactions on Power Systems, vol. 14, no. 4, Nov., 1999, pp. 1452-1459.
13. C. C. Su and Y. Y. Hsu, “ Fuzzy dynamic programming: An application to unit commitment”, IEEE Transactions on Power Systems, vol. 6, no. 3, Aug., 1991, pp. 1231-1237.

14. S. Saremi, S. Mirjalili and A. Lewis, "Grasshopper optimization algorithm: Theory and application", Advances in Engineering Software, vol. 105, Jan., 2017, pp. 30-47.
15. Z. Ouyang and S. M. Shahidehpour, " A hybrid artificial neural network-dynamic programming approach to unit commitment", IEEE Transactions on Power Systems, vol. 7, no. 1, Feb., 1992, pp. 236-242.
16. M. Mafarja, I. Aljarah, H. Faris, A. I. Hammouri, A. Z. Ala'M and S. Mirjalili, "Binary grasshopper optimization algorithm approaches for feature selection problems", Expert Systems with Applications, vol. 117, Sep., 2019, pp. 267-286.
17. A. Saxena, "A comprehensive study of chaos embedded bridging mechanisms and crossover operators for grasshopper optimization algorithm", Expert Systems with Applications, vol. 132, Apr., 2019, pp. 166-188.
18. E. B. Elanchezhaian, S. Subramanian and S. Ganesan, " Cost effective operating strategy for unit commitment and economic dispatch of thermal power plants with cubic cost functions using TLBO algorithm", Journal of Power and Energy Engineering, vol. 3, no. 6, June, 2015, pp. 20-30.
19. Ismail Ziane, Farid Benhamida and Amel Graa, "Simulated annealing algorithm for combined economic and emission power dispatch using max/max price penalty factor," Neural computing and applications, Apr., 2016, pp.1-8.
20. S. K. Tong, S. M. Shahidehpour and Z. Ouyang, "A heuristic short-term unit commitment", IEEE Transactions on Power Systems, vol. 6, no. 3, Aug., 1991, pp. 1210-1216.
21. C. Wang and S. Shahidehpour, "Effects of ramp-rate limits on unit commitment and economic dispatch", IEEE Transactions on Power Systems, vol. 8, no. 3, Aug., 1993, pp. 1341-1350.
22. W. M. Lin, H. J. Gow and M. T. Tsay, "A partition approach algorithm for non-convex economic dispatch", International Journal of Electrical Power & Energy Systems, vol. 29, no. 5, Nov., 2007, pp.432-438.
23. Y. H. Moon, J. D. Park, H. J. Kook and Y. H. Lee, " A new economic dispatch algorithm considering any higher order generation cost functions", International Journal of Electrical Power & Energy Systems, vol. 23, no. 2, May, 2001, pp. 113-118.

AUTHORS PROFILE

R. Karthikeyan, is currently Lecturer (Assistant professor on deputation from Annamalai University), Department of EEE, Alagappa government polytechnic college, Karaikudi, Tamilnadu. He has been teaching Diploma, UG & PG classes well over 12 years. His research interests include power system operations and control.

Dr. S. Subramanian, is currently professor, Department of EEE at Annamalai University, Chidambaram, Tamilnadu. He has been teaching UG & PG classes well over two decades. He has to his credit more than 125 research articles of which most of the papers are SCI/Scopus Indexed. He is a senior member in IEEE, ISTE and IOE.

Dr. E. B. Elanchezhian, is currently Lecturer (Assistant professor on deputation from Annamalai University), Department of EEE, Government polytechnic college, Srirangam, Tamilnadu. He has done Ph.D at Annamalai University in 2016. He has been teaching Diploma, UG & PG classes well over 12 years. He has to his credit 19 research papers of which 6 papers are SCI/Scopus Indexed. He is a senior member in IEEE, ISTE & IOE.