Optimizing Fuel Generation Cost of Thermal Power Plants using Grasshopper Optimization Algorithm

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Abstract

Economic Load Dispatch (ELD) in power system is a non-linear problem which requires an allocation of generation among available generating units to minimize the total generation cost. Conventionally, the optimization of ELD heavily relies of statistical tools and past years' data. This work explores the novel application of nature-inspired metaheuristic computational technique by using Grasshopper Optimization Algorithm (GOA) integrated with interior-point, sequential quadratic programming and active-set schemes is presented for the solution of optimization task of thermal power plant systems. The cost functions of power plants systems are optimized by global search efficacy of GOA hybrid with local search techniques for speedy local convergence. The performance of the design system is assessed on Economic Load Dispatch by considering valve point loading effect for 3 and 13 thermal generating units. The results show that the proposed hybrid algorithm gives the best results among Modified Elephant Herding Optimization (MEHO), Elephant Herding Optimization (EHO), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) algorithms, in terms of cost optimization while solving the same ELD problem with similar constraints.

Keywords: "Grasshopper Optimization Algorithm (GOA), interior-point, sequential quadratic programming, active-set schemes, Economic Load Dispatch (ELD)"

1. Introduction

Many a researcher has been contributing to get the Economic Load Dispatch (ELD) problem solved by introducing different computational techniques. Therefore, some of the correlated proposed work is as follows.

Nowadays, due to rapid increase in the demand of electricity, the fuel cost of generating units has become a big challenge for researchers. Therefore, it is required to reduce the fuel cost of electrical power generating units to meet the demand of electrical energy. To achieve this, it is the need of the hour to get the optimal solution of Economic Load Dispatch (ELD) problem by applying different computational techniques. An optimal solution can easily be obtained with the help of algorithms instead of rigorous conventional methods of finding the iterations for global optimal solution. Because there are many nature-inspired algorithms available that can solve the non-linearity of ELD problems. In reference [1], Genetic Algorithm (GA) and Refined Genetic Algorithm (RGA) have been used to get the optimal solution by minimizing the fuel cost. Furthermore, it is evident that the Improved Tabu Search Algorithm (ITSA) gives better results than that of conventional lambda iteration methods [2] . The conventional methods of iteration cannot solve the problem of slower convergence and high complexity of ELD. It can be addressed with the help of Modified Ant Colony (MAC) optimization [3][4]. Furthermore, to address the non-linear characteristics of generators, Grey Wolf Optimization (GWO) algorithm has been proposed in reference [5]. This algorithm inspired from the natural behaviour of grey wolves and has been tested for four test system consisting on ten, forty, eighty and one forty units. It is found that this algorithm is very effective for calculating optimal solutions. Besides, Modified Elephant Herding Optimization (MEHO), Elephant Herding Optimization (EHO), Ant Colony Optimization (ACO), and Particle Swarm Optimization (PSO) algorithms are proposed [6,7] to address the non-linearity of ELD; however, the PSO algorithm has been applied on three, thirteen and fourteen unit test system for both with and without valve point loading effect for optimal solution. Lastly, the Whale optimization algorithm (WOA) is proposed in [8] to address the said issue of complexity. The WOA gives an optimal solution for ELD problem by reducing the fuel cost of generating units; however, in this proposed work the said algorithm has been tested on IEEE for six and fifteen thermal units. Further WOA results have been compared with Lagrange's algorithm and Particle swarm algorithm (PSO) and it has been concluded that WOA algorithm gives comparatively better results. Besides the above discussed algorithms, this research has also focused to address not only

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the ELD problem by effectively applying the GOA algorithm hybridized with some local techniques but also it compares the results of GOA algorithm with other metaheuristics techniques. Subsequently, it is found that the proposed research gives far better results than that of discussed algorithms.

2. Economic Load Dispatch

ELD problem have been used to optimize the overall operating cost of various interconnected power generators with the help of proper scheduling output power of each generating unit. The expression of fuel cost is as follows

$$f(p) = \sum_{j=1}^{k}(a_j p^2 + b_j p + c_j) \quad (1)$$

In the expression (1), $f(p)$ expresses the overall fuel cost of electrical power generating units in rs/hr, and p_j is the output of any j[th] generating unit; however, k represents the total number of interconnected generating units. a_j, b_j, c_j these three are called the fuel cost coefficents. In order to incorporate valve point loading effect, the combined expression for sinusoidal and quardratic polynomial functoin is as follows.

$$f_{wv}(p) = \sum_{j=1}^{N}\left(a_j p_j^2 + b_j p_j + c_j + \left|W_j * sin\left(V_j\left(p_j^{min} - p_j\right)\right)\right|\right) \quad (2)$$

In the above expression, in order to add valve point loading effect, fuel cost coefficients $W_j and\, V_i$ are incorporated with expression (1). However, p_j^{min} expresses the lowest output of any j[th] electrical power generating unit, and f_{wv} calculates the fuel cost of any particular j[th] generating unit in terms of RS/hr.

2.1 Constraints

a. Equality Constraint

In order to balance the power constraints in ELD, the term equality constraint has been coined. It states that the power produced at the generation end must be equal to the power required at the consumer end.

$$\sum_{j=1}^{k} p_j = p_d \quad (3)$$

b. Inequality Constraint

The generation capacity limit of any generator is also known as inequality constraint in ELD. This generation capacity limit is as follows.

$$p_j^{upperbound} \le p_j \le p_j^{lowerbound} \quad (4)$$

3. Grasshopper Optimization Algorithm

Grasshopper Optimization Algorithm is a natured inspired algorithm that is being used for the purpose of numerical solving problems. The main driving force behind this algorithm is the behaviour and the interaction of a grasshopper in a swarm in nature. Furthermore, let's talk about the life cycle of the grasshopper. There are three phases that a grasshopper passes through. Firstly, the egg stage, a very initial phase that lasts for a few weeks. As soon as the ground temperature increases, the egg starts development and hence nymph phase starts. Secondly, the nymph phase, grasshoppers do not have wings in this phase so that they move slowly over there in search of food. Last but not the least, the adulthood phase, where grasshoppers possess wings due to which they can fly and make sudden jumps for food searching. Therefore, this is the main driving force behind the GOA algorithm. Apart from that, the exploration and exploitation are two processes exercised by a swarm while searching for food. In the exploration phase, swam searches for food sources and, therefore, all the value positions of the grasshoppers along with their fitness values are updated. However, in the exploitation phase, best solution among all the available solutions is found.

3.1 Mathematical Model of Grasshopper Optimization Algorithm

The grasshopper optimization algorithm operates not only on the social behaviour of grasshoppers, but also it follows the hunting method of grasshoppers in nature. This algorithm is based on population where every grasshopper denotes a specific solution in a grasshopper swarm. Therefore, it is necessary to find the position of all the solutions in the swarm. Thus, the mathematical model for finding the solution is as follows.

$$\boldsymbol{X_i = S_i + G_i + A_i} \quad \textbf{(5)}$$

In the above equation, there are three variables that define the position of a grasshopper. Si is the social interaction force between grasshoppers; Gi represents gravitational pull while Ai denotes wind advection.

3.2 The Social Interaction Force

The main driving force that plays an important role about the movement of a grasshopper in a swarm is social interaction force. Mathematical model of this force is as follows.

$$\boldsymbol{S_i = \sum_{j=1, j\neq i}^{M} Z(d_{ij})(\widehat{d_{ij}})} \quad \textbf{(6)}$$

In the above equation, dij is the distance between ith and jth grasshoppers. Besides, d̂ij is a unit vector from the ith to the jth grasshopper, and Z function denotes the power of social forces acting on ith grasshopper. Mathematical models of all these variables are as follows.

$$\boldsymbol{d_{ij} = |\, x_j - x_i \,|} \quad \textbf{(7)}$$

$$\boldsymbol{Z(d) = f * \exp\left(-\frac{d}{l}\right) - \exp\left(-d\right)} \quad \textbf{(8)}$$

$$\boldsymbol{\widehat{d_{ij}} = \frac{x_j - x_i}{d_{ij}}} \quad \textbf{(9)}$$

In equation (9), 'l' represents attractive scale length, 'f' represents attraction strength, and 'Z' describes the forces of attraction and repulsion between grasshoppers.

3.3 Plot of Social Interaction Force (Z) on a Grasshopper with respect to Unit Distance (d).

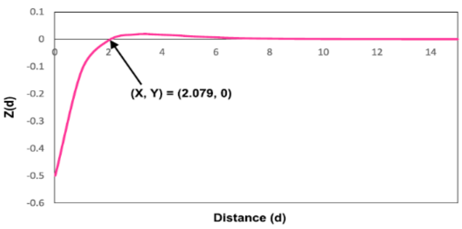

Fig. 1. Plot of **z** with respect to **d** when **f**=0.5 and ***l***=1

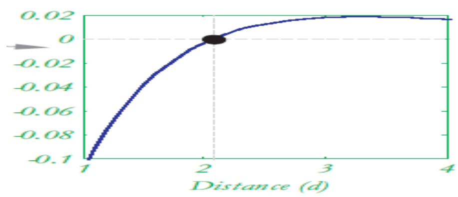

Fig. 2. Plot of **z** with respect to **d** when d is in between 1 and 4 units of distance

Different values of f and l give different zones of attraction, repulsion and comfort as shown in figure 2. However, the above plot can be divided into two zones. Firstly, the comfort zone, when distance is 2.079 units, Z(d) is zero means the grasshopper experiences neither attraction nor any repulsion. Secondly, the attraction zone, when distance goes beyond 2.079, the grasshopper experience attraction to reach the food until 4 units of distance. Furthermore, grasshopper experiences neither attraction nor repulsion beyond 4 units of distance. Hence, it is concluded that this function cannot be used for larger distances between grasshoppers.

3.4 Modified version of Xi=Si + Gi +Ai

A little modification in equation (1) makes it possible to find forces over larger distances between grasshoppers. The modified version is as follows.

$$X_i = \sum_{\substack{j=1 \\ j\neq i}}^{N} Z\left(\left|x_j - x_i\right|\right) \frac{x_j - x_i}{d_{ij}} - g\widehat{e_g} + u\widehat{e_w} \tag{10}$$

In the above expression, -g is gradational pull and ê g is a unit vector. Apart from that, 'u' is a constant drift velocity that a grasshopper attains.

3.5 Mathematical Model for Optimal Solution

Although the equation (10) resolves the issue of large distance between grasshoppers but this expression cannot be used for grasshopper swarm. This is owing to the sharp converging nature of a grasshopper to converge to a specific point; however, a grasshopper swarm cannot converge to a specific point. Therefore, a modified expression is needed to solve the optimization problem. The modified expression for optimization is as follows.

$$X_i^d = c\left(\sum_{\substack{j=1 \\ j\neq i}}^{N} c\left(\frac{uB_d - lB_d}{2}\right) Z\left(\left|x_j^d - x_i^d\right|\right) \frac{x_j - x_i}{d_{ij}}\right) + T_d \tag{11}$$

In the above expression, uBd is upper bound while lBd is lower bound in D^{th} dimension. Besides, c is a decreasing coefficient to shrink the comfort, attractive and repulsive zone which is calculated by $\mathbf{c = cmax - l\frac{cmax - cmin}{L}}$. 'l' indicates current iteration while L is used for maximum number of iterations. However, $Z(|x_j^d - x_i^d|)$ represents whether the grasshopper should be repelled from or attracted to the target. Apart from that, in expression (7), it is supposed that the wind is always directed towards the target (T_d).

Flow Chart of GOA Hybrid with Local Search Methods

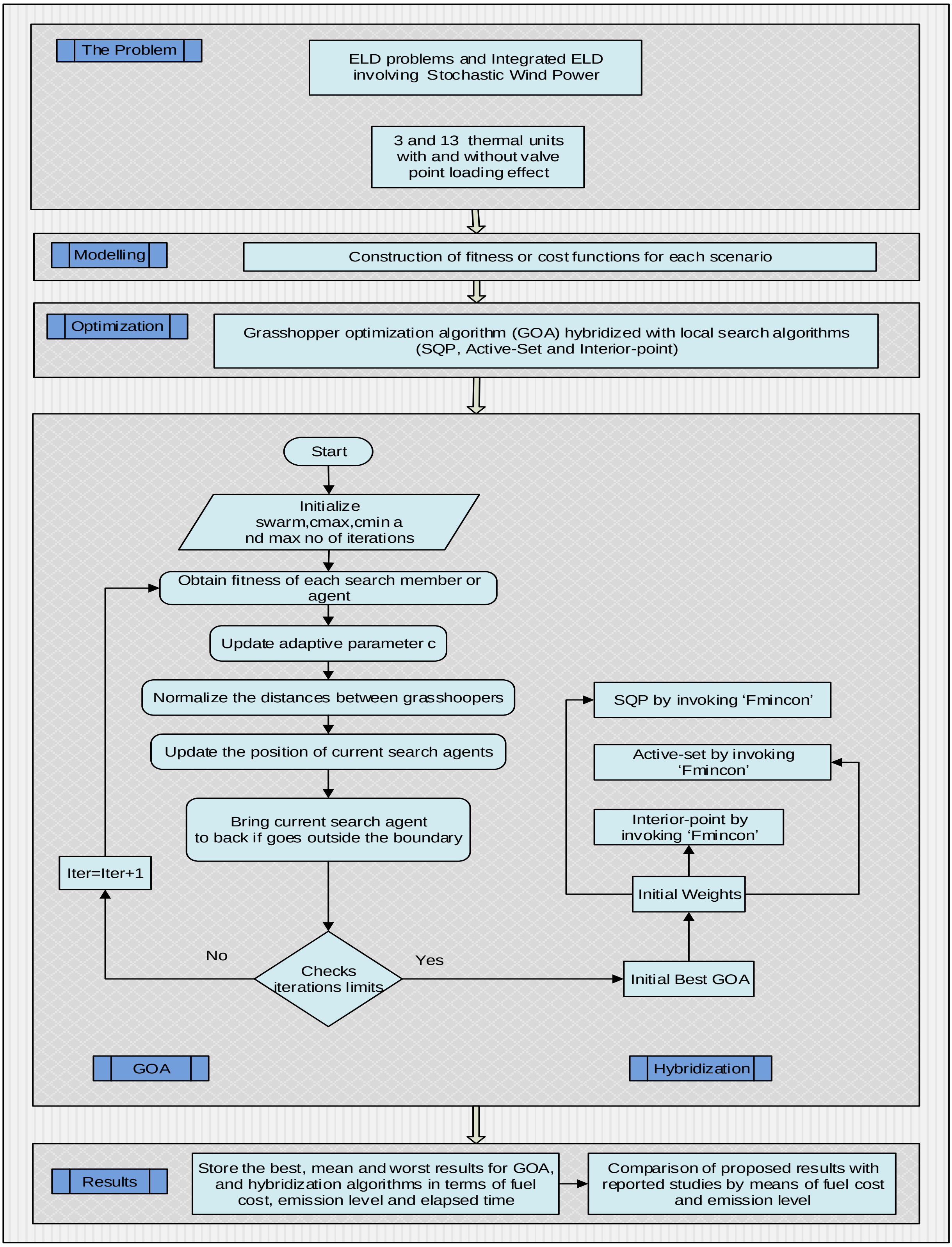

Fig. 3. Flow chart of GOA hybrid with local search methods

4. Results and Discussion

Comprehensive simulation results for ELD problems are presented here for thorough examination of the schemes, i.e., GOA, GOA-IPA, GOA-SQP and GOA-ASA, projected with 3 and 13 generators-based test system for both with and without VPLE scenarios.
The permissible power generation limits for 3 and 13 generating units along with the coefficients of fuel price are taken from [8]. While 850 MW is the power demand for three generating units and 1800 MW is the power demand for thirteen generating units [9]. However, for the purpose of comparative analysis of GOA results with Modified Elephant Herding Optimization (MEHO), Elephant Herding Optimization (EHO), Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO), the date has been taken from [7]. It is evident from the comparison that the results of the GOA are far better than that of MEHO, EHO, PSO, and ACO. Because GOA fuel cost for 13 generating units with VPLE is 18048.3 $/hr ;however, 18969.99, 19219.913, 19245.58 and 18830.95 $/hr are the fuel costs of MEHO, EHO, PSO and ACO, respectively.

4.1. Three Units Test System

The GOA has been applied for solving the ELD problem of three power generating unit system with and without VPLE. In order to find the optimal results, the algorithm has been executed for hundred times for every situation, shown in Fig 4 and 5. Further, the algorithm uses thousands of iterations to solve ELD problem. Here, the Table 1 shows, the complete simulation results by best, worst and mean values in case of including and excluding VPLE with its cost calculations for three units test system.
Subsequently, for the sake of optimization, GOA has been hybridized with some mathematical techniques depend on SQP (GOA-SQP), ASA (GOA-ASA) and IPA (GOA-IPA) not only for VPLE, but also for without VPLE. The result of these hybridized techniques is given in Table 2. Additionally, for three generators the optimization characteristics in terms of 100 independent runs for GOA-IPA, GOA-SQP and GOA-ASA both with and without VPLE are shown in Figs. 6 and 7 respectively. With the help of comparison it is found that GOA-IPA and GOA-SQP for with VPLE gave better convergence and accuracy than that of other hybrid algorithms.

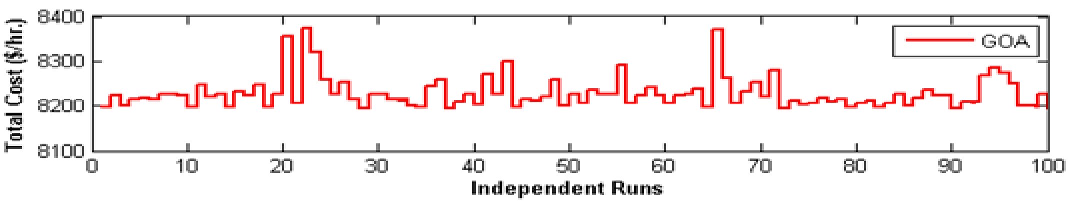

Fig. 4. Independent trials verses fuel cost for three units based ELD without VPLE

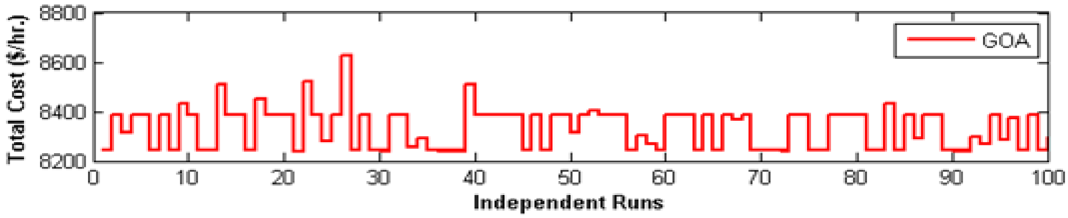

Fig. 5. Independent trials verses fuel cost for three units based ELD with VPLE

Table1: Optimized powers and fuel price for three units ELD by GOA for Pd =850 MW

Generators	Excluding VPLE			Including VPLE		
	Best	Mean	Worst	Best	Mean	Worst
P1 (MW)	391.7667	400.0000	600.0000	300.6138	392.3836	423.5195
P2 (MW)	344.1687	400.0000	100.0000	400.0000	257.6164	226.4805
P3 (MW)	114.0646	50.0000	150.0000	149.3862	200.0000	200.0000
Total Generation	850.0000	850.0000	850.0000	850.0000	850.0000	850.0000
Total Cost ($/hr.)	8194.8578	8227.8700	8371.6700	8240.4398	8368.7836	8624.4998
Execution Time (sec)	0.7046	0.7400	0.7011	0.2770	0.2800	0.2773

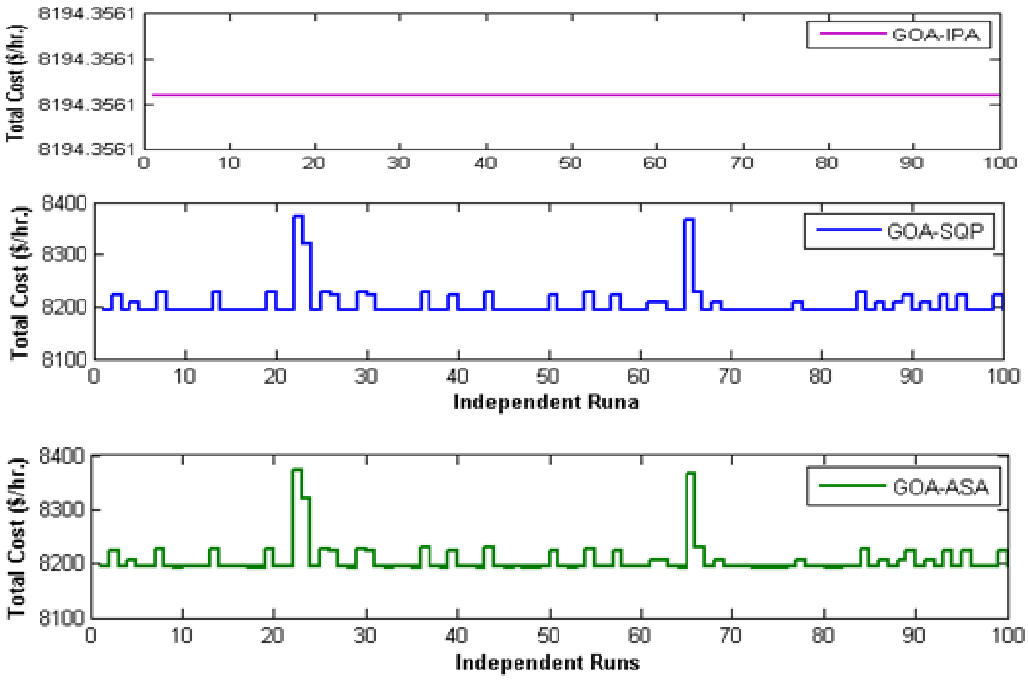

Fig. 6. Independent runs for 3 generators test system involving GOA-IPA, GOA-SQP & GOA-ASA excluding Valve Point Loading Effect

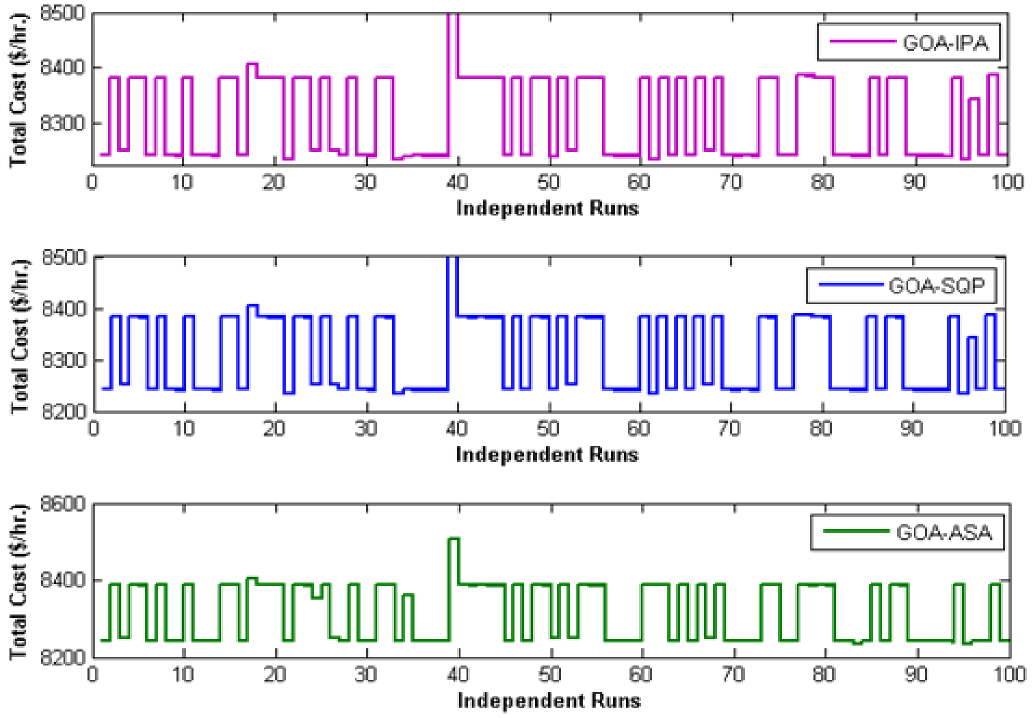

Fig. 7.
Independent runs for 3 generators test system involving GOA-IPA, GOA-SQP & GOA-ASA including Valve Point Loading Effect

Table 2: Comparison of the results for hybridized GOA schemes for three units ELD without VPLE

Generators	Excluding VPLE			Including VPLE		
	GOA-IPA	GOA-SQP	GOA-ASA	GOA-IPA	GOA-SQP	GOA-ASA
P1 (MW)	393.1698	393.1698	393.1698	300.2668	300.2668	300.1957
P2 (MW)	334.6038	334.6038	334.6038	400.0000	400.0000	400.0000
P3 (MW)	122.2264	122.2264	122.2264	149.7332	149.7332	149.8043
Total Generation	850.0000	850.0000	850.0000	850.0000	850.0000	850.0000
Total Cost ($/hr.)	8194.3561	8194.3561	8194.3561	8234.0718	8234.0718	8234.1115
Execution Time (sec)	0.1005	0.0593	0.0357	0.0838	0.0841	0.0490
Iterations	13	21	9	8	8	10
Function Count	109	169	63	98	98	89

4.2. Thirteen Units Test System

The GOA has been applied for solving the ELD problem of thirteen power generating unit system with and without VPLE by setting search agent up to fifteen hundred. In order to find the optimal results, the algorithm has been executed for hundred times for every situation, shown in Fig 8 and 9. Further, the algorithm uses thousands of iterations to solve ELD problem. Here, the Table 3 shows, the complete simulation results by best, worst and mean values in case of including and excluding VPLE with its cost calculations for thirteen units test system.

Subsequently, for the sake of optimization, GOA has been hybridized with some mathematical techniques depend on SQP (GOA-SQP), ASA (GOA-ASA) and IPA (GOA-IPA) not only for VPLE, but also for without VPLE. The result of these hybridized techniques is given in Table 4. However Fig. 10 and 11 represent the independent run of thirteen units for GOA-SQP, GOA-AS and GOA-IPA not only for with VPLE, but also for without VPLE. With the help of comparison, it is found that GOA-IPA with VPLE gave better convergence and accuracy than that of other hybrid algorithms.

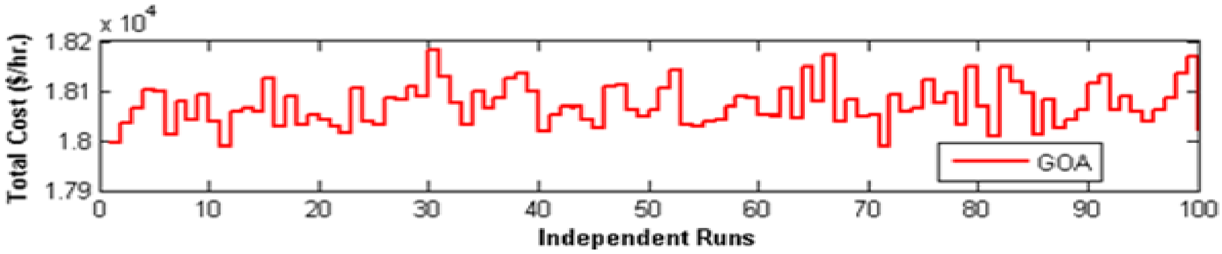

Fig. 8. Independent trials verses fuel cost for thirteen units based ELD (a) without VPLE and (b) with VPLE

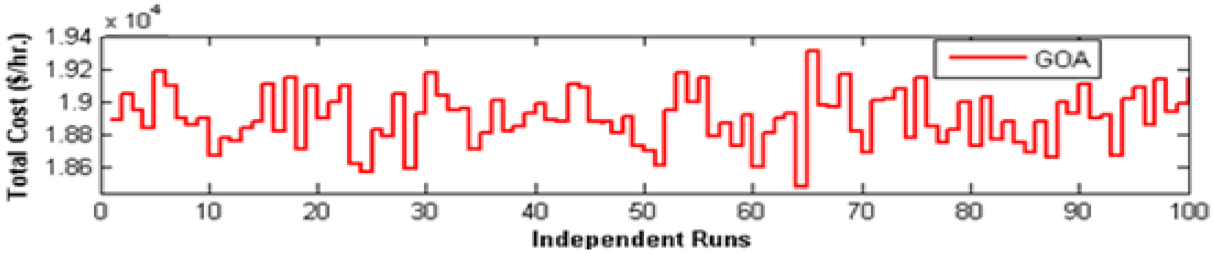

Fig. 9. Independent trials verses fuel cost for thirteen units based ELD (a) without VPLE and (b) with VPLE

Table 3: Optimized values of power and fuel price for 13 Units based ELD by GOA for Pd =1800 MW

Generators	Excluding VPLE			Including VPLE		
	Best	Mean	Worst	Best	Mean	Worst
P1 (MW)	545.8337	183.6017	91.8697	442.0387	526.5770	379.7222
P2 (MW)	192.4585	177.9278	246.2781	226.8745	230.9088	0.0000
P3 (MW)	172.7113	360.0000	259.1089	357.2276	68.5334	241.6555
P4 (MW)	177.1647	180.0000	152.5342	60.0000	162.0409	160.0781
P5 (MW)	101.5264	60.0000	174.2335	60.0000	128.4536	180.0000
P6 (MW)	140.8174	117.1830	173.1370	108.2957	60.0000	122.2586
P7 (MW)	70.0132	180.0000	72.8013	60.0000	60.0000	180.0000
P8 (MW)	71.6106	112.2657	81.9620	105.3182	180.0000	102.1752
P9 (MW)	101.5329	175.5766	126.0759	60.0000	87.4101	87.3257
P10 (MW)	52.6673	86.5219	110.4299	40.2453	74.0287	81.6344
P11 (MW)	45.4343	41.4609	107.0183	40.0000	47.0474	94.8448
P12 (MW)	73.2295	65.8597	105.5041	120.0000	55.0000	115.3055
P13 (MW)	55.0000	59.6028	99.0472	120.0000	120.0000	55.0000
Total Generation	1800.0000	1800.0000	1800.0000	1800.0000	1800.0000	1800.0000
Total Cost ($/hr.)	17988.2729	18074.8307	18181.7942	18479.8787	18903.9545	19301.2741
Execution Time (s)	0.1695	0.1730	0.1655	1.6701	1.6301	1.6239

Table 4: Optimize results of hybridized GOA schemes for ELD system of thirteen units with VPLE

Generators	Excluding VPLE			Including VPLE		
	GOA-IPA	GOA-SQP	GOA-ASA	GOA-IPA	GOA-SQP	GOA-ASA
P1 (MW)	506.9118	506.9118	506.9117	359.0390	359.0382	359.0015
P2 (MW)	253.4559	253.4559	253.4559	224.0575	224.3992	223.5326
P3 (MW)	253.4559	253.4559	253.4559	299.0888	299.1975	298.9371
P4 (MW)	99.3627	99.3628	99.3628	109.7840	109.8662	109.2347
P5 (MW)	99.3627	99.3628	99.3628	159.7269	159.7330	158.9475
P6 (MW)	99.3627	99.3627	99.3628	109.8662	109.8660	109.1028
P7 (MW)	99.3628	99.3627	99.3627	109.8654	109.8664	109.6784
P8 (MW)	99.3628	99.3628	99.3627	109.8539	109.8660	108.1920
P9 (MW)	99.3628	99.3627	99.3628	60.0012	60.0000	60.0000
P10 (MW)	40.0000	40.0000	40.0000	73.6787	70.7687	76.9361
P11 (MW)	40.0000	40.0000	40.0000	75.0362	77.3987	76.4373
P12 (MW)	55.0000	55.0000	55.0000	55.0012	55.0000	55.0000
P13 (MW)	55.0000	55.0000	55.0000	55.0012	55.0000	55.0000
Total Generation	1800.0000	1800.0000	1800.0000	1800.0000	1800.0000	1800.0000
Total Cost ($/hr.)	17932.4741	17932.4741	17932.4741	18050.9515	18048.3000	18058.2052
Execution Time (s)	0.3240	0.3636	0.1952	0.5154	0.2049	0.4658
Iterations	60	81	51	55	56	119
Function Count	1645	2329	1383	1672	1706	3424

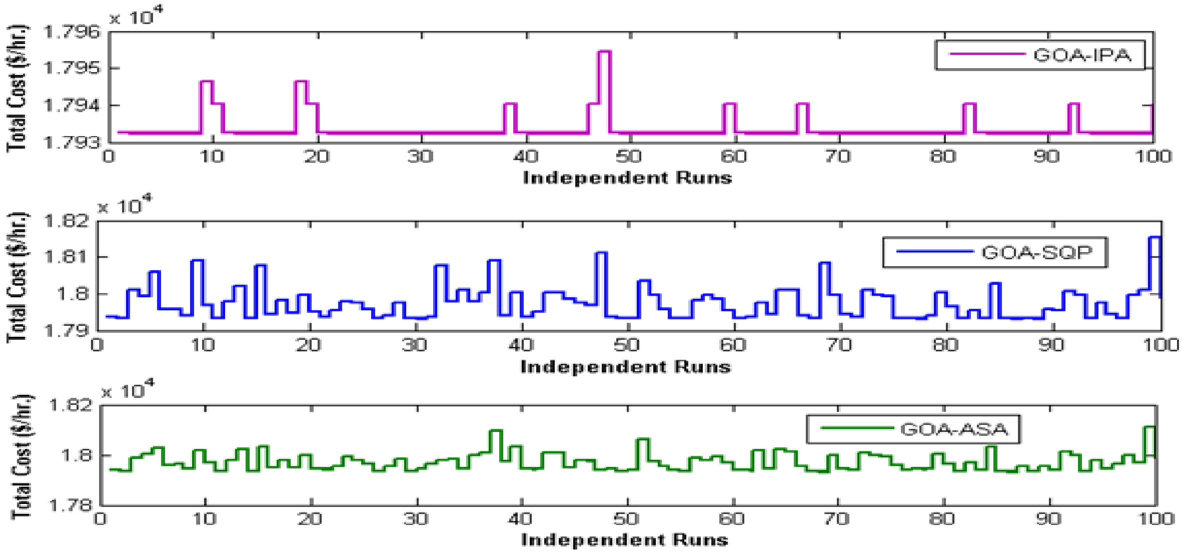

Fig. 10. Independent runs for 13 generators test system excluding Valve Point Loading Effect

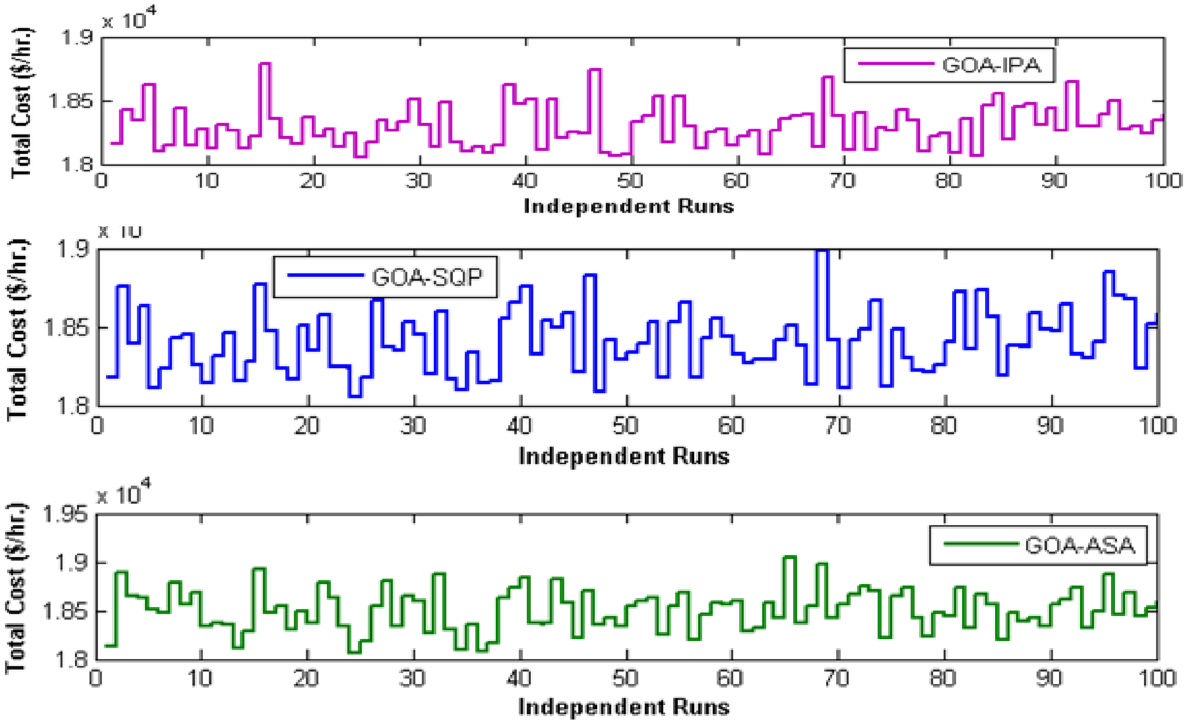

Fig. 11. **Independent runs for 13 generators test system involving GOA-IP, GOA-SQP & GOA-ASA including Valve Point Loading Effect**

4.3. Comparison of GOA results with MEHO, EHO, PSO and ACO

In table 5 and 6, the comparative analyses among different computational techniques have been enlisted. It is found that the GOA algorithm gives the best optimal results among all MEHO, EHO, PSO, and ACO optimization algorithms. The data for comparison has been taken from [7].

Table 5: Comparison of optimized values of fuel cost for 3 Units based ELD by GOA for Pd =850 MW for both with and without VPLE

Algorithms	**Excluding VPLE**		**Including VPLE**	
	Execution Time (sec)	**Fuel Cost (&/hr)**	**Execution Time (sec)**	**Fuel Cost (&/hr)**
MEHO	1.203	8199.147	1.203	9148.823
EHO	1.171	8207.846	1.171	9151.574
PSO	1.502	8203.516	1.502	9165.712
ACO	1.420	8207.98	1.420	9166.779
GOA-SQP	**0.1005**	**8194.3561**	**0.0841**	**8234.0718**

Table 6: Comparison of optimized values of fuel cost for 13 Units based ELD by GOA for Pd =1800 MW for both with and without VPLE

Algorithms	**Excluding VPLE**		**Including VPLE**	
	Execution Time (sec)	**Fuel Cost (&/hr)**	**Execution Time (sec)**	**Fuel Cost (&/hr)**
MEHO	1.704	17973.06	1.704	18969.99
EHO	1.97	17999.797	1.97	19219.913
PSO	1.803	18022.64	1.803	19245.58
ACO	1.712	18004.76	1.712	18830.95
GOA-SQP	**0.3636**	**17932.4741**	**0.2049**	**18050.9515**

5. Conclusion

The GOA is a new nature-inspired technique that has been used along with some other local search approaches like SQP, ASA and IPA for solving the ELD problem. The new hybridized techniques of GOA have been applied for solving the ELD problem of three and thirteen power generating unit system with and without VPLE by setting search agent up to fifteen hundred. It is found that these hybridized techniques give far better results than that of MEHO, EHO, PSO and ACO algorithms, in terms of fuel cost reduction. Further, with the help of comparison it is found that GOA-IPA and GOA-SQP for with VPLE gave better convergence and accuracy than that of other hybrid algorithms
The approach adopted in the present research work may be utilized in the significant areas pertaining to electric power system which formulates coordination in hydro-thermal mechanism, which is integrated with wind and solar form of energy. The research also provides a basis for monitoring the efficiency of the mechanism related to emission of gases from any thermal power system. Moreover, the research work on GOA and its hybrids also opens various avenues for superior optimization capabilities by taking certain evolutionary steps, employing specific and peculiar applications in fractional order systems, energy, power, active noise control systems, fluid dynamics, electric circuits and financial models.

Author Contributions: Waleed provided data, designed the analytical approach proposed with performed detailed simulation with analysis and wrote the paper; Affaq Qamar supervised and conceived the research theme and Babar Sattar help in writeup and make necessary corrections.

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