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An Improved Zebra Optimization Algorithm for Solving Transmission Expansion Planning Problem with Penetration of Renewable Energy Sources

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Abstract: Transmission expansion planning (TEP) is a large-scale and complex problem. Recently, with the high penetration of renewable energy sources (RESs) into the power system, solving the TEP problems has become a challenge for many methodologies. In this paper, an improved zebra optimization algorithm (IZOA) is proposed to resolve the TEP problems with minimal total cost. In order to increase exploration ability, a Lévy flight function is added to the proposed IZOA method. In addition, the exploitation strategy is replaced with a function that does not depend on the number of interactions to help the search process not getting stuck in the local optimal values. The IEEE 24-bus RTS system with and without RESs is used to test the effectiveness of the proposed IZOA algorithm. The simulation results of IZOA are compared with the original ZOA and grey wolf optimization (GWO) method. In addition, to prove the robustness of the proposed method, IZOA is also compared with other existing methods, such as decision analysis (DA) and best-guided artificial bee colony algorithm (GABC), branch and bound (B&B), forensic based investigation optimization (FBIO) and symbiotic organisms Search (SOS). The simulation results show that the optimal value obtained by the proposed IZOA algorithm reduces 39.2% compared with the original ZOA, 36.4% for GWO, and 32.1 % for DA. Thus, the proposed algorithm is one of the suitable methods, powerful, and reliable techniques for solving the TEP problem with the penetration of RESs.

Keywords: Transmission expansion planning, Wind power, Zebra optimization algorithm, TEP, RESs.

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1. Introduction

In recent years, power demands have been increasing all over the world because of the dramatic increase in population and the development of technology. This surge in electricity consumption places considerable stress on existing transmission systems. Consequently, transmission expansion planning has garnered significant attention in recent research endeavors. The primary objective of TEP is to identify the necessary quantity and locations of new transmission lines that must be added to the system in order to meet future load demand while adhering to operational constraints, all while minimizing investment costs.

Besides, the world is facing global warming, and one of the main causes of this problem is emissions from fossil fuels. Moreover, fossil energy sources are gradually depleting, so finding clean and sustainable energy sources to replace them is necessary. Renewable energy sources are known as clean and sustainable energy sources. Thus, using these energy sources to replace fossil energy sources has become the trend in all countries around the world. Among renewable energy sources (RESs), wind energy is considered a promising option due to its minimal environmental impact. However, RESs dependence on natural conditions, such as wind power, are highly depends on the wind speed. The integration of wind power into the power system introduces greater complexity to the TEP problem, primarily due to the intermittent, random, and uncontrollable nature of renewable energy sources (RESs) [1]. Besides, the penetration of RESs requires the power system to be more reliable and stable. Hence, solving the TEP problem while considering RESs is imperative and plays a pivotal role in ensuring the security and stability of the power system. In literature, many techniques have been proposed to deal with the TEP problem such as: linear programming [2], bender's decomposition (BD) [3-5], branch and bound (B&B) [6, 7], constructive heuristic algorithm (CHA) [8], forensic based investigation optimization (FBIO) [9], tabu search algorithms (TS) [10], symbiotic organisms search (SOS) [11], chaos optimal algorithm (COA) [12], social spider algorithm (SS) [13]. In general, all algorithms above have been successfully applied to solve the TEP problem; however, recent studies tend to consider not only the investment cost of the new line but also many aspects of the TEP problem. The investment cost and operation cost under uncertainty conditions were proposed in [14-16]. Examines transmission expansion planning in risk-based conditions has been proposed in [17–19]. In [20], presenting line repair and maintenance impacts on generation-transmission expansion planning along with loss of load and load shedding owing to line outages. Solving these problems requires a lot of computational effort from the algorithms because of the large number of variables. All techniques have their advantages and disadvantages. Mathematical techniques can typically yield optimal solutions to problems quickly, but in the case of large-scale systems, they often demand significant computational resources. Conversely, meta-heuristic algorithms are especially suited to solve complex and combinatorial problems usually identify optimal or sub-optimal solutions even for large systems, but they usually fall into local value [21]. Given the computational limitations of the aforementioned techniques, numerous studies have focused on enhancing algorithms to address the TEP problem. In [22], aiming at two primary problems are minimum investment cost and minimum reliability index – EENS using a hybrid multi-objective grey wolf optimizer (MOGWO) and non-dominated monte carlo simulation (ND-MCS) to solve the TEP problem. The objective of minimizing investment cost, operation cost with uncertainty generation, and unserved energy costs in reliability conditions using the evolutionary particle swarm optimization (EPSO) algorithm are considered in [23]. A modified grey wolf optimization algorithm has been proposed to solve the TEP problem considering investment cost by modifying the exploitation process [24].

In recent years, research about the TEP problem with the penetration of RESs has become the subject of much interest from research groups. In [25], the application of linear decision rules (LDR) to correct the TEP model as a mixed-integer linear programming (MILP) problem considers load and wind power uncertainty. Although this method reduces calculation time compared with the conventional decomposition method, it is still a mathematical technique and requires a lot of computational effort if the number of operating conditions increases. A high-efficiency method, Taguchi's orthogonal array testing (TOAT), has been proposed in [26] to present multiple testing scenarios for TEP problems that consider load and wind power uncertainty. However, this method is complex and requires a high computational effort to find the optimal solution. The studies about TEP problems that consider the investment cost of new lines with the penetration of RESs can be found in [27–29]. In general, most of the above studies consider wind generator cost as a simple equation to solve TEP problems. In practice, wind generator costs should be considered to include three different costs: the penalty cost, the reserve cost, and the direct cost. Moreover, TEP problems are being considered in a large-scale test system with many variables. Therefore, it is necessary to find effective algorithms or improve the algorithms to obtain an optimal solution for the TEP problem.

Recently, a new meta-heuristic algorithm called the zebra optimization algorithm (ZOA) was introduced in [30]. In [30], ZOA has been used to solve 30 benchmark functions and has outperformed other algorithms such as TLBO, PSO, etc. The ZOA is one of the suitable algorithms for solving non-linear and complex problems. However, for TEP problem, the results obtained using the ZOA normally fall within local values because of the unbalance between exploration and exploitation strategies. To overcome the limitations of ZOA above, this study suggests an improved zebra optimization algorithm (IZOA) by adding a Lévy flight function for increasing the exploration ability compared with ZOA. In addtion, the exploitation phase is also modified so that it does not depend on the number of interactions. Compared to other metaheuristic algorithms, the biggest advantages of IZOA are that it does not require specific algorithmic parameters for operations. In IZOA, new locations of the whole herd are updated based on the location of the best member (pioneer zebra) through two phases: foraging behavior and defense strategies against predators' behavior. The elite members of each phase are considered for updating the initial herd, and after each interaction, the best member of the herd is used to update the pioneer zebra. To prove the effect of the proposed method, the IEEE 24-bus system is used and compared with other techniques in the literature. Moreover, solving the TEP problem by the proposed algorithm with penetration of wind power, considering the operation cost and penalty cost, is also introduced in the paper. The main contributions in this paper are as follows:

- A Lévy flight function is applied to the IZOA algorithm for expanding the exploration strategy.
- A modified exploitation strategy is proposed in the IZOA algorithm.
- Proposed IZOA algorithm to solve the TEP problem considers the uncertainty of wind power.
- The IEEE 24-bus system with wind power is considered to solve the TEP problem with the objective function of minimizing total cost consisting of investment cost, fuel cost, and wind power cost.

The rest of the paper is organized as follows: The mathematical model is presented in section 2. The proposed IZOA is introduced in section 3. The simulation results are presented in section 4. Finally, section 5 is the conclusion.

2. Mathematical model

In this section, monte carlo simulation is applied to generate different scenarios based on the probability density function (PDF) of the Weibull probability density function.

2.1 Objective function

The objective functions include line investment costs, fuel costs, and wind power costs, which are considered in the study.

$$Min\, C_{total} = C_{inv} + C_{fuel} + C_{wind} \tag{1}$$

The investment cost of the new lines (C_{inv}) can be calculated as follows:

$$C_{inv} = \sum_{i,j} c_{ij} n_{ij} \ \ \forall(n_{ij}) \in \Omega, i \neq j \tag{2}$$

Where c_{ij} and n_{ij} are the number and cost of new lines built between bus i^{th} and bus j^{th}, and Ω is a set of all candidate lines.

The fuel cost of the thermal plant (C_{fuel}) is represented by the quadratic function considering the valve-point effect can be described as [31]:

$$C_{fuel} = \sum_{i=1}^{N_{GN}} \begin{bmatrix} a_i + P_i b_i + P_i^2 c_i \\ +\left|d_i sin\{e_i(P_i^{min} - P_i)\}\right| \end{bmatrix} \tag{3}$$

Where a_i, b_i, c_i, d_i, e_i are fuel cost coefficients of i^{th} thermal generator, P_i and P_i^{min} are the active power and minimum active power of thermal generators and N_{GN} is the total number of thermal generators.

The cost of wind energy (C_{wind}) can be divided into three different costs: direct cost, penalty cost, and reserve cost.

Direct cost, which is paid by the system operator when they consume wind output power.

$$C_{Wd,i} = k_{d,i} Pw_i^s \tag{4}$$

Where $C_{Wd,i}$ is the direct cost of wind power at i^{th} wind farm, $k_{d,i}$ is the coefficient of direct cost and Pw_i^s is the scheduled output power of i^{th} wind farm.

Penalty cost, which is paid by the system operators if they do not use all available wind power because the wind power generated is more than the expected power. This cost function can be calculated as [32]:

$$C_{Wp,i} = (Pw_{i,av} - Pw_i^s) = k_{p,i}\left(Pw_{i,av} - Pw_i^s\right) = k_{p,i} \int_{Pw_i^s}^{Pw_i^r} (Pw_i - Pw_i^s) f_W(Pw_i) dPw_i \tag{5}$$

Where $C_{Wp,i}$ $(Pw_{i,av} - Pw_i^s)$ is the penalty cost of wind power at i^{th} wind farm, $k_{p,i}$ is the coefficient of penalty cost, $Pw_{i,av}, Pw_i^s, Pw_i^r, Pw_i$ are the available power, scheduled output power, rated and output wind power of i^{th} wind farm respective.

Reserve cost, which is similar to the penalty cost; however, in this case, the wind power generated is less than the expected power. This cost function can be calculated as [32]:

$$C_{Wp,i} = \left(Pw_i^s - Pw_{i,av}\right) = k_{r,i}(Pw_i^s - Pw_{i,av}) = k_{r,i} \int_0^{Pw_i^s} (Pw_i^s - Pw_i) f_W(Pw_i) dPw_i \tag{6}$$

Where $C_{Wr,i}$ $(Pw_i^s - Pw_{i,av})$ is the reserve cost of wind power at i^{th} wind farm, $k_{r,i}$ is the coefficient of reserve cost, $Pw_{i,av}, Pw_i^s, Pw_i$ are the available power, scheduled output power, and output wind power of i^{th} wind farm respective.

Thus, the total cost of wind power can be calculated as follows:

$$C_{wind} = \sum_{i=1}^{N_W} \begin{bmatrix} Cw_{d,i} + Cw_{p,i}\left(Pw_{i,av} - Pw_i^s\right) \\ +Cw_{r,i}\left(Pw_i^s - Pw_{i,av}\right) \end{bmatrix} \tag{7}$$

2.2 Constraints

Equation constraints

The power balance of active power can be described in Eqs. (8) and (9):

$$P_i + Pw_i^s + P_i^{inj} - P_{d,i} = 0, i = 1, \dots, N_b \tag{8}$$

$$P_{ij} - \gamma_{ij}(n_{ij}^0 + n_{ij})(\theta_i - \theta_j) = 0 \quad \forall (n_{ij}) \in \Omega \quad i,j = 1,\dots,N_b \quad i \neq j \tag{9}$$

Inequation constraints

$$|P_{ij}| \le (n_{ij}^0 + n_{ij}) P_{ij}^{max} \quad \forall (n_{ij}) \in \Omega \quad i,j = 1,\dots,N_b \quad i \neq j \tag{10}$$

$$P_i^{min} \le P_i \le P_i^{max} \quad i = 1,\dots,N_{TG} \tag{11}$$

$$0 \le Pw_i^s \le Pw_i^r \quad i = 1,\dots,N_W \tag{12}$$

$$0 \le n_{ij} \le n_{ij}^{max} \forall (n_{ij}) \in \Omega \quad i \neq j \tag{13}$$

2.3 Wind power model and uncertainty of wind speed

Wind energy is known as uncertain energy. Unlike conventional thermal generators, wind power is highly dependent on wind speed, and due to the unpredictable nature of wind, many related models have been studied to simulate wind speed characteristics. The Weibull distribution is well-known and commonly used to simulate wind speed character. The probability of wind speed v (m/s) following the Weibull distribution with the scale factor (C) and shape factor (k) can be calculated:

$$f_v(v) = \left(\frac{k}{C}\right)\left(\frac{v}{C}\right)^{(k-1)} exp^{-\left(\frac{v}{C}\right)^{(k-1)}} \quad 0 \le v \le \infty \tag{14}$$

The scale factor (C) and shape factor (k) is determined as:

$$C = \frac{v^{mean}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{15}$$

$$k = \left(\frac{\sigma^{SD}}{v^{mean}}\right)^{-1.086} \tag{16}$$

Gamma function Γ(x) is described as:

$$\Gamma(\mathrm{x}) = \int_0^\infty e^{-t} t^{x-1} dt \tag{17}$$

The Wind speed based on Weibull distribution can be calculated as:

$$v = C(-ln(rand))^{\frac{1}{k}} \tag{18}$$

Where C is the scale factor, k is the shape factor, v^{mean} is the average wind speed and σ^{SD} is the standard deviation, v is the wind speed, and $rand$ is the random number in the range [0,1].

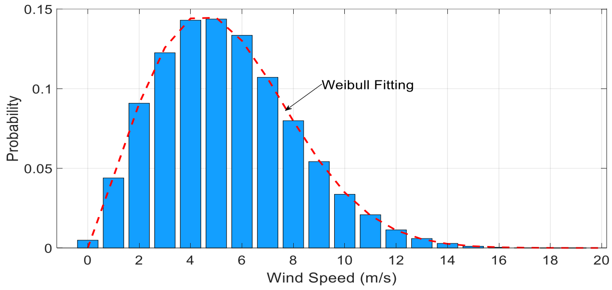

Figure. 1 The probability of wind speed

Wind turbines convert mechanical energy into electrical energy. The output power of wind turbines ranges from zero to its rated value, depending on wind speed, as shown in Eq. (19) [33]

$$Pw(v) = \begin{cases} 0, \ v < v_{ci}, v > v_{co} \\ P_W^r\left(\frac{v - v_{ci}}{v_r - v_{ci}}\right) & , v_{ci} \le v \le v_r \\ P_w^r, \ v_r < v \le \ v_{co} \end{cases} \tag{19}$$

Where $Pw(v)$ is the output power of wind turbines, v_{ci}, v_r, v_{co} are the cut-in, rated, cut-out wind speed, P_W^r is the rated output of wind turbines.

Fig. 1 is an example that shows the probability of wind speed using the Weibull distribution after 15000 monte-carlo sampling. In this study, the parameters of wind farms are chosen as in reference [32] with $v_{ci} = 4$, v_r=12, $v_{co} = 20, v^{mean} = 5.4$, $\sigma^{SD} = 2.7$.

3. Improved zebra optimization algorithm

Recently, a new bio-inspired meta-heuristic algorithm (called ZOA) was developed by Eva Trojovsk` et al. [30]. Like other bio-inspired meta-heuristic algorithms, ZOA is inspired by the behavior of equine animals that come from eastern and southern Africa. Foraging and defense strategies against predator behavior represent exploration and exploitation in the ZOA algorithm. In the exploration strategy, the best member of the zebras is called the pioneer zebra, which will lead other members of the zebras to forage. The exploitation process based on defense strategies against predator behavior can be divided into two cases. In the first phase, when zebras are attacked by lions, they decide to escape in a zigzag pattern and with random sideways turning movements. In the second phase, when zebras are attacked by smaller predators, the whole herd of zebras will move towards the attacked zebra and try to frighten and confuse the predator by creating a defensive structure. In the original ZOA algorithm, the exploitation process received too much attention. Therefore, the new variables found by ZOA commonly fall into local values, which makes the algorithm suitable for solving small and noncomplicated problems. To overcome this, this study suggests an improvement of ZOA called IZOA. The IZOA focuses on improving the exploration and exploitation process for solving TEP problems with RES. In the first phase, the Lévy flight distribution function is suggested to expand the exploration strategy. In addition, a modified exploitation strategy is also proposed in the second phase.

The exploration process using the Lévy flight distribution function can be described as:

$$x_{ij}^{P1} = PZ_j + Levy(\lambda).\left(PZ_j - x_{ij}\right) \quad (20)$$

Where x_{ij}^{P1} is a new position of i^{th} zebra in the first phase, PZ_j is the position of pioneer zebra, *r* is randomly generated in the interval [0,1], *I=round(rand+1)* is the random value [1, 2], x_{ij} is the position of i^{th} zebra, $Levy(\lambda)$ is the Lévy flight distribution function can be calculated as following:

$$levy = s.\frac{w.\sigma}{|k|^{\frac{1}{\lambda}}} \quad (21)$$

In Eq. (21), λ is the random number generated in the range [0, 2], which is set to λ=1.5 in this paper, *s* is a fixed constant set to 0.01, *w* and *k* are random numbers in the interval [0, 1]. σ is calculated by using Eq. (22).

$$\sigma = \left(\frac{\Gamma(1+\lambda).\sin\left(\frac{\pi\lambda}{2}\right)}{\Gamma\left(\frac{1+\lambda}{2}\right).\lambda.2^{\left(\frac{\lambda-1}{2}\right)}}\right) \quad (22)$$

In the second phase, the modification of the exploitation process can be calculated as following:

$$x_{ij}^{P2} = x_{ij} + I.r.\sin(2\pi \times r).\left(PZ_j - \frac{AZ_j + x_{ij}}{2}\right) \quad (23)$$

Where $x_{ij}^{newim,P2}$ is a new position of i^{th} zebra in the second phase, *r* is the random number in the range [0,1], *I=round(rand+1)* is the random value [1, 2], PZ_j and AZ_j are the position of pioneer zebra and attacked zebra, x_{ij} is the position of i^{th} zebra.

Implementation of IZOA for solving the TEP problem can be described in the following steps:

Step 1: Modeling the probability of wind speed by the Weibull probability density function using Eqs. (14)-(18).

Step 2: Using monte-carlo to sample the probability of wind speed and calculate the probability of the output power of the wind turbine using Eq. (19).

Step 3: Input max_iterations, population size, and initial population. Each solution (s) is considered a position of the zebra and is initialized as follows:

$$s_i = s_{min} + rand(0,1).(s_{max} - s_{min}) \quad (24)$$

Where s_i is the i^{th} solution, s_{max} and s_{min} are the upper and lower bounds, which are defined as Eq. (25).

$$\begin{cases} s_{min} = \left[n_1^{min}, \dots, n_\Omega^{min}, P_{G1}^{min}, \dots, P_{GN}^{min}\right] \\ s_{max} = \left[n_1^{max}, \dots, n_\Omega^{max}, P_{G1}^{max}, \dots, P_{GN}^{max}\right] \end{cases} \quad (25)$$

Step 4: Run power flow and evaluate fitness function (FF) using Eq. (26). The position of the zebra with the smallest fitness value is considered as a pioneer zebra (s_{best}).

$$FF_i = C_{total} + K_g \sum_i^{N_{GN}} (P_{G1} - P_{G1}^{lim})^2 + K_b.\sum_{\substack{i,j \\ i \neq j}}^{N_B} (P_{ij} - P_{ij}^{max})^2 \quad (26)$$

Where FF is the fitness function, C_{total} is the total cost as Eq. (1), K_g and K_b are the penalty constants which are set to 10^6 in this study.

Step 5: Update the position of the zebras based on their foraging behavior using Eq. (27). The new position of zebras is calculated as follows:

$$s_i^{P1} = \begin{cases} s_i + r.(s_{best} - I \times s_i), P_z < 0.5 \\ s_{best} + Levy(\lambda).(s_{best} - s_i), else \end{cases} \quad (27)$$

Where P_z is the probability of choosing which are randomly generated in the interval [0, 1], *r* is the random number in range [0, 1], *I=round(rand+1)* is the random value [1, 2].

Step 6: Run power flow and evaluate fitness

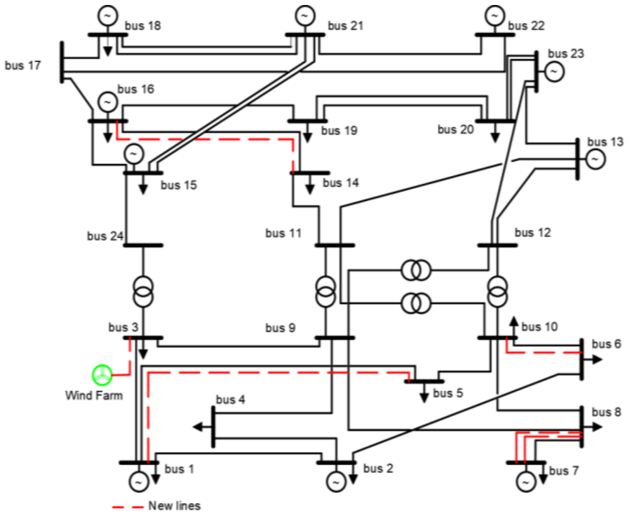

Figure. 2 The IEEE 24 bus RTS system

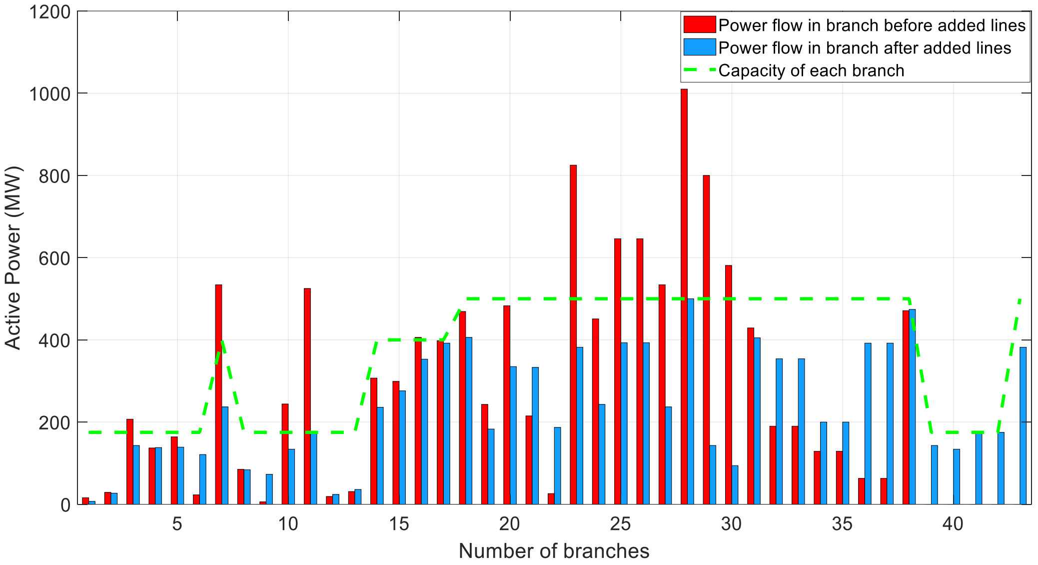

Figure. 3 The power flows on branches before and after added lines

function (FF_i^{P1}) using Eq. (26) for a new solution (s_i^{P1}) and update the population using Eq. (28).

$$s_i = \begin{cases} s_i^{P1}, FF_i^{P1} < FF_i \\ s_i, else \end{cases} \quad (28)$$

Step 7: Update the position of the zebras based on their defense strategies against predators' behavior. s_{rd} is the position of a random zebra that is attacked by predators. The new position of zebras is calculated as Eq. (29).

$$s_i^{P2} = \begin{cases} s_i + R.(2r - 1).\left(1 - \frac{t}{T}\right). \\ s_i, P_s < 0.5 \\ s_i + I.r.\sin(2\pi.r). \\ \left(s_{best} - \frac{s_{rd}+s_i}{2}\right), else \end{cases} \quad (29)$$

Where P_s is the probability of choosing which are randomly generated in the interval [0,1], t and T are the iteration contour and the maximum number of iterations, and value R is determined using Eq. (30).

$$R = 1.5.r.sign(r - 0.5) \quad (30)$$

Step 8: Run power flow and evaluate fitness function (FF_i^{P2}) using Eq. (26) for a new solution (s_i^{P2}) and update the populations using Eq. (31).

$$s_i = \begin{cases} s_i^{P2}, FF_i^{P2} < FF_i \\ s_i, else \end{cases} \quad (31)$$

Step 9: Check stopping criteria: if (t < T) return to step 5 with $t = t+1$; otherwise, go to the next step until the maximum number of iterations is reached.

Step 10: Stop and export the optimal value.

4. Simulation results

In this study, the IEEE 24-bus RTS system is used to test the proposed IZOA for the TEP problem. The results obtained with a population of 50 individuals and 500 iterations are compared with the original ZOA algorithm and exiting other techniques in the literature to prove the effectiveness of the proposed algorithm. The program is developed in the MATLAB environment and runs power flow using MATPOWER 8.0b1 [34].

4.1 IEEE 24-bus RTS system

The IEEE 24-bus RTS system is known as a large and complex system and is commonly used to test the effect of algorithms. The system has 24 buses, 10 generators, and 38 branches, as shown in Fig. 2. The data of the IEEE 24-bus RTS system and parameters of lines can be found in [8, 35]. From the power flow results in Fig. 3, the exiting branches (1–5, 3–24, 6–10, 7-8, 10–11, 14–16, 15–21, 15–24, 16–17, 16–19, and 17–18) are overloaded after increasing load 3 times. So, it is necessary to add the new lines to ensure security as well as reliability in the power system's operation. Two cases are considered as follows:

Case 1: Minimize the total cost without wind power.

Case 2: Minimize the total cost with wind power.

Case 1: IEEE 24-bus RTS system without wind power

As can be observed from Table 1, the total cost obtained using the proposed IZOA algorithm is

Table 1. The comparison of proposed algorithms with other methods for IEEE 24-bus RTS without wind power

	Total cost	Total lines added	Location lines installed
IZOA	152,000,000	5	$n_{6-10} = 1$; $n_{7-8} = 2$; $n_{10-12} = 1$; $n_{14-16} = 1$
ZOA	250,000,000	6	$n_{6-10} = 1$; $n_{7-8} = 2$; $n_{10-11} = 1$; $n_{11-13} = 1$; $n_{14-23} = 1$
GWO	239,000,000	9	$n_{1-2}=2$, $n_{2-4}=1$, $n_{6-10}=2$, $n_{7-8}=2$, $n_{10-12}=1$, $n_{14-23}=1$
DA[35]	224,000,000	7	$n_{1-5} = 1$; $n_{3-24} = 1$; $n_{6-10} = 1$; $n_{7-8} = 2$; $n_{10-12} = 1$; $n_{14-16} = 1$
B&B[6]	152,000,000	5	$n_{6-10} = 1$; $n_{7-8} = 2$; $n_{10-12} = 1$; $n_{14-16} = 1$
FBIO[9]			
SOS[11]			

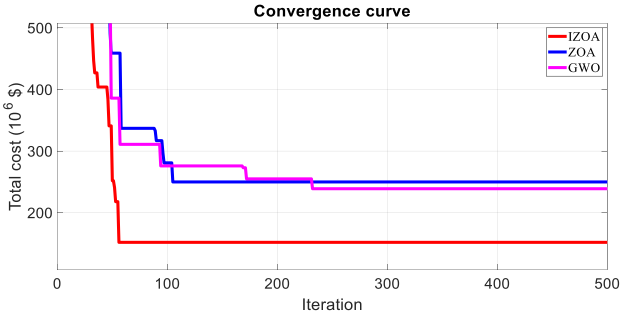

Figure. 4 Convergence curve of IZOA, ZOA and GWO methods

152,000,000$ after adding 5 new lines. The location and number of new lines are: $n_{6-10} = 1$; $n_{7-8} = 2$; $n_{10-12} = 1$; $n_{14-16} = 1$. The results from Table 1 also show that IZOA also finds the best results (152,000,000$), which is equal to recent publications such as FBIO [9] (152,000,000$), B&B [6] (152,000,000) and SOS [11] (152,000,000$). Besides, it is better than the original ZOA (250,000,000$), GWO (239,000,000$), and the DA (224,000,000$) [35]. The total new lines installed is 6 lines for ZOA, 9 lines for GWO while DA [35] is 7 lines installed as shown in Table 1. Moreover, from Fig. 4, it can be seen that the convergence speed of IZOA is better than ZOA and GWO.

Case 2: IEEE 24-bus RTS system with wind power

For case 2, an additional wind farm is installed at bus number 3 with a maximum output of 450 MW. The detailed parameters of the wind and thermal generators are chosen as in reference [32].

Table 2. The comparison of proposed algorithms with other methods in IEEE 24-bus RTS system with wind power

Method	IZOA	ZOA	GABC [32]
C_{total}(\$)	126,348,010.8	337,283,047.4	136,444,300.8
C_{inv} (\$)	124,000,000	335,000,000	136,000,000
C_{fuel} (\$)	2,343,819.7	2,279,166.9	441,095.4
C_{wind}(\$)	4,191.1	3,880.4	3,205.4
Location of installed lines	$n_{1-5} = 1$; $n_{6-10} = 1$; $n_{7-8} = 2$; $n_{14-16} = 1$.	$n_{1-2} = 1$; $n_{1-5} = 1$; $n_{6-10} = 1$; $n_{7-8} = 2$; $n_{10-12} = 1$; $n_{14-16} = 1$; $n_{15-16} = 1$; $n_{16-17} = 1$; $n_{16-19} = 1$; $n_{18-21} = 1$; $n_{20-23} = 1$.	$n_{6-10} = 1$; $n_{7-8} = 1$; $n_{10-12} = 1$; $n_{14-16} = 1$.
Total lines added	5	12	4

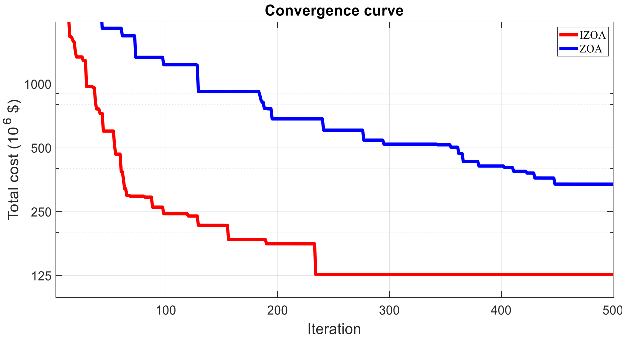

Figure. 5 Convergence curve of IZOA and ZOA algorithm

Table 2 presents the total cost obtained using the proposed IZOA algorithm compared with other methods. The location and number of new lines installed by the proposed method and other methods are also presented in Table 2. From Table 2, it can be seen that the total cost using the proposed IZOA method is 126,348,010.8$, with 5 new lines installed in the power system ($n_{1-5} = 1$; $n_{6-10} = 1$; $n_{7-8} = 2$; $n_{14-16} = 1$). In this case, the fuel cost of the thermal generator and wind cost are 2,343,819.7$ and 4,191.1$, respectively. Observed from Table 2, the total cost using the IZOA (124,000,000$) is better than the ZOA (337,283,047.4$) and GABC (136,444,300.8$) [32]. It is also observed from Fig. 5 that the convergence speed of IZOA is the fastest compared with the ZOA algorithm.

5. Conclusion

The paper presents an improvement in the ZOA method and a way to solve the TEP problems using

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the proposed IZOA algorithm. The effectiveness of IZOA is tested in the IEEE 24-bus RTS system with and without RES by comparing it with the original ZOA, GWO DA, and GABC. The simulation results show that the proposed IZOA reduces by 39.2% compared with the original ZOA, 36.4% for GWO, and 32.1 % for DA [35]. Especially for the IEEE 24-bus RTS system with RES, the proposed IZOA algorithm has also produced better results than the original ZOA and GABC [32]. Therefore, the proposed IZOA is also an effective and suitable tool for solving the TEP problem, even with large-scale and complex problems.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, T. L. D and N. D. H. B; methodology, T. L. D; software, N. D. H. B; validation, T. L. D and N. D. H. B; formal analysis, T. L. D; investigation, N. D. H. B; data curation, N. D. H. B; writing-original draft preparation, N. D. H. B; writing-review and editing, T. L. D; visualization, N. D. H. B; supervision, T. L. D.

References

[1] P. Denholm and M. Hand, “Grid flexibility and storage required to achieve very high penetration of variable renewable electricity”, *Energy Policy*, Vol. 39, No. 3, pp. 1817-1830, 2011.

[2] L. L. Garver, "Transmission Network Estimation Using Linear Programming", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-89, No. 7, pp. 1688-1697, 1970.

[3] C. A. G. MacRae, A. T. Ernst, and M. Ozlen, “A Benders decomposition approach to transmission expansion planning considering energy storage”, *Energy*, Vol. 112, pp. 795-803, 2016.

[4] M. V. F. Pereira, L. M. V. G. Pinto, S. H. F. Cunha, and G. C. Oliveira, "A Decomposition Approach To Automated Generation/Transmission Expansion Planning", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-104, No. 11, pp. 3074-3083, 1985.

[5] Y. Li, J. Wang, and T. Ding, “Clustering-based chance-constrained transmission expansion planning using an improved benders decomposition algorithm”, *IET Generation, Transmission & Distribution*, Vol. 12, No. 04, pp. 935-946, 2018.

[6] R. T. Zoppei, M. A. J. Delgado, L. H. Macedo, M. J. Rider, and R. Romero, "A Branch and Bound Algorithm for Transmission Network Expansion Planning Using Nonconvex Mixed-Integer Nonlinear Programming Models", *IEEE Access*, Vol. 10, pp. 39875-39888, 2022.

[7] S. Haffner, A. Monticelli, A. Garcia, J. Mantovani, and R. Romero, "Branch and bound algorithm for transmission system expansion planning using a transportation model", *IEE Proceedings Generation, Transmission and Distribution*, Vol. 147, No. 3, pp. 149-156, 2000.

[8] R. Romero, C. Rocha, J. R. S. Mantovani, and I. G. Sánchez, “Constructive heuristic algorithm for the DC model in network transmission expansion planning”, *IEE Proceedings - Generation, Transmission and Distribution*, Vol. 152, No. 2, pp. 277-282, 2005.

[9] A. Ova, E. Dogan, and S. Demirbas, "Transmission Expansion Planning Using a Novel Meta-Heuristic Method", *International Journal of Renewable Energy Research*, Vol. 12, No. 4, pp. 1988-2001, 2022 .

[10] R. A. Gallego, R. Romero, and A. J. Monticelli, "Tabu search algorithm for network synthesis", *IEEE Transactions on Power Systems*, Vol. 15, No. 2, pp. 490-495, 2000.

[11] S. Verma and V. Mukherjee, "Investigation of static transmission expansion planning using the symbiotic organisms search algorithm", *Engineering Optimization*, Vol. 50, No. 9, pp. 1544-1560, 2017.

[12] G. Qu, H. Cheng, L. Yao, Z. Ma, and Z. Zhu, “Transmission surplus capacity based power transmission expansion planning”, *Electric Power Systems Research*, Vol. 80, No. 01, pp. 19-27, 2010.

[13] M. S. E. Bages and W. T. Elsayed, “Social spider algorithm for solving the transmission expansion planning problem”, *Electric Power Systems Research*, Vol. 143, pp. 235-243, 2017.

[14] X. Zhang and A. J. Conejo, “Candidate line selection for transmission expansion planning considering long- and short-term uncertainty”, *Electrical Power and Energy Systems*, Vol. 100, pp. 320-330, 2018.

[15] C. Roldán, A. A. S. D. L. Nieta, R. G. Bertrand, and R. Mínguez, “Robust dynamic transmission and renewable generation expansion planning: Walking towards sustainable systems”, *Electrical Power and Energy Systems*, Vol. 96, pp. 52-63, 2018.

[16] X. Zhang and A. J. Conejo, "Robust Transmission Expansion Planning Representing Long- and Short-Term Uncertainty", *IEEE*

Transactions on Power Systems, Vol. 33, No. 2, pp. 1329-1338, 2018.

[17] H. Nemati, M. A. Latify, and G. R. Yousefi, “Coordinated generation and transmission expansion planning for a power system under physical deliberate attacks”, *International Journal of Electrical Power & Energy Systems*, Vol 96, pp. 208-221, 2018.

[18] J. M. Arroyo, N. Alguacil, and M. Carrión, "A Risk-Based Approach for Transmission Network Expansion Planning Under Deliberate Outages", *IEEE Transactions on Power Systems*, Vol. 25, No. 3, pp. 1759-1766, 2010.

[19] M. R. Tavakoli, A. Ebrahimi, and M. A. Latify, “AC transmission expansion planning based on self-organized criticality to mitigate the risk of cascading blackouts”, *IET Generation, Transmission & Distribution*, Vol. 17, No. 9, pp. 2097-2114, 2023.

[20] M. Mahdavi, M. S. Javadi, and J. P. S. Catalao, “Integrated generation-transmission expansion planning considering power system reliability and optimal maintenance activities”, *International Journal of Electrical Power & Energy Systems*, Vol. 145, p. 108688, 2023.

[21] P. V. Gomes and J. T. Saraiva, “State-of-the-art of transmission expansion planning: A survey from restructuring to renewable and distributed electricity markets”, *Electrical Power and Energy Systems*, Vol. 111, pp. 411-424, 2019.

[22] F. L. Miranda, L. W. Oliveira, E. J. Oliveira, E. G. Nepomuceno, and B. H. Dias, “Multi-objective transmission expansion planning based on Pareto dominance and neural networks”, *Electric Power Systems Research*, Vol. 214, Part A, p. 108864, 2023.

[23] P. V. Gomes, J. T. Saraiva, L. Carvalho, B. Dias, and L. W. Oliveira, “Impact of decision-making models in Transmission Expansion Planning considering large shares of renewable energy sources”, *Electric Power Systems Research*, Vol. 174, p. 105852, 2019.

[24] A. Khandelwal, A. Bhargava, A. Sharma, and H. Sharma, “Modified Grey Wolf Optimization Algorithm for Transmission Network Expansion Planning Problem”, *Arabian Journal for Science and Engineering*, Vol. 43, pp. 2899-2908, 2018.

[25] S. Dehghan, N. Amjady, and A. J. Conejo, "Adaptive Robust Transmission Expansion Planning Using Linear Decision Rules", *IEEE Transactions on Power Systems*, Vol. 32, No. 5, pp. 4024-4034, 2017.

[26] H. Yu, C. Y. Chung, and K. P. Wong, "Robust Transmission Network Expansion Planning Method With Taguchi's Orthogonal Array Testing", *IEEE Transactions on Power Systems*, Vol. 26, No. 3, pp. 1573-1580, 2011.

[27] A. A. Ghadimi, M. Amani, M. Bayat, S. Ahmadi, M. R. Miveh, and F. Jurado, “Stochastic transmission expansion planning in the presence of wind farms considering reliability and N-1 contingency using grey wolf optimization technique”, *Electrical Engineering*, Vol. 104, pp. 727-740, 2022.

[28] Y. Xie and Y. Xu, “Transmission Expansion Planning Considering Wind Power and Load Uncertainties”, *Energies*, Vol. 15, No. 19, p. 7140, 2022.

[29] C. Li, Z. Y. Dong, G. Chen, F. Luo, and J. Liu, “Flexible transmission expansion planning associated with large-scale wind farms integration considering demand response”, *IET Generation, Transmission & Distribution*, Vol. 9, No. 15, pp. 2276-2283, 2015.

[30] E. Trojovská, M. Dehghani, and P. Trojovský, "Zebra Optimization Algorithm: A New Bio-Inspired Optimization Algorithm for Solving Optimization Algorithm", *IEEE Access*, Vol. 10, pp. 49445-49473, 2022.

[31] M. Suman, V. P. Sakthivel, and P. D. Sathya, “Squirrel Search Optimizer: Nature Inspired Metaheuristic Strategy for Solving Disparate Economic Dispatch Problems”, *International Journal of Intelligent Engineering and Systems*, Vol. 13, No. 5, pp. 111-121, 2020, doi: 10.22266/ijies2020.1031.11.

[32] H. T. Jadhav and R. Roy, “Gbest guided artificial bee colony algorithm for environmental/economic dispatch considering wind power”, *Expert Systems with Applications*, Vol. 40, No. 16, pp. 6385-6399, 2013.

[33] A. U. Krismanto, I. B. Sulistiawati, F. Y. Limpraptono, A. Priyadi, H. Setiadi, and M. Abdillah, "Impact of Large-Scale Wind Power Penetration on Dynamic Voltage Stability of Interconnected Power System: An Indonesia Case Study", *International Journal of Intelligent Engineering and Systems*, Vol. 14, No. 4, pp. 251-263, 2021, doi: 10.22266/ijies2021.0831.23.

[34] R. D. Zimmerman and C. E. M. Sanchez (2022). *MATPOWER (Version 8.0b1)*, [Software]. Available: https://matpower.org.

[35] R. Fang and D. J. Hill, "A new strategy for transmission expansion in competitive electricity markets", *IEEE Transactions on Power Systems*, Vol. 18, No. 1, pp. 374-380, 2003.

Appendix

Nomenclature	
C_{total}	Total cost including investment cost, operation cost, wind power cost ($)
C_{inv}	Total investment cost of new lines ($)
C_{fuel}	Total fuel cost of thermal generator ($/h)
C_{wind}	Wind power cost including direct cost, penalty cost and reserve cost ($/h)
$C_{Wd,i}$	Direct cost of i^{th} wind generator ($/h)
$C_{Wp,i}$	Penalty cost of i^{th} wind generator ($/h)
$C_{Wr,i}$	reserve cost of i^{th} wind generator ($/h)
FF	Fitness function
a_i, b_i, c_i, d_i, e_i	The coefficients of i^{th} thermal generator
$k_{d,i}$, $k_{p,i}$, $k_{r,i}$	The direct, penalty and reserve coefficients of i^{th} wind generator
P_i	The output power of i^{th} thermal generator
P_i^{min}	The maximum output of i^{th} thermal generator
P_i^{max}	The minimum output of i^{th} thermal generator
Pw_i^s	The scheduled power of i^{th} wind farm
Pw_i^r	The rated power of i^{th} wind farm
Pw_i	The output power of i^{th} wind farm
$Pw_{i,av}$	The available output power of i^{th} wind farm
P_i^{inj}	The injected power into bus i^{th}
$P_{d,i}$	The load demand value at bus i^{th}
P_{ij}	The active power between bus i^{th} and bus j^{th}
γ_{ij}	The susceptance of a branch between bus i^{th} and bus j^{th}
n_{ij}^0	The initial number of lines between bus i^{th} and bus j^{th}
n_{ij}	The number of new lines added between bus i^{th} and bus j^{th}
c_{ij}	The cost of new lines added between bus i^{th} and bus j^{th}
θ_i, θ_j	The phase angle at bus i^{th} and bus j^{th}
P_{ij}^{max}	The maximum active power between bus i^{th} and bus j^{th}
n_{ij}^{max}	The maximum number of new added lines between bus i^{th} and bus j^{th}
C	The scale factor (wind speed)
k	The shape factor (wind speed)
v	Wind speed (m/s)
$Pw(v)$	The output power of wind turbine at wind speed (v)
v_{ci}	The cut-in speed of wind turbine (m/s)
v_r	The rated speed of wind turbine (m/s)
v_{co}	The cut-in wind speed of wind turbine (m/s)
v^{mean}	The wind means speed (m/s)
σ^{SD}	Standard Deviation (wind speed)
Ω	The set of all candidate lines
N_{GN}	Number of generators
N_b	Number of buses
N_W	Number of wind generators
N_{Br}	Number of Branches