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(RESEARCH ARTICLE)

Techno-economic and environmental evaluation of economic load dispatch of Nigerian power system using zebra optimization algorithm (ZOA)

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Abstract

Power systems in developing countries, such as Nigeria continue to face gross inefficiencies in generation dispatch, leading to elevated operational costs, substantial transmission and distribution losses, and an over-reliance on fossil fuel-based generators. This work therefore proposes the techno-economic and environmental assessment of an optimal economic load dispatch in Nigerian power system, with a focus on integrating renewable energy sources. A multi-objective optimization model for ELD that integrates renewable energy sources is formulated in this study to minimize the generation cost, power losses and greenhouse gases emissions and maximize the renewable energy utilization. The formulated objective is optimized using Zebra Optimization Algorithm (ZOA) and its results are compared with the results obtained using Whale Optimization Algorithm (WOA). The proposed methodology is implemented on the practical Nigerian 28 bus transmission system and simulated using MATLAB R2021a. The simulation results show that, the proposed ZOA-based ELD yields reductions of 95.41%, 95.13%, and 96.03% in total transmission losses, generation cost, and greenhouse gas emissions, respectively, relative to the base case. Meanwhile, the WOA-based ELD achieve corresponding reductions of 94.76%, 91.91%, and 89.55%. The outcome of this research demonstrates the superior performance, and optimization capability of the proposed ZOA-based ELD approach in enhancing the techno-economic and environmental efficiency of a transmission network. The findings of this study offer actionable insights for grid operators and energy stakeholders, facilitating the adoption of advanced dispatch strategies and renewable energy technologies.

Keywords: Power system; Optimization; Optimal economic load dispatch; Greenhouse gases reduction

1. Introduction

Globally, power systems persistently encounter inefficiencies in generating dispatch, resulting in increased operational costs, significant transmission and distribution losses, and excessive dependence on fossil fuel-based generators. Economic Load Dispatch (ELD) has long been a central aspect of operational strategy in power systems used to address this inefficiency. The focus of ELD is to determine the optimal allocation of load demand among available generating units in such a way that the total production cost largely represented by fuel expenditure is minimized, subject to generator operational limits [1]. While conventional ELD approaches are good at reducing fuel costs, they frequently ignore the environmental effects of using fossil fuels, such as greenhouse gas emissions and air pollution, which exacerbate public health issues and contribute to climate change [2]. The absence of advanced ELD models that effectively incorporate renewable energy sources aggravates these challenges. Utilities struggle to balance cost efficiency with environmental objectives, as current optimization tools often lack the sophistication to handle the intermittent nature of renewable generation. For example, without accurate forecasting and robust optimization

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algorithms, renewable energy may be curtailed during periods of peak availability, while fossil fuel generators are unnecessarily operated, driving up both operational costs and emissions.

Several works have been reported to address these issues in power system. In [3], the authors address the economic dispatch problem in electric power systems by implementing two metaheuristic algorithms: Ant Lion Optimization Algorithm (ALOA) and Bat Algorithm (BA). These algorithms are applied to both small-scale (three-generator) and large-scale (six-generator) systems, including the IEEE-30 bus test system. The study evaluates the performance of ALOA and BA based on convergence rate, cost, and average run time, demonstrating their suitability for economic dispatch studies. The results show that both algorithms effectively minimize fuel and carbon pollution costs while satisfying technical and operational constraints. In [4], the authors introduce a dynamic economic load dispatch model that incorporates wind power while accounting for system flexibility. Their approach integrates a flexibility index into the total operation cost function, enabling a balanced trade-off between generation costs and the risks of load shedding or renewable energy curtailment. This model enhances power system resilience by optimizing generation flexibility to accommodate the variability of renewable energy sources. Said *et al.* [5] introduce the Search and Rescue Optimization (SRO) algorithm to address ELD and Combined Economic and Emission Dispatch (CEED) problems. The study evaluates SRO's performance across seven benchmark cases—three 6-unit ELD, three 6-unit CEED, and one 10-unit ELD—comparing it with algorithms like earthworm optimization, grey wolf optimizer, tunicate swarm algorithm, and elephant herding optimization. This was done to establish the effectiveness of optimization approach in ELD solution.

In [6], Hassan *et al*. introduce an enhanced beluga whale optimization algorithm to address the ELD problem in large-scale power systems. The algorithm's performance was validated on benchmark functions and tested on 11-, 40-, and 110-unit systems, demonstrating superior fuel cost minimization compared to other optimization techniques. In [7], the authors develop a coordinated neighborhood energy-sharing framework for smart buildings equipped with renewables and storage, using an improved butterfly optimization algorithm to schedule individual home energy management systems and a consensus-based neighborhood energy management system to optimize shared dispatch. Their approach reduce total electricity costs, peak loads, and peak-to-average ratios more effectively than grey wolf optimization while also cutting run-time and iteration counts across both time-of-use and critical peak pricing tariffs. However, the study centers on localized micro-community environments and does not explore how such intelligent scheduling interfaces with broader grid-level ELD frameworks under dynamic system constraints.

Marzbani and Abdelfatah [1] conduct a comprehensive review of the economic dispatch, focusing on determining optimal power generation outputs that meet demand at minimal cost while satisfying system constraints. The work traces the evolution of ELD formulations from traditional to modern strategies, and categorizes solution techniques into conventional mathematical models, uncertainty modeling, AI-based methods, and hybrid algorithms. While the review provides valuable insights into ELD modeling and solution trends, it identifies major limitations, such as the overreliance on single-case studies and the lack of standardized evaluation frameworks, which hinder comparative analysis and practical implementation.

In [8], the authors propose a distributed multi-agent optimization framework using a genetic algorithm to solve the multi-area economic dispatch problem in power systems. Each area is modeled as an autonomous agent that independently solves local dispatch equations while coordinating iteratively with neighboring agents to minimize generation cost and maintain voltage profiles. The model ensures convergence through repeated data exchanges and collaborative consensus, decomposing the overall dispatch problem into smaller sub-problems. Although the approach effectively enhances decentralized coordination and scalability, it does not account for dynamic uncertainties from renewable integration or incorporate emission constraints.

Despite the growing body of literature on economic load dispatch (ELD) in modern power systems, many existing studies focus primarily on either cost minimization or environmental impact in isolation, often neglecting a holistic techno-economic and environmental evaluation. Hence this work presents the techno-economic and environmental evaluation of the optimal economic load dispatch in a practical Nigerian transmission system. This study is of paramount importance in addressing the critical need for sustainable, efficient, and cost-effective power system operations in an era of increasing global energy demand and environmental concerns. Furthermore, this study supports the global transition toward sustainable energy systems, aligning with international frameworks such as the Paris Agreement and the United Nations Sustainable Development Goals, which emphasize the need for clean, affordable, and reliable energy.

2. Problem Formulation

2.1. Load Flow Analysis using Newton Raphson Method

Newton-Raphson (NR) method is one of the most widely used techniques for solving power flow problems in electrical power systems due to its robustness, high accuracy, and quadratic convergence characteristics [9]. In the context of this research, the NR method is employed as a foundational analytical tool to determine the steady-state operating conditions of the power grid, including bus voltages, power flows, and system losses, before and after applying the Economic Load Dispatch (ELD) optimization strategies.

Power flow analysis is essential for determining how electrical power is transmitted from generators to various loads across the network without violating the system constraints. The NR method is particularly effective for modern grid scenarios involving renewable integration, where nonlinearities are more pronounced due to variable generation profiles and complex load dynamics.

The load flow problem involves solving a set of nonlinear algebraic equations derived from Kirchhoff's current law at each bus. Equations (1) and (2) are typically expressed in terms of power mismatch equations, involving both real and reactive power at each bus [10].

$$\Delta P_i = P_i^{scheduled} - P_i^{calculated} \tag{1}$$

$$\Delta Q_i = Q_i^{scheduled} - Q_i^{calculated} \tag{2}$$

Newton-Raphson method solves these nonlinear equations with iterative updates as given in Equation (3).

$$\begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial |V|} \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{3}$$

Here, θ represents the voltage angle and $|V|$ represents the voltage magnitude at the buses. The Jacobian matrix encapsulates the sensitivity of the real and reactive power mismatches to changes in voltage magnitude and angle. During each iteration, voltage angle and magnitude values are updated using Equations (4) and (5), respectively [11].

$$\theta^{k+1} = \theta^k + \Delta\theta \tag{4}$$

$$|V|^{k+1} = |V|^k + \Delta|V| \tag{5}$$

This process continues until the power mismatches ΔP_i and ΔQ_i fall below a specified convergence tolerance.

2.2. Formulation of ELD Optimization Problem

This study considers ELD problem as a multi-objective function that is aimed to minimize real power loss, generation cost, and greenhouse gases (CO_2, SO_2 and NO_x) emission. This multi-objective function unified multiple variables using weighted function. The multi-objective function considered in this study is summarized as:

$$F = \min(k_1 \times RPL + k_2 \times C_{gen} + k_3 \times E_{emission}) \tag{6}$$

Where *RPL*, C_{gen}, and $E_{emission}$ are real power loss, generation cost, and greenhouse gases emission, respectively while k_1, k_2, and k_3 are the weighted functions used to combine the objectives.

This objective function is to be minimized subject to the following constraints:

2.2.1. Real power balance constraint

As adduced in [12], the algebraic sum of the total generated power, total load demand and entire losses in the transmission system must be equal to zero.

$$P_{gen} - P_{Dem} - P_{loss} = 0 \tag{7}$$

where P_{gen} is the generated power, P_{Dem} is the load demand connected to the transmission network and P_{loss} is the transmission network power losses.

2.2.2. Generator capacity constraint

For N-generators, the active power generated by each of the generating units is confined within a specified lower limit and an upper limit [12].

$$P_i^{min} \le P_i \le P_i^{max}, for\ i = 1, 2, 3, \dots, N \tag{8}$$

3. Zebra Optimization Algorithm

Zebra Optimization Algorithm (ZOA) is a bio-inspired metaheuristic algorithm. The fundamental inspiration of ZOA is based on the behavior of zebras in nature. ZOA simulates the foraging behavior of zebras and their defense strategy against predators' attacks [13]. The mathematical modeling of the intelligent and natural behaviors of zebras is the fundamental inspiration for creating ZOA technique. These are explained below.

3.1. Initialization

The population-based ZOA comprises zebras as members of its population. From a mathematical perspective, each zebra represents a potential solution to the problem, while the plain where the zebras are located is the problem's search space. The values of the decision factors depend on where each zebra is located in the search space. The values of the problem variables are thus represented as the elements of a vector used to model each zebra as a member of the ZOA. A matrix can be used to mathematically model the zebra population. The zebras are initially placed in the search space at random. The ZOA population matrix is presented in Equation (9) [13].

$$ZP = \begin{bmatrix} ZP_1 \\ \vdots \\ ZP_i \\ \vdots \\ ZP_N \end{bmatrix}_{x \times y} = \begin{bmatrix} zp_{1,1} & \cdots & zp_{1,j} & \cdots & zp_{1,y} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ zp_{i,1} & \cdots & zp_{i,j} & \cdots & zp_{i,y} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ zp_{x,1} & \cdots & zp_{x,j} & \cdots & zp_{x,y} \end{bmatrix}_{x \times y}, \tag{9}$$

where *ZP* is the zebra population, *ZPi* is the i^{th} zebra, $zp_{i,j}$ is the value for the j^{th} problem variable proposed by the i^{th} zebra, *x* is the number of population members (zebras), and *y* is the number of decision variables.

Each zebra in the search space denotes a candidate solution to the optimization problem. Therefore, the objective function can be evaluated based on the proposed values of each zebra for the problem variables. The values obtained for the objective function are given as a vector using Equation (10).

$$OF = \begin{bmatrix} OF_1 \\ \vdots \\ OF_i \\ \vdots \\ OF_x \end{bmatrix}_{x \times 1} = ZP = \begin{bmatrix} OF(ZP_1) \\ \vdots \\ OF(ZP_i) \\ \vdots \\ OF(ZP_x) \end{bmatrix}_{x \times 1}, \tag{10}$$

where OF is the vector of objective function values, and OF_i is the objective function value obtained for the i^{th} zebra. Comparing the values obtained for the objective function effectively analyzes the quality of their corresponding candidate solutions and identifies the best candidate solution for the given problem.

In minimization problems, the zebra with the least value of objective function is the best candidate solution. In contrast, in maximization problems, the zebra with the highest value of the objective function is the best candidate solution. Since in each iteration, the positions of the zebras and consequently the values of the objective function are updated, the best candidate solution must also be identified in each iteration. Two natural behaviors of zebras in the wild have been used to update ZOA members. These two types of behavior are foraging and defense strategies against predators. Therefore, in each iteration, members of the ZOA population are updated in two different phases.

3.2. Phase 1: Foraging Behavior

In the first phase, population members are updated based on simulations of zebra behavior when searching for forage. The main diet of zebras is mainly grasses and sedges, but if their favorite foods are scarce, they may also eat buds, fruits, bark, roots, and leaves. Depending on the quality and availability of vegetation, zebras may spend 60–80 percent of their time eating. Among the zebras, there is a zebra called the plains zebra, which is a pioneer grazer, by devouring the canopy of upper and less nutritious grass, provides conditions for other species that need shorter and more nutritious grasses below. In ZOA, the best member of the population is considered as the pioneer zebra and leads other population members towards its position in the search space. Therefore, updating the position of zebras in the foraging phase can be mathematically modeled using Equations (11) and (12).

$$zp_{i,j}^{new,P_1} = zp_{i,j} + r \cdot \left(PZ_j - I \cdot zp_{i,j} \right) \tag{11}$$

$$ZP_i = \begin{cases} zp_i^{new,P_1}, OF_i^{new,P_1} < OF_i \\ \quad ZP_i, \qquad else, \end{cases}, \tag{12}$$

where zp_i^{new,P_1} is the new status of the i^{th} zebra based on first phase, $zp_{i,j}^{new,P_1}$ is its j^{th} dimension value, OF_i^{new,P_1} is its objective function value, PZ is the pioneer zebra which is the best member, PZ_j is its j^{th} dimension, r is a random number in interval [0,1],

$$I = round(1 + rand) \tag{13}$$

where $rand$ is a random number in the interval [0; 1]. Thus, $I \in \{1,2\}$ and if parameter I =2, then there are much more changes in population movement.

3.3. Phase 2: Defense Strategies Against Predators

In the second phase, simulations of the zebra's defense strategy against predator attacks are employed to update the position of population members of ZOA in the search space. The main predators of zebras are lions; however, they are threatened by cheetahs, leopards, wild dogs, brown hyenas, and spotted hyenas. In the ZOA design, it is assumed that one of the following two conditions occurs with the same probability: the lion attacks the zebra, and thus, the zebra chooses an escape strategy; other predators attack the zebra, and the zebra will choose the offensive strategy.

In the first strategy, when the zebras are attacked by lions, the zebras escape from the lion's attack in the vicinity of the situation in which they are located. Therefore, mathematically, this strategy can be modeled using the mode $S1$ in Equation (13). In the second strategy, when other predators attack one of the zebras, the other zebras in the herd move towards the attacked zebra and try to frighten and confuse the predator by creating a defensive structure. This strategy of zebras is mathematically modeled using the mode $S2$ in Equation (14). In updating the position of zebras, the new position is accepted for a zebra if it has a better value for the objective function in that new position. This update condition is modeled using Equation (15).

$$zp_{i,j}^{new,P_2} = \begin{cases} S_1 : zp_{i,j} + R \cdot (2r-1) \cdot \left(1 - \frac{t}{T}\right) . zp_{i,j},\ P_s < 0.5; \\ S_2 : zp_{i,j} + r \cdot \left(AZ_j - 1 \cdot zp_{i,j}\right), \qquad ,else, \end{cases} \tag{14}$$

$$ZP_i = \begin{cases} zp_i^{new,P_2}, OF_i^{new,P_2} < OF_i; \\ ZP_i, \qquad else, \end{cases} \tag{15}$$

Where zp_i^{new,P_2} is the new status of the i^{th} zebra based on the second phase, $zp_{i,j}^{new,P_2}$ is its j^{th} dimension value, F_i^{new,P_2} is its objective function value, t is the iteration contour, T is the maximum number of iterations, R is the constant number equal to 0.01, P_s is the probability of choosing one of two strategies that are randomly generated in the interval [0*;* 1], AZ is the status of attacked zebra, and AZ_j is its j^{th} dimension value.

3.4. Repetitions Process

Each ZOA iteration is completed by updating the population members based on the first and second phases. The process of updating the algorithm population continues based on Equation (11 – 15) until the end of the full implementation of the algorithm. The best candidate solution is updated and saved during successive iterations. Once fully implemented, ZOA makes the best candidate solution available as the optimal solution to the given problem.

The formulated multi-objective function in Equation (6) is optimized using ZOA to minimize the transmission losses, generation cost and emission and improve the bus voltage profile without violating the operational constraints. The optimization methodology of the Whale Optimization Algorithm (WOA) as detailed in [14] is adapted by substituting the original objective function with the multi-objective formulation in Equation (6). The efficacy and superior performance of the proposed ZOA is demonstrated by comparing the results obtained with the algorithm with WOA-generated results. In order to ensure a fair comparative study of ZOA and WOA, the same simulation parameters are used for the implementation of both algorithms. The simulation parameters are presented in Table 1.

Table 1 Simulation Parameters

Parameters	**Values**
Number of Search Agents (Otherwise known as the population size)	40
Maximum number of iterations	100
Number of independent runs for statistical analysis	5

4. Results and Discussion

4.1. Load Flow Analysis Results for the Base Case

The Load flow analysis is carried out to assess the steady state performance of the Nigerian 28 bus transmission network in terms of the power flow on each line and the voltages across the buses. Newton Raphson load flow method is considered in this work due to its compatibility and computational efficiency in analyzing the power flow on transmission system. The line and bus data of the Nigerian 28-Bus Transmission network as well as some of the constant variables for cost are adopted as presented by Okozi in [15]. The load flow is carried out on the Nigerian 28-Bus Transmission network to evaluate the performance of the system at the steady state before the implementation of the optimal economic dispatch and the integration of the Renewable Energy (RE). The voltage magnitude per unit and the equivalent angles on each bus are presented in Table 2. It can be observed from the presented results that most of the bus voltages level fall under normal category according to the IEEE standard for monitoring electric power quality. However, some bus fall under the overvoltage category, meaning that there is a need to improve the voltage profile of the system.

The line losses on each line are presented in Table 3, showing the line serial number, to and fro connectivity and their equivalent losses. The highest loss is recorded in line 17-20, meaning that it stands out among the susceptible lines that need compensation. From these results, it can be said that the steady state condition of the network as revealed in the load flow analysis needs to be compensated to mitigate the losses and also improve the state of the system. Furthermore, it can be observed that the losses in the network are not evenly distributed on the lines, but concentrated on few lines, meaning that an effective optimization approach is needed to optimally integrate the renewable energies.

The total real power loss for the Nigerian 28 bus transmission network is found to be 802.3720 MW, while its operation cost is NGN 27,347,595,201 and its equivalent emission is 20018586.53 kg. The results of the system before the implementation of the proposed method are considered as the Base case (Case 1) and they are used as the benchmarks to measure the effectiveness of the proposed method.

Table 2 Voltage Profile for the Nigerian 28 Transmission System for Case 1

Bus number	Voltage magnitude (p.u.)	Voltage angle (degree)
1	1	0
2	1	18.379
3	1.05	14.335
4	1.05	16.318
5	1.05	13.406
6	1.01	14.868
7	1.02	34.828
8	1	0.074
9	1	25.789
10	1.05	41.431
11	1.197	11.569
12	1.013	14.684
13	1.192	11.848
14	1.047	15.42
15	1.007	7.737
16	1.026	9.585
17	1.061	12.023
18	1.075	11.211
19	0.973	5.596
20	0.977	6.043
21	0.999	24.034
22	1.008	27.257
23	1.011	33.875
24	1.026	15.764
25	0.995	-0.332
26	1.089	12.49
27	1.122	14.281
28	1.147	13.874

Table 3 Line flow for Nigerian 28 Transmission System for the Base Case

Line			**Line Loss**	
Line serial number	**From**	**To**	**Real Power Loss (MW)**	**Reactive Power Loss (MVAR)**
1	1	8	0.097	0.387
2	1	20	53.138	385.249
3	1	25	0.123	0.998
4	3	17	3.86	30.4
5	2	24	5.543	43.654
6	3	26	1.195	8.862
7	3	12	2.032	16.659
8	4	27	7.701	67.905
9	4	12	0.881	9.372
10	4	14	1.999	1.488
11	5	17	6.824	51.182
12	5	24	4.791	37.726
13	6	12	1.262	5.048
14	7	23	14.796	11.836
15	9	21	1.859	14.639
16	10	23	70.43	60.492
17	11	13	1.052	0.888
18	12	16	6.214	51.998
19	13	27	4.755	35.573
20	15	16	1.822	14.015
21	15	20	1.549	12.97
22	16	17	1.487	12.589
23	16	20	3.893	26.781
24	17	18	0.242	2.083
25	17	20	443.394	208.656
26	17	21	41.111	357.153
27	19	20	0.153	1.249
28	21	22	3.758	33.139
29	21	23	105.471	90.589
30	22	23	10.5	78.064
31	27	28	0.44	3.289
	Total Loss (MW)		802.3720	1674.933

4.2. ZOA-optimized ELD for Nigerian 28-bus transmission system

The proposed ZOA-optimized ELD is implemented on the Nigerian 28-bus transmission network to evaluate its performance on a practical power system. Three operational cases are analyzed for this network, these are: the base case (Case 1), optimal economic load dispatch without renewable energy integration (Case 2), and optimal economic load dispatch with renewable energy integration (Case 3). Table 4 presents the summarized results for all the cases considered. For the base case (Case 1), the initial generator outputs in MW as presented in the line and bus data adopted from [15] are 0, 882, 760, 600, 1020, 578, 931.6000, 302, 480, and 600, and these values are used to perform load flow analysis using the Newton–Raphson technique. As shown in Table 4, the system experiences a high real power loss of 802.37 kW, a substantial generation cost of ₦27,347,595,201.11, and a greenhouse gas emission level of 20,018,586.53 kg. Additionally, the minimum bus voltage magnitude is 0.9733 p.u. at Bus 19, indicating a weak voltage profile and highlighting the need for system improvement.

In Case 2, the proposed ZOA is used to optimally schedule the generation output without renewable energy integration. The optimal outputs determined by the ZOA after the optimization process in MW are 275.0000, 266.7016, 154.0628, 267.4171, 113.9068, 128.0127, 168.5929, 233.5833, 253.0620, and 100.6702. As a result, real power loss, generation cost, and greenhouse gas emissions are reduced by 94.84%, 92.74%, and 91.13%, respectively, compared to Case 1. Moreover, the minimum bus voltage improved from 0.9733 p.u. at Bus 19 to 0.995064 p.u. at Bus 25. This improvement is due to the optimal rescheduling of generator outputs to operate efficiently within their permissible limits.

Table 4 Simulation Results for Nigerian 28 Bus Transmission System Using ZOA

Metrics	Case 1	Case 2	Case 3
Real Power Loss (kW)	802.37	41.43	36.83
% Loss reduction	-	94.84	95.41
Generation cost (NGN)	27347595201.11	1986406316.73	1331630939.69
% cost reduction	-	92.74	95.13
Total CO2 Emission (kg)	20018586.53	1776463.85	793918.51
% CO2 emission reduction		91.13	96.03
Minimum Voltage magnitude	0.973288 at 19	0.995064 at 25	0.995064 at 25

In Case 3, renewable energy sources are incorporated alongside optimal generator scheduling. The ZOA allocated 3.8609 MW of PV generation at Bus 5 and 4.1542 MW of wind generation at Bus 4. With these additions, the ZOA-based optimal dispatch determines new generator outputs as 275, 85.4256, 137.5000, 135, 50.1728, 50, 100, 135, 150, and 100 MW. These values are gotten after the ZOA optimization process and it implies that, for the techno-economic and environmental benefits to be realized on the Nigerian 28 bus system, such values are required from the generator units as their output power. Consequently, compared to Case 1, real power loss, generation cost, and emissions are significantly reduced by 95.41%, 95.13%, and 96.03%, respectively—the highest improvements among all cases. The minimum bus voltage magnitude also improves to 0.995064 p.u. at Bus 25, confirming enhanced voltage stability. This improvement demonstrates the applicability and effectiveness of the proposed methodology in minimizing real power losses, reducing generation costs, lowering greenhouse gas emissions, and improving the voltage profile of the transmission system.

The comparison of the total real power losses, generation cost, greenhouse gases emission and voltage profiles for the three cases considered are presented in Figure 1, 2, 3 and 4, respectively. The significant improvement observed in Case 3 (where the ZOA-based optimal economic load dispatch is carried out with PV and wind integration) is primarily attributed to the localized injection of clean energy at strategic buses, which reduces transmission loading and associated losses. Furthermore, the decreased dependence on conventional generators results in reduced fuel consumption, thereby achieving lower operational costs and decreased emissions. Overall, the coordinated scheduling of generator outputs alongside renewable energy integration optimizes power flow, enhances system performance, and provides combined technical, economic, and environmental benefits.

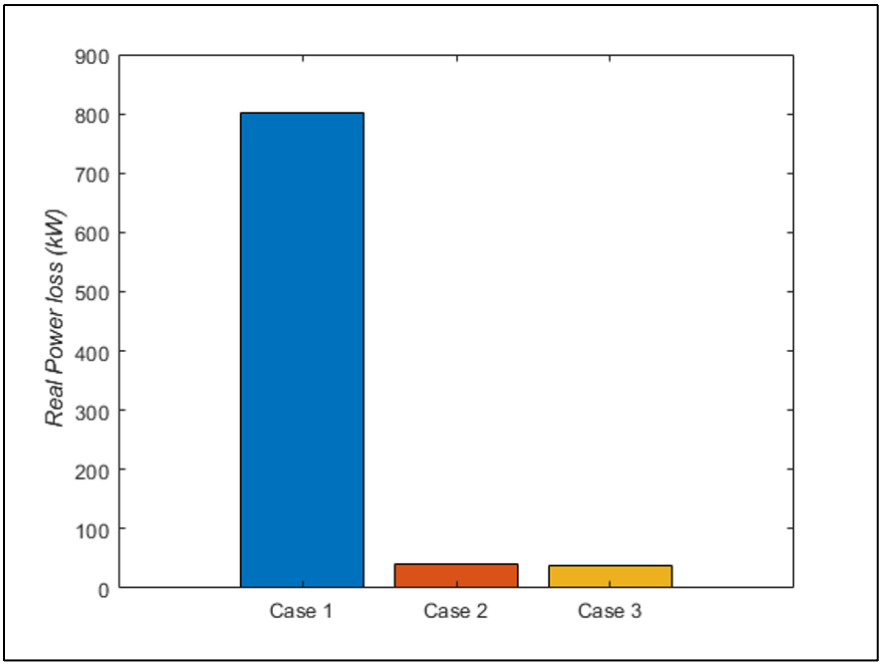

Figure 1 Real Power Loss of all the Cases considered

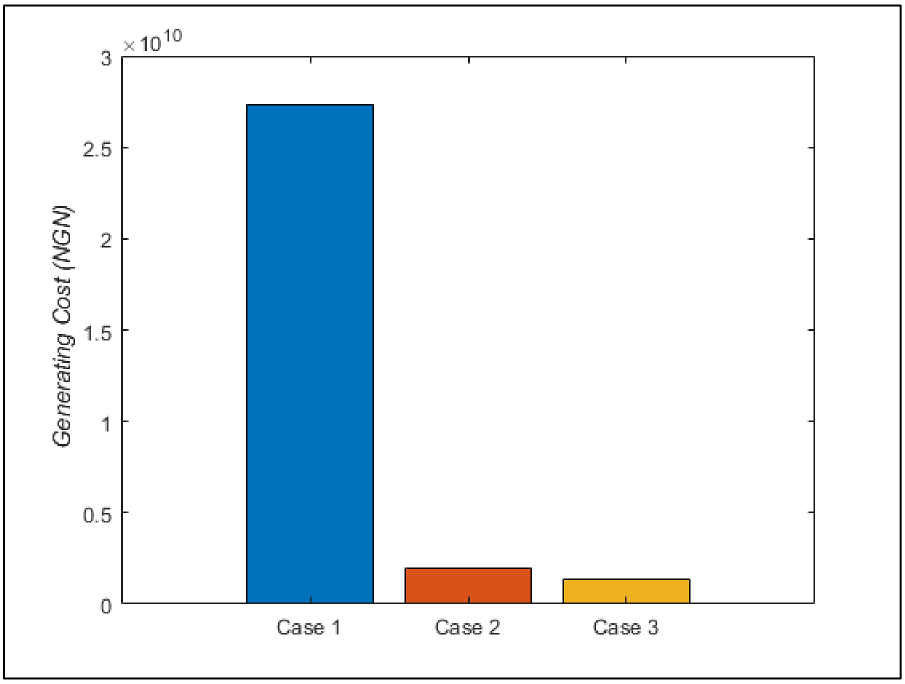

Figure 2 Generation cost of all the Cases considered

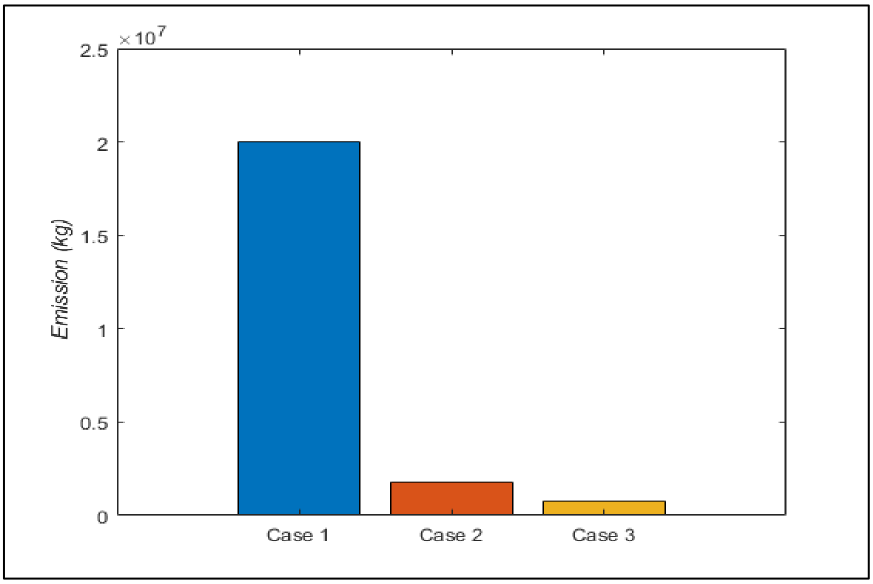

Figure 3 Greenhouse Gases Emission of all the Cases considered

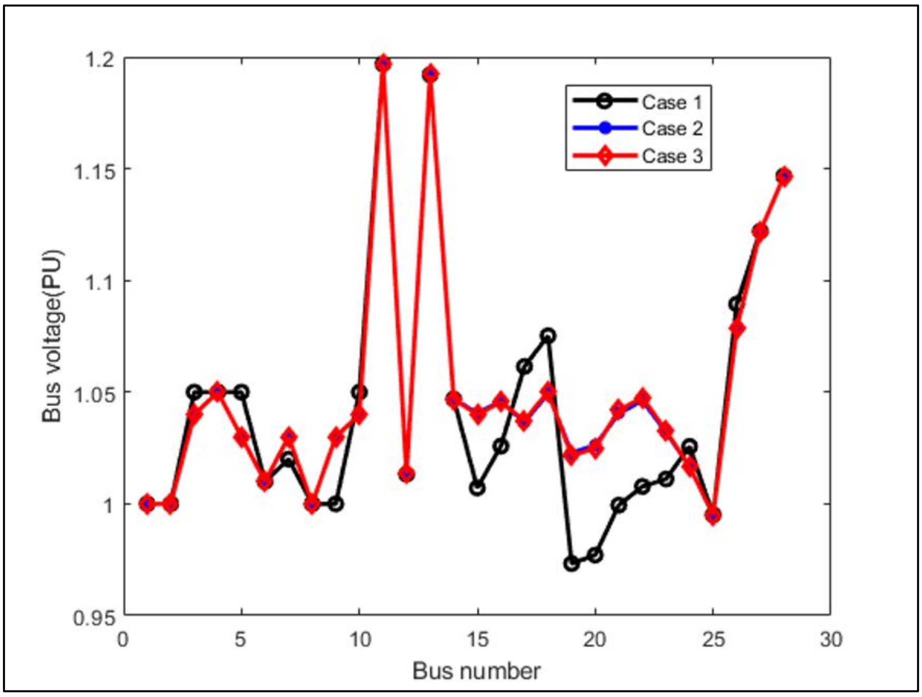

Figure 4 Voltage Profile of all the Cases considered

4.3. Comparative Analysis of WOA-Optimized ELD and ZOA-Optimized ELD

The Whale Optimization Algorithm (WOA) is also employed to optimize the proposed economic load dispatch (ELD) model, aiming to minimize power loss, generation cost, and greenhouse gas emissions while improving the voltage profile of the transmission network. The WOA-based ELD is implemented to assess the impact of the optimization approach on the model's performance in terms of solution quality, result consistency, convergence behavior, and computational efficiency. The implementation is also carried out on the Nigerian 28-bus transmission network and the simulation results are compared with those obtained using the proposed ZOA-based ELD, as presented in Tables 5.

The simulation results show that WOA-based ELD with RE integration achieves reductions of 35.14%, 62.65%, and 78.43% in real power loss, generation cost, and greenhouse gas emissions, respectively, compared to the base case.

However, when compared to the proposed ZOA-based ELD, the ZOA provides superior performance, achieving reductions of 36.85%, 82.16%, and 96.86% for the same metrics (as illustrated in Figure 5). This demonstrates the higher optimization efficiency of the ZOA-based ELD, which consistently provide lower values of power loss, cost, and emissions.

In terms of voltage performance, both algorithms significantly improve the minimum bus voltage magnitude compared to the base case, indicating that both optimizers effectively enhance system voltage stability. The convergence characteristics of both optimizers, as presented in Figure 6, reveal that the proposed ZOA converges faster while still maintaining global optimality.

In conclusion, the proposed ZOA-based ELD outperforms the WOA-based ELD in terms of technical, economic, and environmental performance. Its faster convergence rate, improved stability, and superior optimization capability make it a robust and efficient approach for optimal economic load dispatch in modern power systems.

Table 5 Comparative Study of the Simulation Results for Nigerian 28 bus transmission system using ZOA and WOA

Metrics	**Base Case**	**ZOA-Based ELD**	**WOA-Based ELD**
Real Power Loss (kW)	802.37	36.83	42.02
% Loss reduction	-	95.41	94.76
Generation cost (NGN)	27347595201.11	1331630939.69	2212694420.25
% cost reduction	-	95.13	91.91
Total CO2 Emission (kg)	20018586.53	793918.51	2092364.44
% CO2 emission reduction	-	96.03	89.55
Minimum Voltage magnitude p.u. (location)	0.973288 (19)	0.995064 (25)	0.995064 (25)

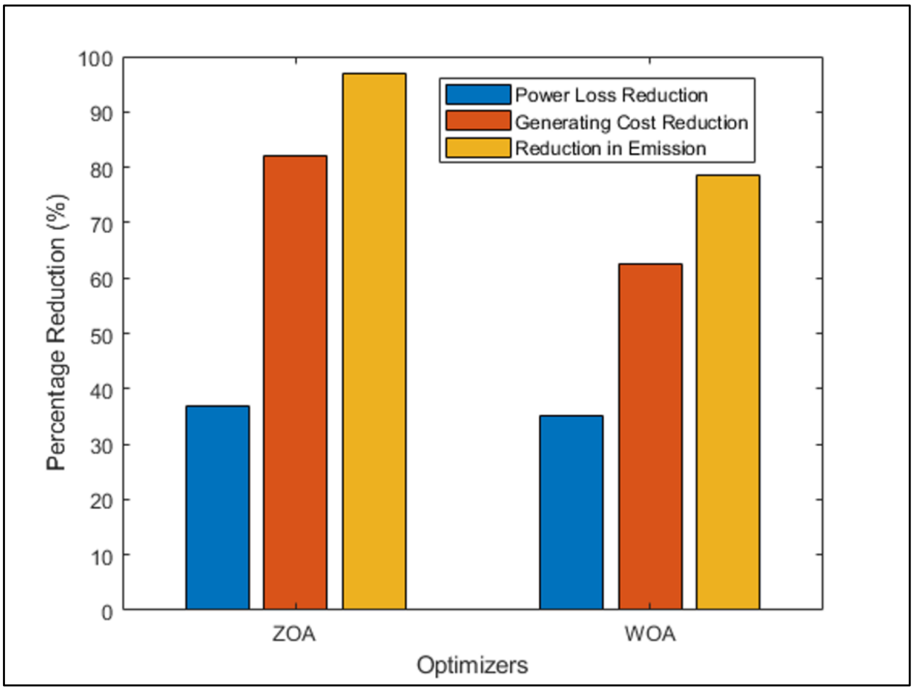

Figure 5 Comparison between ZOA and WOA in terms of Percentage Reduction

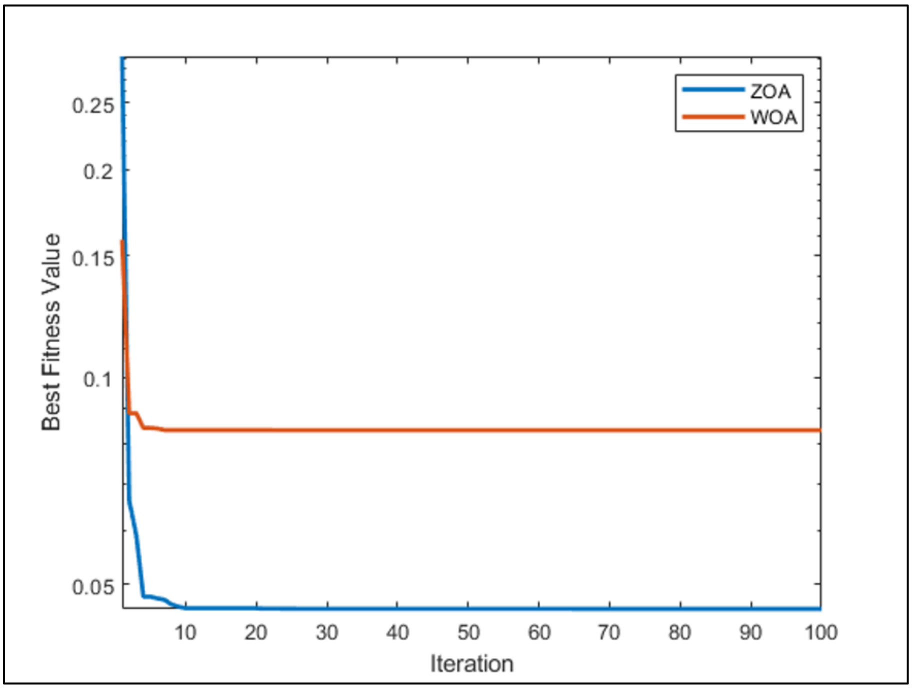

Figure 6 Convergence Characteristics curve for ZOA and WOA

5. Conclusion

The load flow analysis conducted on the Nigerian 28 bus transmission network reveals significant losses, high generation cost, and elevated greenhouse gas emissions, as well as low bus voltage magnitudes, emphasizing the need for optimization to enhance system efficiency. The application of the proposed Zebra Optimization Algorithm (ZOA)-based ELD on the Nigerian 28 bus transmission network demonstrates its techno-economic and environmental advantages, achieving reductions in line losses, generation cost, and emissions while improving voltage profiles. By comparing the performance of the developed ZOA-based ELD with that of the WOA-based ELD on the Nigerian 28 bus system, it is established that the superior performance of the developed ZOA-based ELD is pronounced in terms of the quality of solution and the convergence characteristics. This study has therefore demonstrated the applicability and effectiveness of the ZOA-based ELD in enhancing transmission system performance. The proposed approach efficiently minimizes line losses, generation cost, and greenhouse gas emissions while maintaining acceptable voltage level, thereby offering techno-economic and environmental benefits for the modern power systems with renewable energy integration.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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