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Article

Economic Load Dispatch Optimization Using the Jaya Algorithm: A Case Study on the Libyan Power Grid

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Abstract: Economic Load Dispatch (ELD) is a central optimization problem in modern power system operation, aiming to minimize generation costs while satisfying operating constraints. The respective paper presents a new data-driven technique developed to tackle the ELD problem in specific cases of Libya. In our implementation we use the Jaya Optimization Algorithm (JOA) algorithm, which is a simple and parameter-free metaheuristic. In this model, a 24-hour load profile is included in addition to the quadratic function, fuel cost function, and generator limits that reflect reality. Then, JOA is compared to PSO and WOA. The experimental results show that JOA has a shorter computational time and superior solution quality and stability in comparison to PSO and WOA. Analysis of the two alternative fuels demonstrated that switching to heavy fuel is cost-effective, and that JOA provides a good quality heuristic for practical ELD problems.
Keywords: Economic Load Dispatch; Jaya Optimization Algorithm; cost function

1. Introduction

General Electricity Company of Libya (GECOL) is one of the basic builders in maintaining elements of economic development and social balance. The operational characteristics of the Libyan power grid differ, including high dependence on thermal and gas power, downside risk in fuel supply availability, the age of generation units, and load variability [1-2]. Libya has been experiencing considerable power shortages and blackouts over the past two years as a result of war damage, the destruction of essential infrastructure listed for reconstruction, and a series of cases of sabotage or vandalism at sites hosting installations associated with power-generating stations connected to the transmission network [3]. The high operating costs and low power-generation efficiency have provoked these concerns, making it even more urgent to introduce advanced optimization technologies to improve system operation and reliability.

Among many optimization problems, such as ELD at the operational level of the power system. Economic load dispatch (ELD) is the process of determining the optimal outputs of all generating units in a power system that minimize total fuel cost, subject to system constraints and operational limits [4].

Proper resolution of the ELD problem can result in lower fuel and operating costs, thereby enhancing the performance of electrical power systems (e.g., the Libyan grid).

The economic dispatching problem is essentially about the input-output properties of power plants. Some classical tools developed to tackle economic power distribution problems, including the gradient method, the lambda iteration method, Newton's method, dynamic programming, linear programming [5], and interior point methods, have been employed to solve economic power dispatch problems. Optimization methods like Genetic Algorithm (GA) [6], simulated annealing (SA) [7], Ant Colony Optimization (ACO) [8], Artificial Bee Colony (ABC) [9], evolutionary programming [10], Whale Optimization Algorithm(WOA) [11], particle swarm optimization (PSO) [12] and differential evolution (DE) [13] have also been considered to be viable options with good results along with Bat Algorithm(BA) [14].

Nonetheless, the performance of these algorithms is very sensitive to parameter tuning, and finding generally good values has proven rather difficult, which can, from time to time, lead to slow convergence and premature stagnation.

A new, simple metaheuristic optimization approach, the Jaya Optimization Algorithm (JOA), was developed by Rao et al. in 2016. Compared to numerous population-based techniques, the most significant advantage of the Jaya algorithm is that it requires no tuning of any algorithm-specific parameters throughout this optimization process. The basic idea is to bring the solution closer to the fittest candidate(s) and farther from the least-fit candidates, based on their fitness values. Such an absolute, parameter-free nature makes the Jaya algorithm very interesting for practical power system applications, where ease of implementation and computational efficiency are important to some extent [15-16].

Various researchers have shown that Jaya can be used to solve ELD, in both non-convex and constrained forms. The algorithm has an excellent convergence rate and solution accuracy and is more stable than those of traditional and parameter-greedy metaheuristic methods [17-18]. However, most research to date has been conducted on practical components using traditional test systems, and only a few successful applications in real/near-real national power grids have been reported

2. Contributions

This paper investigates a comprehensive, smooth model of an ELD solution in the Libyan Power System using the Jaya (JOA) optimization algorithm. Unlike most studies conducted to date, which mostly analyses the standardized IEEE benchmark systems, the proposed approach in this work can be used on its own and also increases practical relevance and applicability, as it is based on real 24-h load demand data obtained from the Libyan national grid. This research also compares the impacts of light and heavy fuel oil on generation and economics. Next, we conduct a comparative analysis between Jaya and the classical metaheuristics PSO and WOA, showing that our proposal is superior to both algorithms in optimal solution time, performance measures (fitness) associated with finding high-quality solutions, and longest runtime. This, therefore, provides an interface between non-linear optimization methods and real-life applications (power system design), especially in the implementation in a developing country such as Libya.

3. Mathematical Formulation of the ELD Problem

The Economic Load Dispatch (ELD) problem is a long-standing optimization issue in power system operations. It aims to determine the desired power outputs of all committed generating units, while accounting for various constraints and objective functions to minimize total generation cost. In thermal power systems, fuel costs are a major component of operating costs. This means that precise modeling of the fuel cost function and all system constraints is necessary to maintain both economic and reliable system operation [19-20].

Then the fuel cost function of each generating unit is usually modeled as a quadratic function:

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

Where: $F_i(P_i)$: Fuel cost of generator i (LDY/hour), P_i: Power output of generator i (MW), and a_i , b_i and c_i i Cost coefficients of generator.

A practical economic dispatch study will involve using a simple cost function, such as the quadratic function [21], which provides a reasonably good approximation to most real generator cost curves

3.1. Objective Function

The ELD problem aims to minimize total generation cost:

$$Min\ F_T = \sum_{i=1}^{N} F_i(P_i) \tag{2}$$

Where: $\boldsymbol{F_T}$: Total generation cost, and **N**: Number of generators.

3.2. Power Balance Constraint

The sum of the active generated power must equal the load demand in a system.

$$\sum_{i=1}^{N} P_i = D + P_l \tag{3}$$

Where: $\boldsymbol{D}$ load demand (M), and $\boldsymbol{P_l}$ represents the total transmission line loss(MW).

For simplified ELD models, when the transmission losses are not considered, the power balance equation can be written as.

$$\sum_{i=1}^{n} P_i = D \tag{4}$$

3.3. Generator Limits

Every generator is modeled to operate between minimum and maximum limits:

$$P_{i,max} \leq P_i \leq P_{i,min} \tag{5}$$

Where: $\boldsymbol{P_{i,max}}$ Maximum power limit, and $\boldsymbol{P_{i,min}}$ Minimum power limit

3.4. Transmission Loss (Optional)

When transmission losses are considered, they can be expressed using B-coefficients:

$$P_{loss} = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i B_{ij} P_j + \sum_{i=1}^{N} B_{i0} P_I + B_{00} \tag{6}$$

Where: $\boldsymbol{B_{ij}}$, $\boldsymbol{B_{i0}}$, $\boldsymbol{B_{00}}$ transmission loss coefficients

The ELD problem becomes increasingly nonlinear and complex with transmission loss, so solutions from classical optimization methods cannot reach their optimal points.

4. Jaya Optimization Algorithm

The Jaya Optimization Algorithm is a generic population-based optimization algorithm developed for unconstrained and constrained optimization problems [22]. Jaya itself means victory, and this is the process defined along with the basic objective, which states that, in the end, it tries to provide a good solution by updating the number of solutions on the western side candidates throughout optimization. Unlike most traditional metaheuristic algorithms, the Jaya algorithm is a parameter-less global optimization approach, with no algorithm-dependent control parameters (such as crossover probability, mutation rate, or inertia weight or acceleration coefficients) [2324-].

Let f(x) be the objective well defined to minimize (or maximize). Assume we have 'm' number of design variables (j=1, 2, ..., m) and 'n' candidate solutions (population size, k=1,2, ..., n) in any given iteration i. The best f(x) value is obtained by the best candidate solution across all candidates, and the worst candidate achieves a worse f(x) level than appears in all other candidate solutions (that is, f(x)worst). It states that if the value of the $k-th$ candidate in the $i-th$ iteration is Xj,k,i, then its step-size update is given by Eq (5).

$$X'_{j,k,i} = X_{j,k\,i} + r_{1,j,i}\left(X_{j,best,i} - \left|X_{j,k,i}\right|\right) - r_{2,j,i}\left(X_{j,\mathrm{worst},i} - \left|X_{j,k,i}\right|\right) \tag{6}$$

Xj, $best$, i is a j parameter value of the best candidate, and Xj, wors3 mi is a similar value for the worst member of the solution set. $X'j,k,i$ new value for Xj,k,i. Where $r1$,,i and $r2$,j,i are the two random numbers for the jth variable at the $i-th$ iteration in [0–1]. Where the term" $r\_(1,j,i)$ $(X\_(j,best,i) - |X\_(j,k,i)|)$" represents how close the candidate is to the best solution, and "$r\_(2,j,i)$ $(X\_(j,worst,i) - |X\_(j,k,i)|)$" considers how far it is away from heterogeneous pairs towards the worst solution as well. If $X'j,k,i$ has a better function value, it is used.

Eventually, all the function values accepted in each iteration will serve as input in the next iteration. The flowchart of the Jaya algorithm in Fig. 1 shows the population initialization, solution update, selection, and termination [25-26].

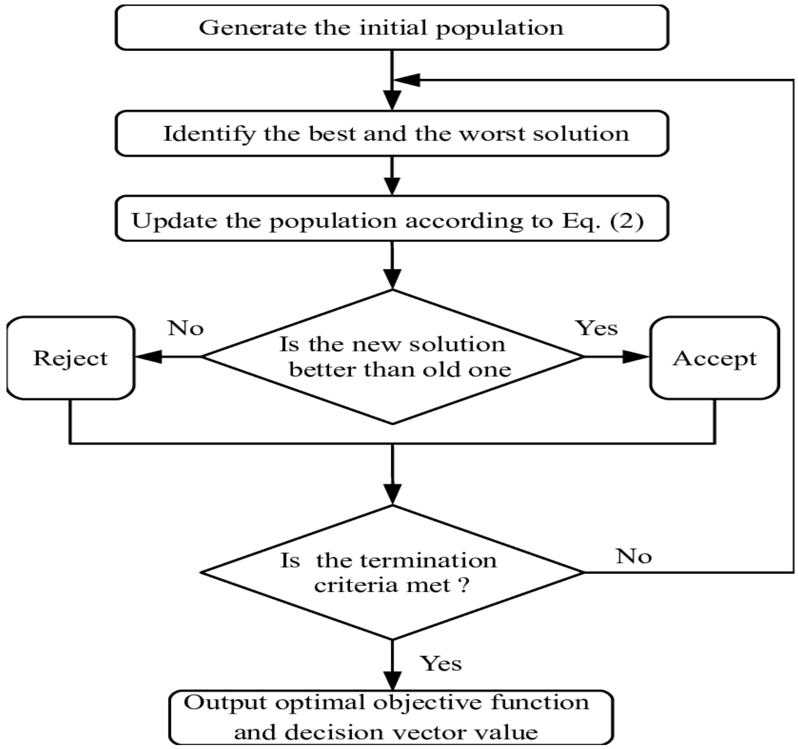

Figure 1. Flowchart of the Jaya algorithm**.**

5. Case Study Description: Libyan Power System

The Libyan power system is a centrally interconnected national grid that supports the country's economic activities and social development. It supplies electricity to major urban, industrial, and residential areas. Its large geographical area and reliance on conventional generation cause operational and economic challenges, making it a realistic case study for Economic Load Dispatch (ELD) optimization research [27].

To properly study the economic load dispatch (ELD) problem, a simplified yet representative model of the Libyan power system is adopted in this work. Two operating conditions are studied, each containing three generating units selected from the major Libyan power stations.

5.1. Case 1 (Light Fuel Oil–Fired Units):

The purpose here is to specify the fuel type for power plant units, including large generating stations in the Libyan power system, with light fuel oil as the primary fuel option in this case. These include Al-Khums Generating Station, South Tripoli Power Station, and Zawiya Power Plant. The non-linear relationship between fuel consumption and power output is reflected in the quadratic fuel cost curve applied to each generating unit.

The fuel cost coefficients a, b, and c for each unit are given in Table 1, which serve as the basic inputs for the ELD analysis under light fuel oil–fired conditions [28].

The optimal ELD problem is mathematically modeled based on the basic operational constraints of power systems; therefore, every generating unit works within its generation limits in both directions to keep the system not only operating securely but also as economically as possible.

Table 1. Cost coefficients for the three-unit system

Generator Unit	*a*	*b*	*c*	Min Power (MW)	Max Power (MW)
G1	0.1551	7.363	2731	50	120

G2	0.0424	26.12	1038.6	45	110
G3	0.0491	32.37	1339.3	40	105

5.2. Case 2 (Heavy Fuel Units):

This work evaluates decisions regarding power generation units running on heavy fuel oil, in line with a common practice in the Libyan power system [29]. The plants evaluated include Misurata Power Plant, Al-Khums Power Plant, and West Tripoli Power Plant. A quadratic fuel cost function is used to represent the nonlinear relationship between fuel consumption and power output of each generating unit. The fuel cost coefficients a, b, and c that characterize the operating cost under heavy fuel conditions are summarized in Table 2 and serve as important input variables for the Economic Load Dispatch (ELD) Analysis.

In the present case, basic operational constraints are included to address practical considerations when formulating the ELD problem, ensuring secure, stable, and economically viable performance of the power system. More specifically, each generating unit must produce power within the defined minimum and maximum generation limits, ensuring that the dispatch solution meets technical and operational constraints.

Table 2. Cost coefficients for the three-unit system

Generator Unit	*a*	*b*	*c*	Min Power (MW)	Max Power (MW)
G1	0.0076	7.8569	87.603	40	110
G2	0.007605	7.815	88.58	40	110
G3	0.005580	8.450	147.64	50	105

The system load is considered from a 24 h load curve that describes the daily demand variation of the Libyan power system. Here, the load demand is very low during off-peak hours, rises during the daytime , and peaks in the evening. This hourly demand profile is used to test the sensitivity and effectiveness of the optimization algorithm under different load conditions. As shown in Table 3, the hourly load data for the 24 hours are extracted from GECOL to ensure realistic operating conditions for the national grid.

Table 3. Power demand for a period of 24 hours

Time	Load (MW)	Time	Load (MW)	Time	Load (MW)	Time	Load (MW)
1	222	7	213	13	262	19	268
2	193	8	230	14	266	20	284
3	179	9	234	15	255	21	278
4	178	10	245	16	242	22	273
5	177	11	244	17	250	23	258
6	190	12	266	18	267	24	227

6- Results and discussion

The simulation results confirm the effectiveness of the Jaya Optimization Algorithm (JOA) in solving the ELD problem for the Libyan power system over 24 hours, with 500 iterations for each case. Table 4 under Case 1 shows the optimal hourly power outputs for the three generating units (G1, G2, and G3) and their respective total operating costs. The output exploration system load ranges from 177 MW to 284 MW, and the generation schedule meets the power balance constraint. Hourly operating costs total 278,406.34 LYD, ranging from a minimum of 9,618.95 LYD during off-peak periods to 13,139.84 LYD during peak demand. JOA achieved the lowest total operating cost of 278,406.34 LYD, compared with 279288.19 LYD for WOA and 279,810.20 LYD for PSO. As a result, JOA improved economic performance by 0.3157% relative to WOA and 0.5017% relative to PSO. These outcomes indicate that the JOA algorithm can find more economically efficient solutions than those obtained for the Economic Dispatch Problem.

Table 4: Optimal Hourly Generation and Operating Cost

Hour	G1	G2	G3	Total Cost PSO	Total Cost WOA	Total Cost JOA
1	81.17	86.13	54.70	11143	11083	11080.04
2	79.38	73.62	40.00	10168	10150	10126.21
3	76.73	62.27	40.00	9735.4	9780.8	9680.75
4	77.42	60.57	40.00	9658.7	9664.8	9652.15
5	77.64	59.36	40.00	9666.1	9647.5	9618.95
6	84.55	65.45	40.00	10165	10048	10035.49
7	82.70	84.62	45.68	10788	10838	10782.06
8	78.70	77.33	73.98	11346	11379	11344.68
9	83.74	81.00	69.26	11548	11539	11474.70
10	82.76	77.77	84.48	11865	11843	11841.30
11	77.96	73.22	92.82	11952	11811	11814.98
12	83.97	78.41	103.62	12574	12600	12538.18
13	80.56	88.26	93.18	12458	12528	12405.71
14	88.75	88.16	89.09	12623	12634	12540.66
15	84.61	92.18	78.20	12217	12177	12176.61
16	82.04	81.49	78.48	11787	11783	11738.50
17	85.43	86.14	78.43	12057	12055	12003.63
18	83.46	85.36	98.19	12780	12580	12571.22
19	76.59	86.41	105.00	12673	12637	12609.25
20	83.18	95.82	105.00	13179	13205	13139.84
21	87.48	86.01	104.51	12960	12939	12938.68
22	83.93	84.07	105.00	12804	12779	12768.44
23	80.48	72.52	105.00	12330	12277	12276.41
24	80.22	73.30	73.48	11333	11310	11247.90

Figure 2 illustrates the total generation-to-load ratio (24-hour data). It is clearly shown how the power balance constraint is satisfied by the Jaya Optimization Algorithm (JOA) in the generation following this load profile. That being evident, we observe generation dips between Hours 3–5, and the maximum output of 284 MW is reached in peak hours (Hours 19–22). The close, flatness of these curves indicates that the system is running quite stably in terms of accuracy, as there are no spikes visible.

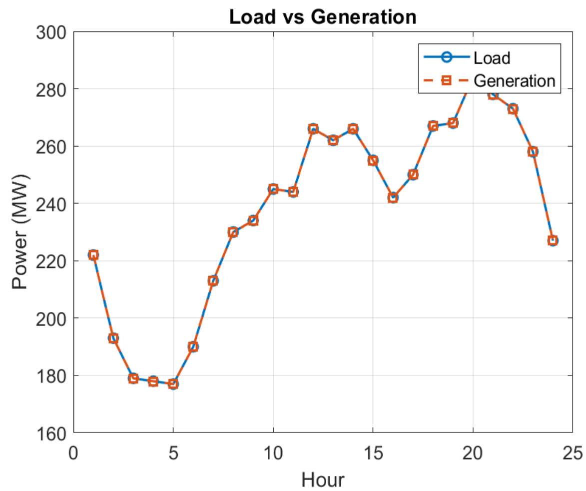

Figure 2. Load Demand versus Total Generation Profile.

Figure 3 shows the hourly generation cost obtained using the Jaya Optimization Algorithm (JOA) and shows that the cost profile closely follows the load demand profile. The lowest cost is during the non-peak hours (Hours 3–5), and the highest cost reaches about 13,139.84 LYD at Hour 20. This tendency is consistent with the nonlinearity of demand and operating costs, which validates both the effectiveness of the quadratic cost model and the efficiency of the dispatch strategy shown in this paper.

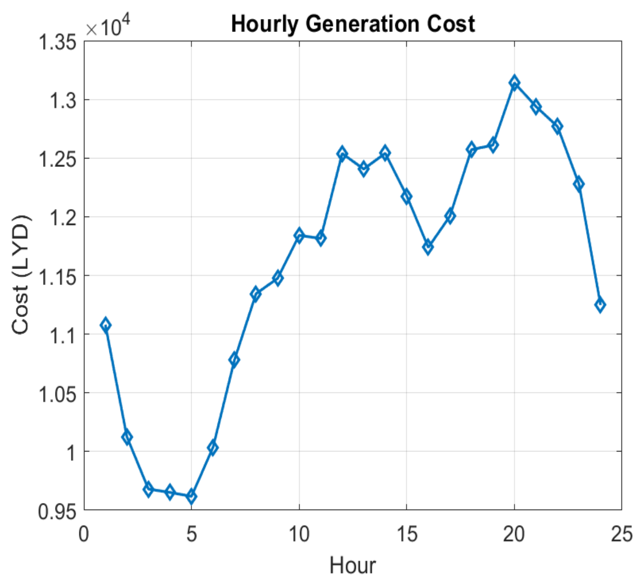

Figure 3. interactive hourly operating cost.

The convergence behavior of the Jaya optimization algorithm (JOA) is shown in Figure 4, where the cost decreases significantly in the early iterations, then stabilizes as we approach the optimal value. These results indicate fast convergence and stable behavior, indicating that the algorithm can reach an optimal solution without oscillating.

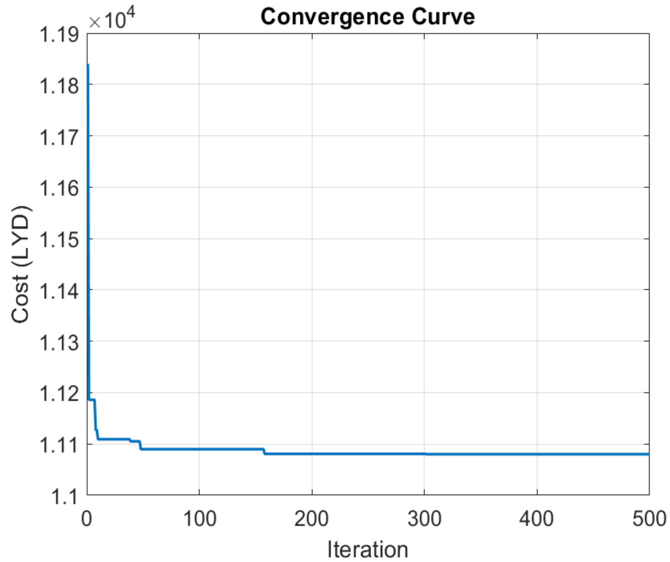

Figure 4. Cost convergence curves.

The power generation of the three units in 24 h is given in Figure 5. The stacked plot shows that each generator adjusts its contribution depending on the load requirements (i.e., more during peak hours 19–22 and less during off-peak Hours 3–5). However, upon initial examination, it is apparent that Generator 3 has a distinct economic advantage and will supply most of the output during peak demand conditions. Such Behavior Proves that the Jaya Optimization Algorithm Effectively Enables Optimal Array and Balanced Generation Scheduling.

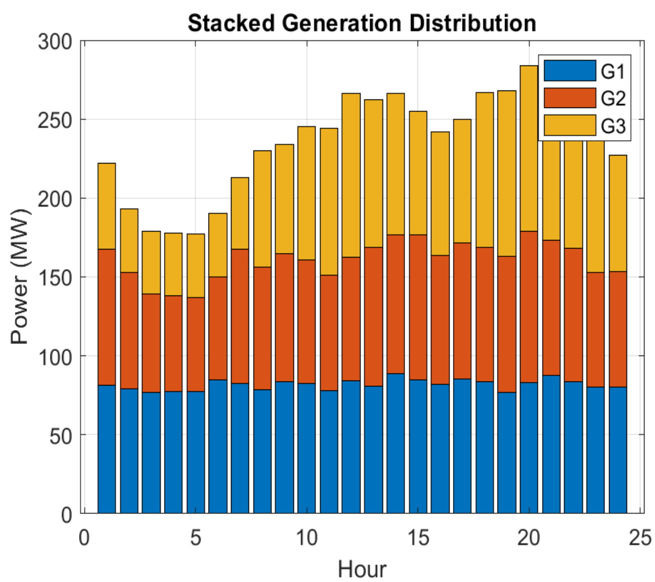

Figure 5. Stacked Generation Distribution.

In Table 5, the optimal hourly power dispatch and operating cost for Case 2 are presented using JOA, with 500 iterations per case. The results indicate that generation is appropriately allocated across the user units based on load demand, meeting the power balance constraint entirely over a 24-h period. Using JOA, the total operating cost is about 56833.73 LDY across the discretized 24–hour horizon. The lowest cost occurs during off-peak hours, at 1817.61 LDY at Hour 5, while the highest occurs during peak demand, at 2793.89 LDY at Hour 20. For the considered load range, the best total operating cost of 56833.73 LDY was obtained by JOA, which performed better than WOA (56929.10 LDY) and PSO (56948.05 LDY). So JOA enhances the economic performance by 0.1675% when compared with WOA and by 0.2007% compare to PSO, respectively. These figures reveal the ability of JOA to achieve more economical solutions for the Economic Dispatch problem.

Table 5: Optimal Hourly Generation and Operating Cost

Hour	G1	G2	G3	Total Cost PSO	Total Cost WOA	Total Cost JOA
1	59.89	77.44	84.66	2229.6	2234.3	2231.65
2	73.85	68.91	50.24	1971.9	1967.0	1958.99
3	82.58	46.42	50.00	1842.0	1837.3	1840.58
4	56.05	69.99	51.96	1832.1	1836.1	1828.98
5	68.63	58.37	50.00	1836.0	1822.1	1817.61
6	54.05	85.95	50.00	1935.0	1934.5	1935.66
7	75.65	77.07	60.29	2156.4	2146.7	2139.51
8	81.06	78.82	70.12	2305.8	2303.1	2295.08
9	75.94	82.47	75.59	2341.2	2335.6	2331.48
10	72.46	95.86	76.68	2438.3	2444.5	2434.48
11	97.38	95.65	50.97	2426.6	2423.0	2423.41
12	103.79	97.31	64.91	2633.2	2644.7	2628.27
13	91.77	74.83	95.40	2592.2	2600.6	2593.74
14	110.00	106.00	50.00	2626.2	2625.1	2630.43
15	67.85	110.00	77.15	2523.5	2523.9	2530.15
16	68.47	89.85	83.68	2429.4	2412.0	2407.87
17	87.80	98.92	63.28	2479.3	2486.7	2478.09
18	89.44	97.00	80.56	2634.9	2636.0	2635.19
19	96.03	102.95	69.03	2646.8	2642.9	2643.48
20	104.75	110.00	69.25	2793.6	2802.2	2793.89
21	87.37	85.63	105.00	2738.0	2744.0	2742.08
22	89.80	110.00	73.21	2698.4	2691.3	2691.25
23	104.06	88.11	65.83	2552.2	2554.4	2552.83
24	74.07	97.03	55.91	2285.4	2280.9	2269.03

The relationship between load demand and total generation over 24 hours is shown in Figure 6. It can be seen that generation closely follows the load profile, indicating proper satisfaction of the power balance constraint.

The load is minimal during off-peak hours (Hours 3–5) and begins to rise as you enter peak hours, peaking in the evening (Hours 19–22). The degree of overlap between load and generation curves impacts whether JOA operates the system stably, reliably, and efficiently at demand scenarios.

As shown in Figure 6, the hourly generation cost throughout a 24-hour period clearly follows the load demand profile, with lower values off-peak and higher during peak hours. As we can see from the graph, during Hours 3–5, when the load is much lower, this yields the minimum cost, and around Hour 20, under peak load conditions, we have the maximum cost. This trend shows that power demand is a direct function of operating cost, and the continuous variation of this curve indicates that the Jaya optimization algorithm (JOA) has operated stably and more efficiently in terms of generation cost.

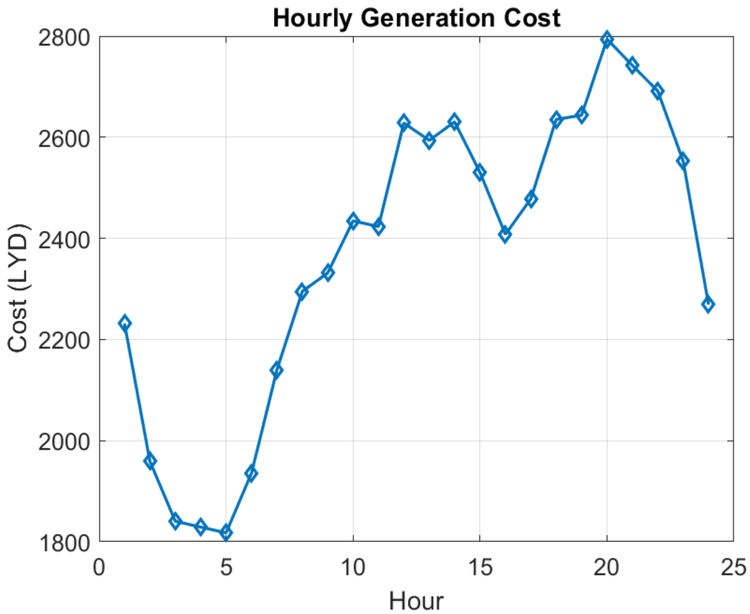

Figure 6. hourly operating cost over a 24-hour

Figure 7 depicts the convergence behavior of the Jaya Optimization Algorithm (JOA). The costs drop quickly in the first few iterations, indicating that exploration is quite strong, and remain stable afterward as they approach an optimum solution (as seen). The very smooth shape of the convergence pattern demonstrates that JOA can be considered an effective, stable, and fast-converging algorithm for solving the Economic Load Dispatch (ELD) problem.

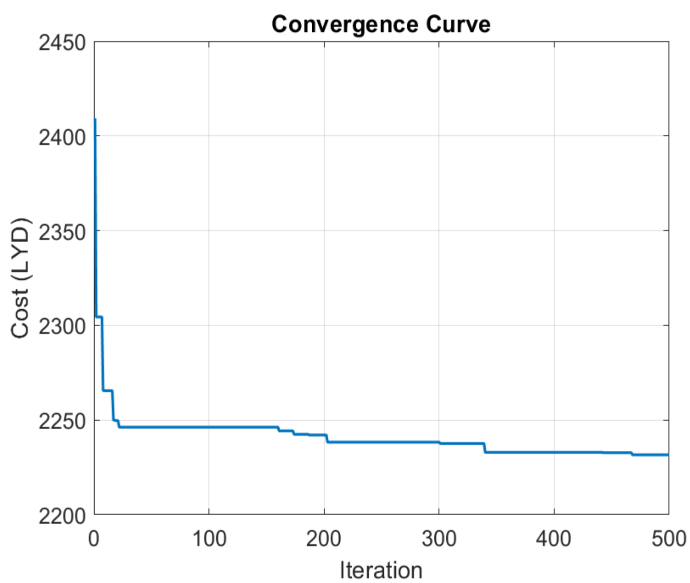

Figure 7. Cost convergence curves.

Figure. 8 shows the output from the three generating units (G1, G2, and G3) over 24 hours to meet the total demand, with all units contributing varying outputs to meet the load separately. Their contribution declines during low-load periods and increases during high-load periods (Hours 19–22). Moreover, it is clear that generator G1 has lower power output than generators G2 and G3 due to its economic or operational characteristics. In general, this distribution of load shapes shows better load sharing and confirms that the Jaya Optimization Algorithm (JOA) successfully allocates generation under diverse conditions.

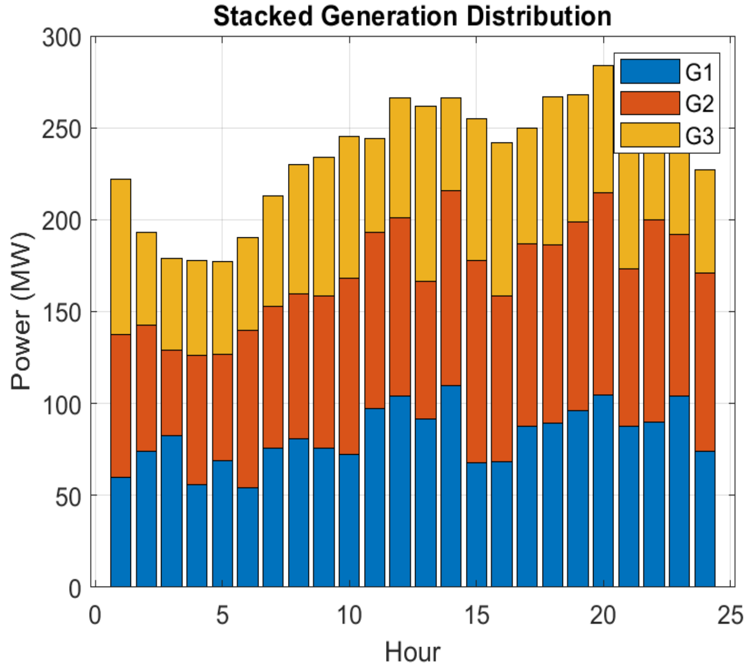

figure 8. Stacked Generation Distribution.

Data Availability Statement: Data is contained within the article.

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Abbreviations

The following abbreviations are used in this manuscript:

ELD	Economic Load Dispatch
JOA	Jaya Optimization Algorithm
WOA	Whale Optimization Algorithm
PSO	particle swarm optimization
LDY	Libya Dinar
MW	Mega Watt
G	Generating

7. Conclusion

In this paper, Jaya Optimization Algorithm (JOA) has been utilized to solve the Economic Load Dispatch (ELD) for the Libyan 3-unit power system with realistic 24-hour load profiles. Two scenarios of practical operations of the system have been studied. The scenario of Light Fuel Oil (LFO) generating units as well as that of the Heavy Fuel Oil (HFO) generating units have been studied.

The results show that JOA was able to maintain equality constraints as well as constraints of the generators while trying to minimize the total fuel cost. The best total fuel cost is obtained in Case 1 (Light Fuel Oil) where the total fuel cost equals 278,406.34 LYD. This cost is lower than the costs calculated by WOA (279,288.19 LYD) and

PSO (279,810.20 LYD). Also in Case 2 (Heavy Fuel Oil), JOA was able to obtain the minimum fuel cost of 56,833.73 LYD. This cost is lower than the cost obtained by WOA (56,929.10 LYD) and PSO (56,948.05 LYD). These results confirm that JOA is a powerful optimization tool for solving ELD problems of power systems in Libyan context. JOA is simple, parameter-free, and has consistent results and it is as good as or better than other meta-heuristics used for similar problems. Therefore, it can be effectively used for solving other real-world optimization problems.

In summary, the simulation results presented and the results obtained using JOA, WOA and PSO show that JOA is a very simple, efficient, robust and effective optimization technique. It is a parameter-free optimization technique that can be applied for solving a wide variety of optimization problems efficiently. Thus, it can be considered as an alternative optimization technique to the existing metaheuristics to solve ELD problem of the power systems of Libya efficiently.

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