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Development of a Non-Convex Economic Load Dispatch Across Small to Very Large-Scale Power Systems Using Improved Sine Cosine Algorithm

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Abstract
The Economic Load Dispatch (ELD) problem is fundamental to power system operation, requiring the optimal allocation of generation among committed units to minimize fuel cost while satisfying demand and operational constraints. The incorporation of valve-point loading effects (VPLE) introduces non-convex and multimodal characteristics that can cause conventional and standard metaheuristic optimization methods to become trapped in local optima. This study proposes an Improved Sine Cosine Algorithm (ISCA) for solving non-convex ELD problems with VPLE across small-, medium-, large-, and very large-scale power systems. The novelty of ISCA lies in the integration of three complementary mechanisms into the conventional Sine Cosine Algorithm: (i) an adaptive parameter control strategy that dynamically regulates exploration and exploitation, (ii) a Lévy flight-based search mechanism that improves global exploration and facilitates escape from local optima, and (iii) an enhanced power-balance adjustment strategy that enforces the supply-demand equality constraint with high numerical precision. The proposed algorithm is evaluated on five benchmark systems comprising 3, 13, 40, 80, and 140 generating units, with load demands of 850, 2,520, 10,500, 21,000, and 49,342 MW, respectively. For each test system, 30 independent runs are conducted to evaluate solution quality, convergence behavior, robustness, and constraint satisfaction using best and statistical fuel-cost measures, convergence characteristics, cost distributions, and power-balance errors. ISCA obtained best fuel costs of 8,284.67 USD/h, 21,670.76 USD/h, 90,158.27 USD/h, 182,013.39 USD/h, and 428,106.68 USD/h for the 3-, 13-, 40-, 80-, and 140-unit systems, respectively. The observed standard deviations were as low as 0.01 USD/h for the smaller system and remained below 0.05% of the corresponding total generation cost for the 140-unit system, indicating stable performance across repeated runs. In addition, power-balance errors remained below 10^{-13} MW, demonstrating accurate satisfaction of the equality constraint. Comparative analysis across the benchmark systems indicates that the proposed enhancements improve the search capability and solution consistency of the conventional SCA, particularly as problem dimensionality increases. Overall, the results demonstrate that ISCA provides a robust and scalable optimization framework for non-convex ELD with VPLE. However, its computational competitiveness should be assessed alongside solution quality using runtime or function-evaluation measures and statistically validated comparisons with established algorithms.

Keywords: *Convergence Analysis, Economic Load Dispatch, Improved Sine Cosine Algorithm, Large-Scale Optimization, Power Systems, Robustness, Valve-Point Loading Effect.*

1.0 Introduction

The global demand for electrical energy continues to increase as a result of population growth, industrialization, urbanization, and technological development [1,2]. This increasing demand places greater emphasis on the economic, reliable, and efficient operation of electric power systems, particularly on the effective scheduling of available generating resources [2.3]. One of the fundamental optimization problems associated with power system operation is the Economic Load Dispatch (ELD) problem. ELD determines the optimal real-power output of committed generating units such that the system demand is satisfied at minimum generation cost while respecting generator and network operating constraints [4,5].

Traditional ELD solutions have commonly relied on mathematical and classical optimization techniques, including Lambda Iteration, Gradient-Based Methods, and Linear Programming. Although these approaches can provide efficient solutions for simplified ELD formulations with smooth, convex, and differentiable objective functions, their effectiveness decreases when practical characteristics of thermal generating units and network operation are incorporated. In realistic power systems, the generation-cost function may become non-smooth and non-convex because of the Valve Point Loading Effect (VPLE), while operational restrictions such as Ramp-Rate Limits (RRLs), Prohibited Operating Zones (POZs), and transmission power losses further increase the complexity of the optimization problem [6,7,8]. Consequently, the resulting ELD problem is characterized by a multimodal search space containing multiple local optima, discontinuities, and tightly coupled equality and inequality constraints. These characteristics make the direct application of conventional optimization methods increasingly challenging, particularly for large-scale generating systems.

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The limitations associated with conventional techniques have motivated the application of population-based and nature-inspired metaheuristic optimization algorithms to non-convex ELD problems. Algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE) have been widely investigated because of their ability to explore complex search spaces without requiring gradient information [6]. Metaheuristic approaches are particularly attractive for non-convex ELD because they can employ population-based search mechanisms to explore multiple regions of the solution space and reduce the likelihood of premature convergence. Nevertheless, their performance is highly dependent on the exploration-exploitation balance, parameter settings, constraint-handling strategy, problem dimensionality, and characteristics of the objective function. Therefore, no single metaheuristic algorithm can be assumed to provide consistently superior performance for all ELD formulations.

Among the population-based metaheuristic algorithms, the Sine-Cosine Algorithm (SCA) has attracted attention because of its relatively simple mathematical structure and its use of sine- and cosine-based position-update mechanisms to regulate the movement of candidate solutions toward promising regions of the search space. The oscillatory search mechanism enables SCA to alternate between exploratory and exploitative movements, making it applicable to a range of continuous optimization problems. However, the standard SCA can experience limitations when applied to highly non-convex, constrained, and high-dimensional ELD problems. In particular, its fixed or predetermined search-control mechanism may not provide sufficient adaptation to changes in the optimization landscape, while its exploitation capability may become inadequate during the later stages of the search. These limitations can result in premature convergence, slower refinement of promising solutions, and reduced solution consistency when the dimensionality and constraint complexity of the ELD problem increase [6,9].

Recent efforts to improve SCA have introduced different modifications involving parameter adaptation, alternative population initialization, local search, chaotic strategies, hybridization, and other search operators. Although these variants have improved SCA performance for particular optimization problems, important challenges remain for constrained ELD with VPLE. First, an effective balance between global exploration and local exploitation is required because the discontinuous and multimodal nature of VPLE can cause conventional search mechanisms to become trapped around local optima. Second, the search process must retain sufficient diversity as the dimensionality of the generating system increases. Third, the equality constraint between total generation and system demand, particularly when transmission losses are considered, must be handled accurately without degrading the quality of the objective function. Finally, improvements in solution quality should be demonstrated not only through a single best result but also through repeated independent trials, convergence behavior, variability, and comparative statistical performance.

These limitations establish the research gap addressed in this study. Existing SCA-based approaches do not sufficiently address the combined requirements of adaptive exploration-exploitation control, effective escape from local optima, and high-precision power-balance enforcement for large-scale non-convex ELD with multiple practical constraints. The present study therefore proposes an Improved Sine-Cosine Algorithm (ISCA) specifically designed to address these limitations. Rather than relying solely on the original oscillatory search mechanism of SCA, the proposed approach incorporates three complementary modifications. First, an adaptive parameter-control mechanism dynamically adjusts the exploration and exploitation characteristics of the search process according to the optimization stage. Second, a Lévy flight-based search mechanism is incorporated to generate long-range exploratory movements and improve the ability of the algorithm to escape local optima. Third, an enhanced power-balance adjustment strategy is employed to improve the feasibility of candidate solutions by enforcing the supply-demand equality constraint with high numerical precision.

The proposed ISCA is evaluated using a comprehensive non-convex ELD formulation that incorporates VPLE, transmission power losses, RRLs, and POZs. The performance of the algorithm is investigated on five benchmark systems comprising 3, 13, 40, 80, and 140 generating units, representing increasing levels of problem dimensionality. In addition to evaluating the best generation cost, the study considers repeated independent optimization runs, convergence characteristics, cost-distribution behavior, solution variability, and power-balance errors. This evaluation framework is intended to determine whether the proposed modifications provide measurable improvements in solution quality, stability, convergence behavior, and scalability rather than assessing performance solely from a single optimization run.

The main contributions of this study are therefore summarized as follows:

1. **Development of an Improved Sine-Cosine Algorithm:** An enhanced SCA framework is developed by integrating adaptive parameter control and Lévy flight-based search to improve the exploration-exploitation balance and reduce susceptibility to premature convergence in non-convex ELD.
2. **Comprehensive non-convex ELD formulation:** The proposed method is applied to an ELD formulation incorporating Valve Point Loading Effects, transmission power losses, Ramp-Rate Limits, and Prohibited Operating Zones, thereby representing multiple practical sources of non-linearity and constraint complexity.

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3. **Enhanced constraint-handling mechanism:** A dedicated power-balance adjustment and solution-repair strategy is incorporated to maintain feasible generation schedules and minimize violations of the system supply-demand equality constraint.
4. **Scalability and robustness assessment:** ISCA is evaluated on 3-, 13-, 40-, 80-, and 140-unit benchmark systems to examine its behavior as problem dimensionality increases.
5. **Comparative and statistical evaluation:** The performance of ISCA is assessed using 30 independent runs and compared with the standard SCA and other established ELD optimization approaches reported in the literature. Best and statistical performance measures, convergence behavior, solution variability, and power-balance errors are considered to provide a more comprehensive assessment of the proposed method.

1.2 Problem Formulation

The Economic Load Dispatch (ELD) problem is formally defined as a complex constrained optimization task. The goal is to determine the optimal active power generation levels $P_{g,i}$ for each committed generating unit *i* such that the overall cost of generation is minimized, while simultaneously satisfying all system demand and operational limitations. Mathematically, this involves minimizing the objective function subject to several equality and inequality constraints.

A. Objective Function

The objective of the ELD problem is to minimize the total fuel cost of all online generating units over a specified operating period. This cost is primarily a function of the active power output of each generator. In a realistic power system, the input-output characteristic of a thermal unit is not purely quadratic due to the Valve Point Loading Effect (VPLE), which arises from the sequential opening and closing of steam admission valves. To accurately model this non-smooth characteristic, a sinusoidal term is incorporated into the standard quadratic cost function.

$$C_t = \sum_{i=1}^{m} \propto_i + \beta_i P_i + \gamma_i P_i^2 \quad (1)$$

$$\sum_{i=1}^{m} P_i = P_d + P_l \quad (2)$$

$$P_{i_{min}} \leq P_i \leq P_{i_{max}} \quad (3)$$

where C_t represents the total generation cost, with cost coefficients for the ith generator depicted by $\propto_i$, β_i, and γ_i. P_d and P_l represents the power demand and loss respectively. The output limits for the ith generator are shown as $P_{i_{max}}$ and $P_{i_{min}}$.

B. Equality Constraint

The primary physical constraint in the ELD problem is the power balance requirement. This constraint ensures that the total active power generated by all online units must exactly match the total system load demand P_d plus the total power lost in the transmission network P_L. Failure to satisfy this constraint results in system instability. The power balance equation serves as the main equality constraint that the proposed algorithm must satisfy to yield a feasible solution. The transmission network losses are typically calculated using the B-coefficient matrix method (or Kron's formula), which relates the losses to the power outputs of all generating units.

C. Inequality Constraints

In addition to the power balance, the operation of thermal generating units is constrained by several practical and physical limitations. These operational limits define the feasible search space for the optimization algorithm. A successful ELD solution must satisfy all these inequality constraints simultaneously.

1. Generator Capacity Limits

Each generating unit has a physical capacity range within which it can operate safely and efficiently. This defines the minimum $P_{g,i}$ and maximum $P_{g,i}$ active power output limits for every unit *i*.

2. Ramp-Rate Limits (RRLs)

These constraints restrict the speed at which a unit's power output can change between two successive time periods (or iterations). This ensures that the generated solution is practically achievable from the unit's previous state, accounting for the thermal and mechanical inertia of the generation equipment.

3. Prohibited Operating Zones (POZs)

Due to mechanical resonance or unstable boiler operations, certain output ranges must be avoided. These prohibited operating zones divide the feasible power output range of a unit into several disconnected, continuous sub-regions. A solution is only feasible if the generator output falls outside all defined POZs.

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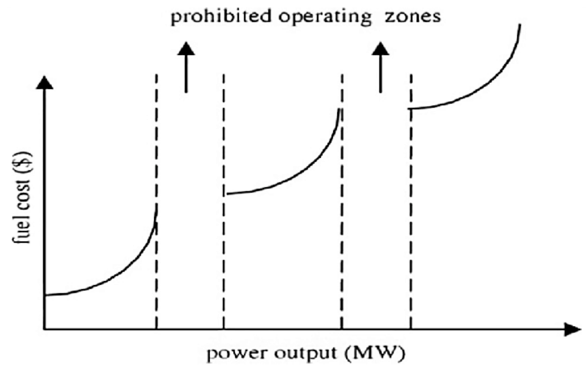

Figure 1: Prohibited Operating Zones

The feasible operating zones are described by the following inequality constraints

$$Pg_i^{min} \leq Pg_i \leq Pg_{i,1}^{max} \quad (4)$$

$$Pg_{i,k-1}^{u} \leq Pg_i \leq Pg_{i,k}^{max}, \quad \forall k = 2,3, \ldots., zo_i \quad (5)$$

$$Pg_{i,zo_i}^{u} \leq Pg_i \leq Pg_i^{max} \quad (6)$$

Where $Pg_{i,k}^{max}$ and $Pg_{i,k}^{u}$ represents the upper and lower bounds of the kth prohibited zone of unit i, respectively, k is the index of prohibited zones, zo_i.

2.0 Materials and Methods/Methodology

The complexity and non-convex nature of the constrained Economic Load Dispatch (ELD) problem necessitate the use of advanced optimization techniques capable of efficiently navigating a high-dimensional search space and avoiding premature convergence to local optima [4]. This study proposes an Improved Sine-Cosine Algorithm (ISCA) to address these challenges. The original Sine-Cosine Algorithm (SCA) is a powerful, population-based metaheuristic that uses the mathematical properties of sine and cosine functions to balance the exploration and exploitation phases of the search [14].

The path search can be expressed as follows:

$$X_i^{t+1} = r_1 X_i^t + c_1 \times \sin(r_2) \times \left(P_{best-i}^t - X_i^t\right), \quad r_3 < 0.5 \quad (7)$$

$$X_i^{t+1} = r_1 X_i^t + c_1 \times \cos(r_2) \times \left(P_{best-i}^t - X_i^t\right), \quad r_3 > 0.5 \quad (8)$$

Where X_i is the location of the present optimal solution, P_i represents the optimal solution, r_1 denotes the convergence factor which ensures balance between the phases. Through the association of the linear path and the original path, the search will be more rigorous and suitable for the complex optimization problem. The search range will find the global optimum in a more precise range

A. Standard Sine-Cosine Algorithm (SCA)

The standard SCA initializes a random set of candidate solutions (the population). In each iteration, the positions of these solutions are updated based on the sine and cosine functions, which drive the search agents either toward or away from the current best solution found so far (Visutarrom & Chiang, 2024). The core mechanism is a transition from exploration (searching globally) to exploitation (searching locally) as the iterations progress.

$$X_i^{t+1} = X_i^t + r_1 \times \sin(r_2) \times \left|r_3 P_i^t - X_i^t\right| \quad (9)$$

$$X_i^{t+1} = X_i^t + r_1 \times \cos(r_2) \times \left|r_3 P_i^t - X_i^t\right| \quad (10)$$

where r_1, r_2, r_3 represent random numbers, X_i^t depicts the position of the current solution in ith dimension, Pi denotes the position of the destination point in ith direction and $|-2, 2|$ indicates the absolute value.

A conceptual description of the sine and cosine functions while updating the process of the position within the range in [-2,2] is depicted in figure 2.5. this change is performed with the second random number r_2 (Rizk-Allah & Hassanien, 2023).

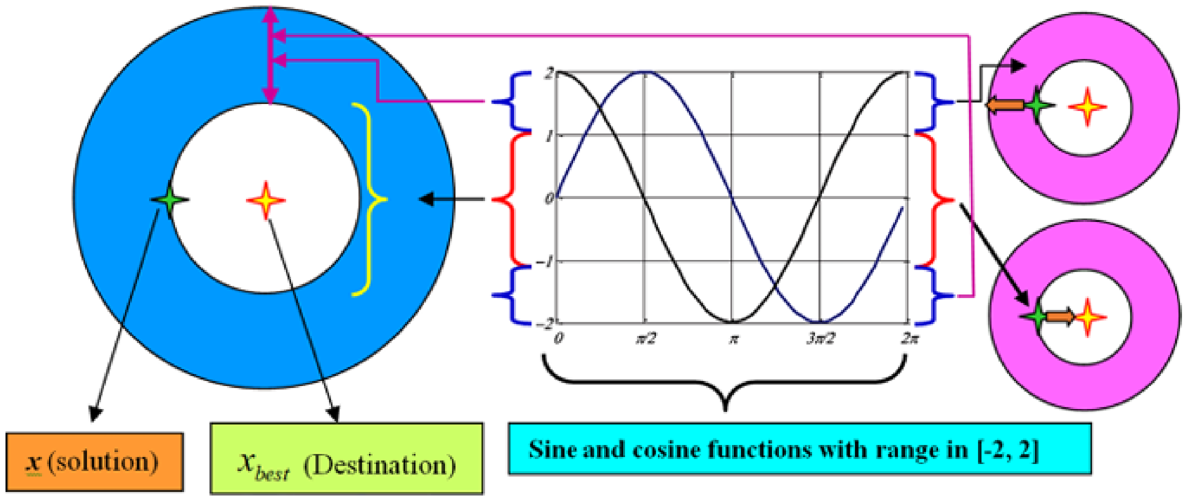

Figure 2: Graphical Representation of a Sine-Cosine Algorithm

B. Constraint Handling and Solution Repair

The nature of the constrained ELD problem requires that the solution generated by the metaheuristic algorithm strictly adheres to all equality and inequality constraints defined in Section II. Since the standard SCA position update may lead to infeasible solutions (e.g., generator outputs outside their limits or total generation not balancing the load), a robust mechanism is essential to project the solution back into the feasible search space.

In this study, a dedicated Solution Repair Mechanism is integrated into the ISCA to ensure the feasibility of the active power output vector P_g. This mechanism operates in two critical stages after each position update:

1. Handling Inequality Constraints

The mechanism first checks and enforces the generator capacity limits $P_{g,i}^{min}$ and $P_{g,i}^{max}$, Ramp-Rate Limits (RRLs), and Prohibited Operating Zones (POZs). Any generated output that violates these bounds is immediately adjusted to the nearest feasible boundary or to a neighboring feasible operating zone.

2. Handling the Equality Constraint

The power balance equation, where total generation must cover the demand and losses = $P_d + P_L$), is the equality constraint. The repair strategy involves selecting a designated slack generator (often the largest or most flexible unit) to absorb the generation mismatch (δP) that occurs after the initial position update and inequality constraint handling. The output of the slack unit is adjusted by ∂P to ensure the system power balance is achieved.

$$P_{slack}^{new} = P_{slack}^{old} + \partial P \qquad (11)$$

The adjustment is subject to the slack unit's capacity limits. If the adjustment pushes the slack unit outside its limits, a proportional adjustment mechanism is employed across the remaining units to restore feasibility.

The integrated constraint handling approach guarantees that every evaluated candidate solution represents a valid operating state of the power system, thereby making the ISCA a highly reliable tool for solving the constrained ELD problem.

3.0 Results and Discussion

The performance of the proposed Improved Sine-Cosine Algorithm (ISCA) was evaluated using five non-convex Economic Load Dispatch (ELD) test systems comprising 3, 13, 40, 80, and 140 generating units, with corresponding load demands of 850, 2,520, 10,500, 21,000, and 49,342 MW, respectively. Each test system was independently optimized over 30 runs to account for the stochastic nature of the metaheuristic search process. The evaluation considered solution quality, variability across independent runs, convergence behaviour, constraint satisfaction, and the effect of increasing problem dimensionality.

A. Statistical Performance across Test Systems

Table 1 summarizes the statistical performance of ISCA across the five investigated systems. The reported best and mean costs provide measures of solution quality and average performance, respectively, while the standard deviation quantifies the variability of the solutions obtained over the 30 independent runs.

Table 1: Summary of the statistical performance of ISCA across the five investigated systems

System	Units	Load (MW)	Best Cost (USD/h)	Mean Cost (USD/h)	Standard Deviation (USD/h)
3-unit	3	850	8,284.67	8,284.67	0.01

System	Units	Load (MW)	Best Cost (USD/h)	Mean Cost (USD/h)	Standard Deviation (USD/h)
13-unit	13	2,520	21,670.76	21,735.75	32.11
40-unit	40	10,500	90,158.27	90,288.59	67.84
80-unit	80	21,000	182,013.39	182,212.42	100.78
140-unit	140	49,342	428,106.68	428,454.60	189.67

For the 3-unit system, ISCA obtained a best cost of 8,284.67 USD/h, while the mean cost over the 30 runs was also 8,284.67 USD/h. The standard deviation of 0.01 USD/h indicates extremely small variation between independent runs. This suggests that the algorithm repeatedly identified solutions within a very narrow cost range for the small-dimensional problem.

As the number of generating units increased, the absolute standard deviation also increased from 32.11 USD/h for the 13-unit system to 189.67 USD/h for the 140-unit system. However, the increase in absolute variation should be interpreted relative to the corresponding generation cost because the systems differ substantially in scale. The ratio of standard deviation to mean cost remains very small across the investigated systems, indicating that the variability of the obtained costs represents only a small proportion of the total generation cost.

The difference between the best and mean costs also provides an indication of run-to-run consistency. For the 13-, 40-, 80-, and 140-unit systems, the differences between the best and mean costs were 64.99, 130.32, 199.03, and 347.92 USD/h, respectively. Although the absolute difference increases with system size, it remains relatively small compared with the corresponding total generation cost. This behaviour suggests that the proposed method maintained relatively stable solution quality as the dimensionality of the optimization problem increased.

However, these results should not be interpreted as proof that ISCA always obtains the global optimum. Rather, they demonstrate that ISCA consistently produced high-quality solutions under the experimental conditions considered.

The convergence characteristics of ISCA were examined using the objective-function trajectories obtained during the optimization process. For the 3-unit system, the convergence curve shows a substantial reduction in generation cost during the early iterations, followed by progressive stabilization. The algorithm approached its final solution within approximately the first 100 iterations.

For the 13-unit system, convergence was comparatively more gradual because of the increased number of decision variables and the resulting enlargement of the search space. Nevertheless, the objective function decreased progressively before reaching a stable region around the final solution. The best and mean costs of 21,670.76 and 21,735.75 USD/h, respectively, indicate that the final solutions obtained across the 30 runs remained relatively close.

A similar trend was observed for the 40-unit system. The convergence curve indicates continued improvement in the objective function as the iterations progressed, with a best cost of 90,158.27 USD/h and a mean cost of 90,288.59 USD/h. The slightly longer convergence behaviour relative to the smaller systems is consistent with the greater dimensionality and increased number of constraints.

For the 80-unit system, ISCA obtained a best cost of 182,013.39 USD/h and a mean cost of 182,212.42 USD/h. The convergence curve indicates that the algorithm continued to refine candidate solutions as the optimization progressed before reaching a relatively stable region. For the 140-unit system, the largest problem considered, the best and mean costs were 428,106.68 and 428,454.60 USD/h, respectively. Although convergence required more iterations than in the smaller systems, the algorithm maintained a stable reduction in the objective function.

The observed convergence patterns are consistent with the intended role of the adaptive search mechanism and Lévy-flight component. The adaptive mechanism is designed to regulate the transition between exploration and exploitation, while Lévy-flight movements provide the possibility of larger search steps when additional exploration is required. Nevertheless, convergence curves alone cannot establish global optimality. Therefore, the observed convergence should be interpreted as evidence of the algorithm's ability to obtain stable high-quality solutions rather than definitive proof that the global optimum was reached.

Robustness and Run-to-Run Variability

Robustness was assessed using the results of the 30 independent runs and the corresponding distributions of final generation costs. Figures 1-5 present the boxplots for the five test systems.

The 3-unit system exhibits an extremely narrow distribution, consistent with its standard deviation of 0.01 USD/h. The small dispersion indicates that ISCA produced highly similar solutions across repeated runs. For the 13-unit system, the distribution is wider, with a standard deviation of 32.11 USD/h, indicating increased stochastic variation as the problem dimensionality increases.

The 40-unit system produced a standard deviation of 67.84 USD/h, while the corresponding values for the 80- and 140-unit systems were 100.78 and 189.67 USD/h, respectively. The increase in absolute dispersion is expected as the number of decision variables increases. Importantly, the relative dispersion remains small compared with the corresponding mean generation costs.

Using the reported results, the approximate coefficients of variation are:

Table 2: The approximate coefficients of variation

System	Mean Cost (USD/h)	SD (USD/h)	CV (%)
3-unit	8,284.67	0.01	0.00012
13-unit	21,735.75	32.11	0.148
40-unit	90,288.59	67.84	0.075
80-unit	182,212.42	100.78	0.055
140-unit	428,454.60	189.67	0.044

The relatively small coefficients of variation indicate that the dispersion of the final costs is low relative to the scale of each problem. In particular, the CV decreases from approximately 0.148% for the 13-unit system to approximately 0.044% for the 140-unit system. This provides stronger evidence for consistency than standard deviation alone because it normalizes variability according to system cost.

Comparative Performance

To establish whether the observed performance represents a meaningful improvement over the conventional SCA and other optimization methods, a consolidated comparison should be provided in Table 3. The comparison include the best cost, mean cost, worst cost, standard deviation, computational time, and number of objective-function evaluations where these values are available.

Table 3: A consolidated comparison

Test System	Algorithm	Best Cost	Mean Cost	Worst Cost	SD	Runtime (s)	Function Evaluations
3-unit	SCA	—	—	—	—	—	—
	ISCA	8,284.67	8,284.67	—	0.01	—	—
13-unit	SCA	—	—	—	—	—	—
	ISCA	21,670.76	21,735.75	—	32.11	—	—
40-unit	SCA	—	—	—	—	—	—
	ISCA	90,158.27	90,288.59	—	67.84	—	—
80-unit	SCA	—	—	—	—	—	—
	ISCA	182,013.39	182,212.42	—	100.78	—	—
140-unit	SCA	—	—	—	—	—	—
	ISCA	428,106.68	428,454.60	—	189.67	—	—

The results demonstrate that ISCA produced stable and competitive solutions across ELD problems ranging from 3 to 140 generating units. The best generation costs increased from 8,284.67 USD/h for the 3-unit system to 428,106.68 USD/h for the 140-unit system, consistent with the substantially greater generation requirements of the larger systems. More importantly, the repeated-run results exhibited relatively small variability compared with the corresponding mean costs.

The convergence and statistical results indicate that ISCA can maintain stable optimization behaviour as problem dimensionality increases. However, the present results should be interpreted as evidence of competitive solution quality and repeatability rather than definitive proof of global optimality. Claims of computational superiority and scalability should likewise be supported by measured execution time, function evaluations, and complexity analysis.

Therefore, the principal evidence supporting the effectiveness of ISCA is its combination of competitive generation costs, low run-to-run variability, progressive convergence, and accurate power-balance enforcement across multiple system sizes. A formal comparison with established algorithms, statistical significance testing, component-level ablation, and complete feasibility verification would provide a stronger basis for establishing the extent to which each proposed modification contributes to the observed performance.

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4.0 Conclusion

This study developed and evaluated an Improved Sine-Cosine Algorithm (ISCA) for solving the non-convex Economic Load Dispatch (ELD) problem under practical operating constraints. The formulated ELD model incorporated the Valve Point Loading Effect (VPLE), transmission power losses represented using the B-coefficient matrix, Ramp-Rate Limits (RRLs), and Prohibited Operating Zones (POZs), thereby providing a more challenging optimization framework than the conventional smooth and unconstrained ELD formulation. The proposed ISCA extends the standard Sine-Cosine Algorithm through adaptive parameter control, Lévy flight-based exploration, and an enhanced power-balance adjustment mechanism designed to improve the balance between exploration and exploitation while maintaining feasibility.

The computational results demonstrate that ISCA was able to obtain competitive generation-cost solutions across the investigated test systems, ranging from small to very large-scale ELD problems. For the 3-, 13-, 40-, 80-, and 140-unit systems, the best fuel costs obtained by ISCA were 8,284.67, 21,670.76, 90,158.27, 182,013.39, and 428,106.68 USD/h, respectively. Across 30 independent runs, the relatively small standard deviations observed for the test systems indicate that the proposed method produced consistent solutions rather than relying on a single favorable optimization run. In particular, the standard deviation remained below 0.05% of the corresponding total generation cost for the largest 140-unit system. Furthermore, the reported power-balance errors remained below 10^{-13} MW, demonstrating that the proposed adjustment strategy maintained the generation-demand equality constraint with high numerical precision.

The comparative and convergence analyses indicate that the proposed modifications provide advantages over the standard SCA and, where comparisons were available, competitive performance relative to established metaheuristic approaches such as PSO and GA. The convergence behavior also shows that ISCA can reach high-quality solutions within a relatively limited number of iterations, with convergence generally occurring between approximately 80 and 900 iterations depending on system dimensionality. These findings suggest that the adaptive search mechanism and Lévy flight strategy contribute to maintaining effective exploration while improving convergence and solution consistency as the problem size increases.

Nevertheless, the results should be interpreted within the scope of the benchmark systems and experimental conditions considered in this study. Although ISCA demonstrated competitive solution quality and stability, the results do not by themselves establish that the obtained solutions are the global optimum for every test system. Similarly, claims concerning computational superiority should be supported by explicit measures such as execution time, function evaluations, and computational complexity. The study is also limited by its reliance on benchmark test systems and the adopted mathematical representation of network losses and operating constraints. Future research should therefore evaluate ISCA using additional large-scale and practical power-system cases, incorporate renewable generation and uncertainty, and undertake more extensive statistical testing against state-of-the-art optimization algorithms.

Overall, the findings indicate that ISCA is a promising and scalable metaheuristic approach for non-convex ELD problems with VPLE and multiple operational constraints. Its consistent performance across different system sizes, accurate power-balance enforcement, and competitive generation-cost results provide evidence of its potential for further investigation in more complex power-system scheduling environments.

Future Work: Future research will focus on extending the application of the ISCA to more advanced power system optimization problems, including:

- Multi-objective ELD, where cost minimization is balanced with emission minimization.
- Security-Constrained Economic Dispatch (SCED).
- Integrated operation of thermal units with renewable energy sources (e.g., wind and solar power) considering their inherent uncertainties.
- Application to real-time, dynamic ELD problems.

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