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Sustainable Economic Load Dispatch Integrating Renewable Energy for Multi-Load Systems

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Abstract:- The growing adoption of renewable energy in power networks calls for effective strategies to manage economic load dispatch (ELD) sustainably. This study introduces an innovative approach to Sustainable Economic Load Dispatch (SELD) by integrating multiple renewable sources, such as solar and wind energy, into a system serving diverse loads. The proposed method utilizes the Botox Optimization Algorithm (BOA), a nature-inspired metaheuristic, to enhance power distribution while reducing operational expenses and environmental impact. BOA efficiently tackles challenges related to fluctuations and unpredictability in renewable energy by improving solution accuracy and dynamically balancing load demand. The model incorporates key system constraints, including power equilibrium and generation limits, ensuring steady and optimized performance. A comparative assessment against conventional and advanced optimization methods highlights BOA's effectiveness in cutting costs and maximizing renewable energy penetration. Findings demonstrate that the proposed SELD framework offers a resilient and adaptable approach for managing energy in smart grids and microgrid systems. This research supports the shift toward a cost-efficient, environmentally friendly, and reliable power infrastructure.

Keywords*: Economic Load Dispatch, Renewable Energy, Multi-Load System, Botox Optimization Algorithm, Sustainable Power Systems.*

1. Introduction

The rapid shift toward sustainable sources has transformed modern power systems, necessitating efficient and adaptive economic load dispatch strategies [1-2]. Traditional ELD methods primarily focus on minimizing generation costs while ensuring demand-supply balance [3]. However, with the increasing penetration of sustainable sources, new challenges emerge, including intermittency, uncertainty, and grid balance concerns. To address these issues, metaheuristic techniques, plays a vital role in addressing these issues and optimizing them. Numerous existing studies concentrate solely on specialized classifications of optimization methodologies or particular theoretical frameworks [4-7]. Incorporating these variable energy sources into the power grid poses challenges for the rapid adaptation of generation capacity, leading to inefficiencies in resource utilization and elevated operational expenses [8]. Therefore, exploring strategies for seamlessly incorporating wind, solar, and hydropower is

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essential to stabilize grid performance, maximize resource efficiency, and improve economic viability.

Researchers have addressed the optimization of wind and solar power synergy by focusing on capacity planning and operational scheduling. They developed a multi-objective approach to determine the optimal sizing and coordination of a hybrid renewable energy system [9]. Existing optimization algorithms for dispatch in systems face challenges in handling nonlinear, non-convex, and multi-modal problems, often converging to local optima. Conventional methods struggle with renewable energy variability, while heuristic approaches suffer from slow convergence, high computational costs, and sensitivity to parameter tuning. Many lack adaptability in real-time dispatch and fail to balance cost, emissions, and consistency, underscoring the need for more efficient and adaptive optimization techniques for sustainable dispatch. Hence sustainable economic load dispatch (SELD) is being proposed that integrates sustainable sources into a multi-load system using the BOA [10] aiming to optimize power distribution while promoting environmental sustainability. BOA enhances optimization efficiency by improving convergence speed and handling the unpredictable nature of sustainable sources. The methodology considers key constraints such as power balance, generation limits, and consistent requirements, ensuring a stable and cost-effective energy management solution.

This research paper is systematically structured to provide a comprehensive analysis of the proposed approach. Section 2 delves into the optimization framework, outlining the fundamental principles and methodologies that underpin the study. Section 3 offers an in-depth examination of the proposed and implemented algorithm, specifically the Botox Optimization Algorithm, detailing its working mechanism, advantages, and application in solving optimization problems. Section 4 is dedicated to the formulation of the sustainable economic load dispatch problem, addressing key constraints, objective functions, and mathematical modeling required for an effective solution. In Section 5, the results obtained through the proposed approach are thoroughly analyzed and discussed, with comparative evaluations highlighting its efficiency and superiority over existing methods. Finally, Section 6 presents the concluding remarks, summarizing the key findings and implications of the study while suggesting potential directions for future research.

2. Objectives

Developing an efficient SELD strategy in sustainable power networks requires a structured optimization approach. The goal is to allocate power among conventional and renewable energy sources in a way that minimizes generation costs, emission levels, and energy losses, while ensuring system reliability. The formulation considers essential operational constraints, including power balance, generation capacity limits, and grid stability, to achieve an optimal dispatch solution. The inherent variability and unpredictability of renewable sources, such as

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solar and wind energy, introduce additional complexities, requiring adaptive optimization techniques to maintain system efficiency. This study develops a robust mathematical representation that incorporates multifaceted criteria to enhance the economic, environmental, and technical performance of modern microgrid systems. The specifications of the objective function and the associated constraints are outlined in equations as demonstrated [11].

$$Min\ (FCG) = \sum_{I=1}^{NOG} FC_I PG_I \quad (1)$$

FCG resembles the cumulative cost of fuel used for generation. FC_I and PG_I is the expense on combusting fuel of generators demonstrated by PG_I. The $FC_I\ PG_I$ is calculated as defined in Eq. 2.

$$\sum_{I=1}^{NOG} FC_I PG_I = \breve{A}_I + \check{C}_I(PG_I) + \check{K}_I(PG_I)^2 \quad (2)$$

Ă, Č and Ǩ are the expenditure coefficients. This development also incorporates two constraints, the equality constraint, and the inequality constraint**,** outlined in Eq. (3 to 4).

$$\sum_{I=1}^{NOG} PG_I = PG_{Load} \quad (3)$$

$$PG_I^{Min} \le PG_I \le PG_I^{Max} \quad (4)$$

PG_I^{Min} and PG_I^{Max} are the lower and upper limits of generators.

With the integration of sustainable energy sources [11], the objective function defined in Eq. (1) is revised and represented in Eq. (5) including equality constraint.

$$\sum_{I=1}^{NOG} FC_I PG_I + S_{POW} + W_{POW} = PG_{Load} \quad (5)$$

S_{POW} and W_{POW} are the power production from solar and wind generators.

3. Algorithm Overview

The process of refining facial appearance by administering injectable treatments to correct imperfections offers a unique conceptual basis for developing a novel optimization approach. To bridge this gap in metaheuristic algorithm research, this study proposes a new human-inspired optimization technique, designed by mathematically modeling the strategic application of Botox injections to specific facial areas, as elaborated in the subsequent section. Figure 1 below shows effective illustration of the optimization process. This section provides a comprehensive explanation of the BOA, starting with its conceptual foundation and inspiration. It then outlines the mathematical framework and procedural steps involved in its implementation [10].

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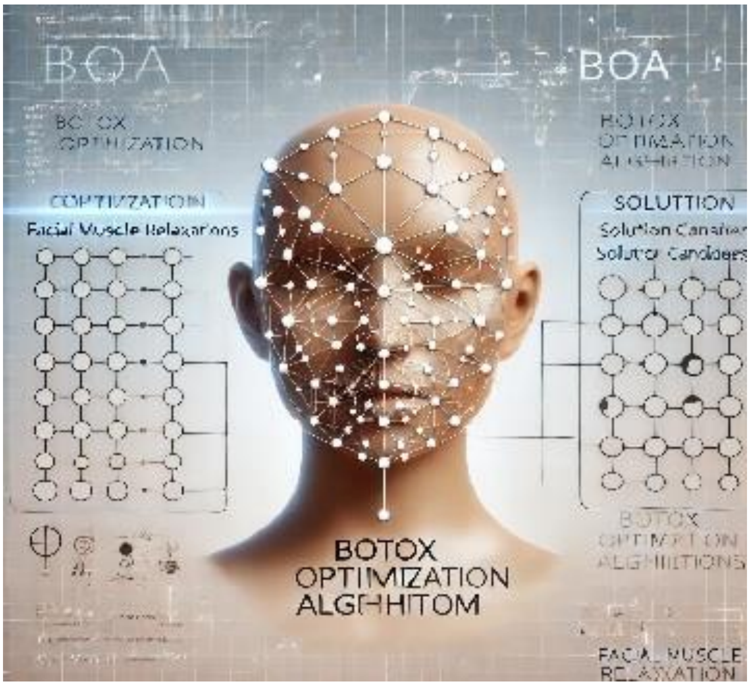

Fig. 1 Botox Optimization Algorithm

3.1 Inspiration

Botulinum toxin (Botox) is used to reduce facial wrinkles by temporarily relaxing overactive muscles, enhancing aesthetics. Its precise and targeted application inspired the development of the Botox Optimization Algorithm (BOA).

3.2 Parameter Initialization

The BOA operates as a population-based optimizer, where individuals represent candidate solutions as demonstrated in Eq. (6). Their positions in the search space are randomly initialized and updated iteratively. The objective function evaluates each solution, selecting the best candidate for optimization.

$$P_{i,D} = LB_D + R_{i,D}(UB_D - LB_D), i = 1, \dots, S \text{ } and \text{ } D = 1, \dots, T \tag{6}$$

$P_{i,\,D}$ is the population initialization; LB_D and UB_D are the lowly and upper limit of D^{th} dimension.

3.3 Simulation of BOA

The BOA models Botox injections mathematically, where each solution updates based on selected variables, akin to muscles treated by a doctor. Positions adjust iteratively using defined equations, optimizing the objective function by mimicking Botox's effect on wrinkles.

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$$B_{NM} = \left[1 + \frac{T}{S}\right] \leq T_S \quad (7)$$

B_{NM} is the muscle count seeking Botox infusion, S is the current value of the iteration.

$$ASB_i = \{D_1, D_2, \dots D_K, \dots, D_{B_{NM}}\}, D_K \in \{1, 2, \dots, T\} \text{ and } \forall H, K \in \{1, 2, \dots, B_{NM}\}: D_H \neq D_K \quad (8)$$

ASB_i is the bunch of applicant's decision variable chosen for Botox infusion.

In BOA, like a doctor deciding Botox dosage, injection amounts for each member are calculated using Eq. (9).

$$CB_{INJ} = \begin{cases} \overrightarrow{Z_{MEAN}} - \overrightarrow{Z_\iota}, & S < \frac{T}{2} \\ \overrightarrow{Z_{BEST}} - \overrightarrow{Z_\iota}, & ELSE \end{cases} \quad (9)$$

Z_{MEAN} is the mean position of population.

In BOA, Botox injection simulates position updates; if the objective function improves, the new position replaces the old one using Eq. (10).

$$\overrightarrow{Z_\iota} = \begin{cases} \overrightarrow{Z_\iota}^{NEW}, & NOF_i^{NEW} < NOF_i \\ \overrightarrow{Z_\iota}, & ELSE \end{cases} \quad (10)$$

$\overrightarrow{Z_\iota}^{NEW}$ is the new location of the BOA applicant after Botox infusion.

3.4 Iteration Procedure, Algorithm Outline, and BOA Flow Diagram

The BOA iterates by updating positions until completion, continuously refining the best solution, which is stored and presented as the final result.

3.5 Variation in Population, Search Exploration, and Intensification Analysis

BOA's population diversity reflects member distribution in the search space, guiding exploration and exploitation. Measuring this diversity helps balance both processes for effective optimization.

4. Problem Formulation

This study examines two distinct scenarios. In the first scenario, the BOA framework is employed to meet prevailing load demands, and its performance is benchmarked against

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alternative optimization methodologies. The second scenario extends the BOA approach to incorporate sustainable generation, ensuring a holistic assessment of its efficacy in a greener energy landscape. The corresponding results are meticulously analyzed and presented, highlighting the algorithm's effectiveness. Additionally, the reduction in daily fuel costs is quantified, demonstrating the economic benefits. The BOA algorithm is implemented on the IEEE three-generator system, with load values referenced from [11]. The various renewable energy sources complementing conventional power generation are illustrated in Figures 2 and 3, as presented below. Specifically, Figure 2 depicts solar energy generation, while Figure 3 represents wind energy generation. Figure 4 illustrates the fluctuations in load demand over a 24-hour period, capturing the dynamic variations in energy consumption throughout the day. This graphical representation provides insight into the hourly changes in system load, highlighting peak and off-peak demand periods, which are crucial for optimizing power generation and distribution strategies.

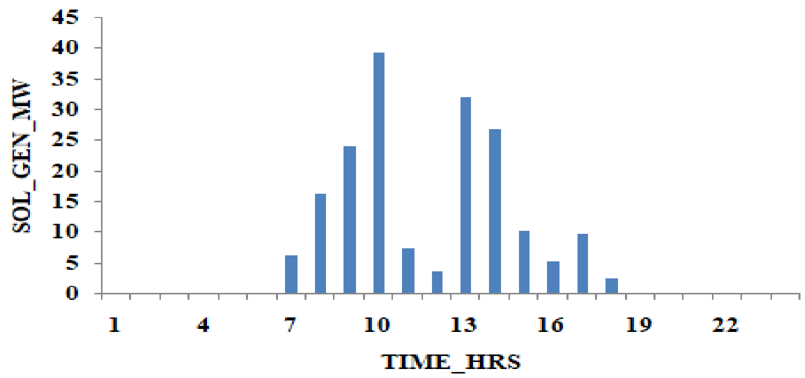

Fig. 2 Daily Solar Generation

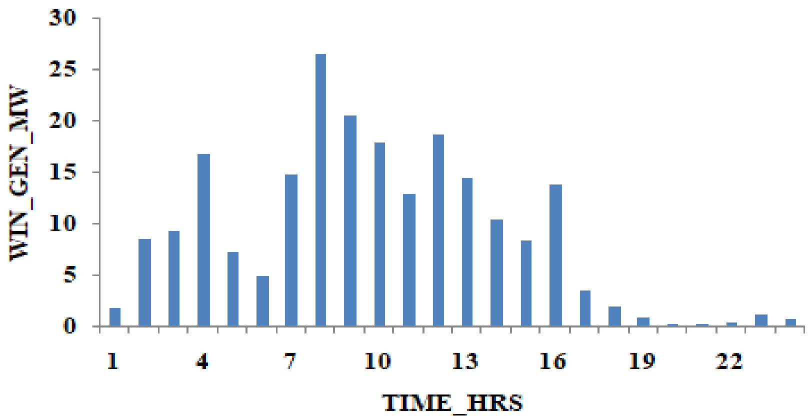

Fig. 3 Daily Wind Generation

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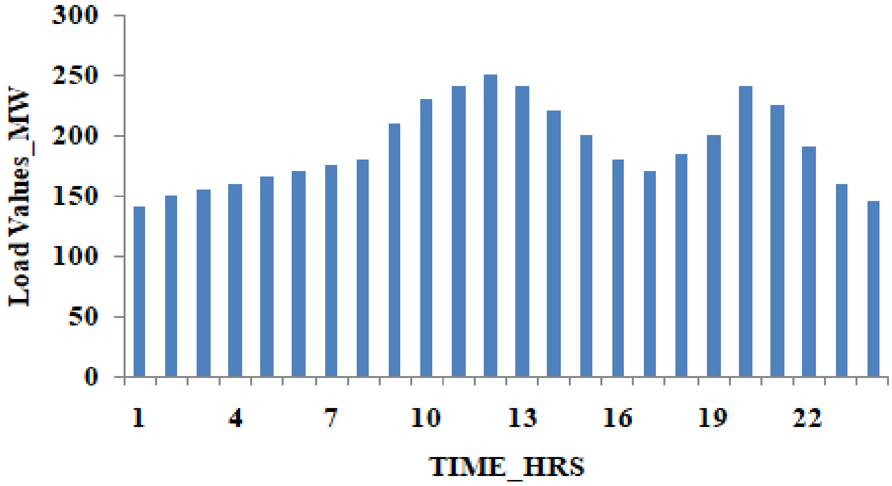

Fig. 4 Daily Load Variation

5. Result and Discussion

This section presents a comprehensive evaluation of the proposed algorithm using an IEEE-3Bus system, both with and without the integration of renewable energy sources. A detailed breakdown of the computational framework underlying the proposed methodology is provided, offering insights into its operational mechanics. To rigorously assess the BOA algorithm's efficacy, its performance is examined under varying operational scenarios by simulating two distinct cases within the system. The results obtained serve to validate the robustness and adaptability of the proposed approach across diverse generation configurations.

5.1 Case I: System Excluding Sustainable Sources

Without renewable energy, power grids rely heavily on fossil fuels, leading to higher costs, environmental damage, and operational inefficiencies. Fuel price volatility increases electricity expenses, while emissions contribute to climate change and pollution. Fossil fuel plants are less flexible, slow to respond to demand fluctuations, and increase the risk of blackouts. Without renewable sources grids remain costly, less consistent, and environmentally unsustainable, making the transition to a cleaner and more efficient energy future difficult. In this scenario the case for heavy load demands above 220 MW is analyzed

and is given in the Table 1 below, load dispatch is optimized using three conventional generation units. The power generation is distributed among these units using BOA algorithm to minimize fuel costs while meeting system constraints such as generation limits and power balance.

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Table 1 Load Demands for Economic Dispatch

TIME_HRS	LOAD_DISPATCH
10	230
11	240
12	250
13	240
20	240
21	225

The examined test scenario consists solely of traditional thermal generators, with no integration of renewable energy sources to meet the system's load requirements. Under these conditions, the generation cost computed using the BOA methodology demonstrates a notable reduction compared to previously implemented optimization techniques. The comparative analysis, as depicted in the results, highlights the superior cost-effectiveness of BOA in minimizing operational expenses in a purely conventional generation setup. The specific time instance and corresponding demand load for each hour are referenced from Table 1. Figure 5 presents a detailed comparative analysis of the generation costs derived using the BOA approach alongside those obtained from [12] previously implemented optimization techniques using reduced gradient method (RGM), ant colony optimization (ACO), cuckoo search algorithm (CSA), interior search algorithm (ISA) moth flame optimization (MFO) and moth flame and may fly optimization (MFMFO).

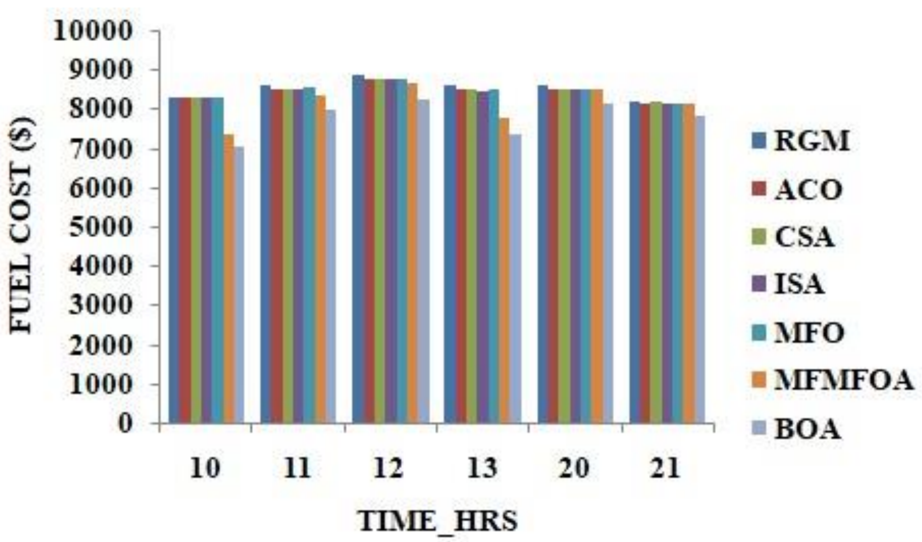

Fig. 5 Comprehensive Cost Evaluation Excluding Sustainable Energy

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The percentage reduction in cost after dispatch is presented in Table 2, offering a more detailed and comprehensive comparison of BOA to other methods. This data allows for a clearer understanding of the cost savings achieved through the proposed approach, highlighting its efficiency in optimizing economic dispatch. This comparison effectively highlights the cost-efficiency of BOA in minimizing operational expenses, demonstrating its superiority over earlier methodologies in economic dispatch scenarios.

Table 2 Comparative Percentage Reduction in Cost using BOA for Case I

Sr. No.	RGM with BOA in %	ACO with BOA in %	CSA with BOA in %	ISA with BOA in %	MFO with BOA in %	MFMFOA with BOA in %
1	15.31852	15.12575	15.03188	15.03188	15.00652	4.068007
2	6.78777	6.134251	6.185624	6.185624	6.234786	4.133559
3	6.811166	5.816591	5.853528	5.853528	5.866716	4.872075
4	14.15289	13.49937	13.59832	12.76842	13.58102	4.966698
5	5.328977	4.675458	4.717407	4.683821	4.703427	4.696698
6	4.216895	3.98428	4.028901	4.017127	3.980373	3.978994

5.2 Case II: System Including Sustainable Sources

During periods of peak electricity demand, conventional thermal power plants, such as coal and gas-fired units, are required to operate at higher output levels to meet the increased load. This leads to a rise in marginal costs due to factors such as higher fuel consumption, increased wear and tear on equipment, and the need for additional operational adjustments. Moreover, as demand surges, grid operators may have to activate less efficient and more expensive generating units, further escalating generation costs. Hence before dispatching the load demand given in Table 1, sustainable sources integration is done.

Integrating sources like solar and wind into the grid during peak load conditions provides a cost-effective alternative to mitigate these expenses as shown in Figure 6. Unlike fossil fuel-based power generation, sustainable sources have minimal operating costs since they do not require fuel combustion. The availability of solar energy is particularly advantageous during daytime peaks, when electricity demand is highest due to cooling and industrial requirements. Similarly, wind energy, depending on regional conditions, can contribute significantly to the supply mix, reducing reliance on costly conventional generation. In this case also the outcome of BOA is compared to the results obtained in [12] as shown in the Figure 6. Hence, it is evident that the BOA has demonstrated superior performance compared to previously applied algorithms. The results clearly indicate that BOA achieves enhanced optimization efficiency, yielding more accurate and cost-effective solutions.

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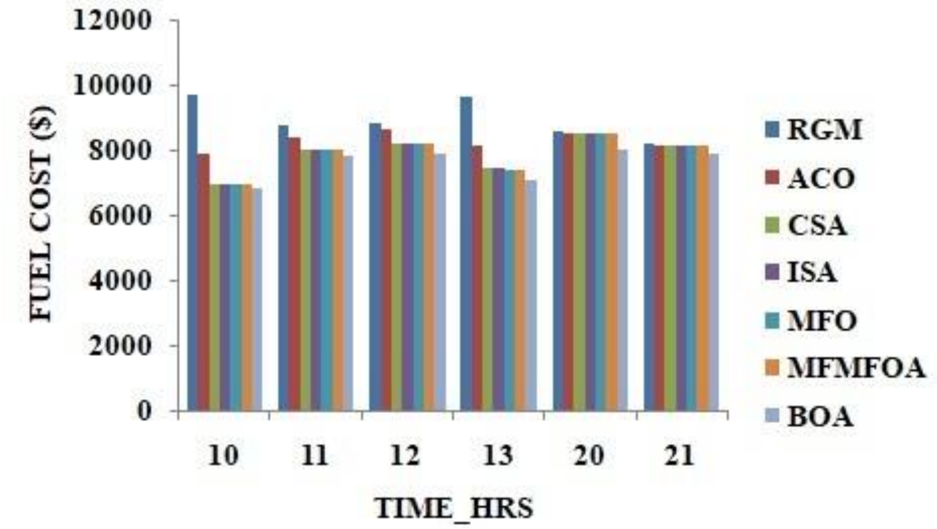

Fig. 6 Comprehensive Cost Evaluation Including Sustainable Energy

Table 3 illustrates the percentage decrease in cost for BOA following dispatch, providing a more in-depth and thorough comparison. This information offers a clearer perspective on the cost savings attained through the proposed method, emphasizing its effectiveness in enhancing economic dispatch optimization. Its ability to navigate the search space effectively, converge faster, and provide improved computational accuracy further validates its superiority over traditional methodologies.

Table 3 Comparative Percentage Reduction in Cost using BOA for Case II

Sr. No.	RGM with BOA in %	ACO with BOA in %	CSA with BOA in %	ISA with BOA in %	MFO with BOA in %	MFMFOA with BOA in %
1	29.98601	10.82612	1.869278	1.954167	1.554623	1.551074
2	10.74024	6.566888	2.999801	2.999801	2.957446	2.952643
3	10.1505	7.876222	3.82954	3.794411	3.798101	3.795337
4	26.55627	10.9358	4.50831	4.289174	4.18275	4.177648
5	6.436325	5.852691	5.809636	5.809636	5.788768	5.787428
6	3.326007	3.154586	3.124356	3.100577	3.066802	3.054662

By leveraging renewable during peak demand periods, utilities can effectively lower the overall cost of electricity production, minimize dependency on expensive fossil fuels, and enhance the economic efficiency of power systems. This approach not only results in direct

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financial savings but also contributes to grid stability and long-term sustainability by reducing carbon emissions and promoting cleaner energy alternatives.

6. Conclusion

The effectiveness of the proposed approach is evaluated through comparative analysis with existing optimization techniques. The results demonstrate that BOA outperforms conventional methods in terms of cost reduction, emission minimization, and renewable energy utilization. This research contributes to advancing smart grids and microgrid operations, fostering a low-carbon, flexible, and economically viable energy infrastructure. The comprehensive evaluation of BOA across multiple test scenarios underscores its superior capability in optimizing economic dispatch, both with and without the integration of renewable energy sources. In Case I, where only conventional thermal generators were utilized, the BOA demonstrated a significant reduction in operational costs compared to previously implemented algorithms, reinforcing its effectiveness in cost minimization within traditional power systems. The comparative analysis clearly highlights BOA's ability to allocate generation efficiently while adhering to system constraints, ultimately improving the economic viability of fossil-fuel-based power generation.

In Case II, the inclusion of sustainable energy sources further amplified the cost-efficiency of BOA. By integrating renewable resources such as solar and wind, the proposed methodology effectively reduced dependency on high-cost fossil fuel generation, particularly during peak demand periods. This not only resulted in substantial economic benefits but also contributed to grid stability and environmental sustainability by lowering carbon emissions. The comparative results demonstrated that BOA outperforms conventional heuristic techniques by achieving higher optimization accuracy, faster convergence, and improved computational efficiency.

The findings of this study establish BOA as a highly effective optimization tool for economic dispatch in modern power systems. Its adaptability across diverse generation configurations and its capacity to handle dynamic grid conditions make it a valuable solution for real-world applications. As the global energy landscape transitions towards a more sustainable paradigm, the integration of BOA into smart grid operations and renewable energy planning can play a pivotal role in enhancing economic efficiency, reducing environmental impact, and ensuring long-term energy security.

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