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Solving the Economic Dispatch Problem Using Wild Horse Optimizer Algorithm

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ABSTRACT

The economic dispatch problem is a very important and fundamental topic in the economic operation of power system, emphasizing the efficient allocation of generation resources to minimize fuel costs while satisfying demand and adhering to different operational constraints. Since its introduction, many of the optimization methods, techniques, and algorithms have been applied to solve this complex and nonlinear hard-problem. This research introduces the wild horse optimizer algorithm (WHOA), as a new metaheuristic optimization technique, for efficient solving of the economic dispatch (ED) problem, which includes various equality and inequality constraints, such as prohibited operating zones (POZ), valve-point loading effects (VPLE), and ramp rate limits (RRLs) of thermal power plants in the presence of transmission power losses. The effectiveness of the mentioned technique is validated through implementation it on four different case studies comprising 6, 15 ,40 and 140 generating units in terms of obtained results. The simulation results of quadruple test cases confirm the WHOA ability in reducing the best previous operation costs of RCBA, emended salp swarm algorithm (ESSA), new PSO- simple local random search (NPSO-LRS), and modified MTS (MTLA) algorithms, by at least 0.0423 %, 0.0101%, 0.040054%, and 0.12839 %.

Abbreviations

AA (Distr.)	Auction algorithm
ACO	Ant colony optimization
AIS	Artificial immune system
APSO	Adaptive particle swarm optimization
BSA	Backtracking search algorithm
CACO-LD-AP	Constrained ant colony optimization-adaptive penalty
CBA	Chaotic bat algorithm
CCPSO	Chaotic sequences and crossover operation particle swarm optimization
CHPEDP	Combined heat and power economic dispatch problem
CHPE2DP	Combined heat and power economic emission dispatch problem
CLCS-CLM	Comprehensive learning cuckoo search - chaos-lambda method
CMFA	Chaos mutation firefly algorithm
COPSO	Crossover operation PSO
CSO	Cuckoo Search optimization
CSPSO	Chaotic sequences PSO
CTPSO	Conventional treatment strategy-PSO
DE	Differential evolution
DHS	Differential harmony search algorithm
ED	Economic dispatch
E2DP	Economic emission dispatch problem
EP	Evolutionary programming
EPSO	Evolutionary PSO

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EP-SQP	Evolutionary programming -sequential quadratic programming
ESSA	Emended salp swarm algorithm
GA	Genetic algorithm
GAAPI	Genetic algorithm-Ant colony algorithm for continuous domains
Ijaya	Improved Jaya algorithm
IPSO	Improved PSO
Jaya-SML	Jaya algorithm-self-adaptive multi-population and Lévy flights
L-HMDE	Linear population size reduction -hybrid mutation strategy differential evolution
LM	Integration of machine learning
MABC	Modified artificial bee colony algorithm
MCSA	Modified cuckoo search algorithm
MDE	Modified differential evolution algorithm
MHS	Modified harmony search algorithm
MILP	Mixed integer linear programming
MPSO-TVAC	Modified PSO with Time Varying Acceleration Coefficients
MSSA	Modified social spider algorithm
MTLA	Modified teaching-learning algorithm
MTS	Multiple tabu search algorithm
NPSO-LRS	New PSO local random search
NPSO-LRS	New particle swarm optimization -local random search
OIWO	Oppositional invasive weed optimization
POZ	Prohibited operating zones
PSO	Particle swarm optimization
PSO-SQP	Particle swarm optimization - sequential quadratic programming
RCBA	Random black hole model and Chaotic maps into Bat Algorithm
SCA	Society-civilization algorithm
SGA	String structure-genetic algorithm
SOH-PSO	Self-organizing hierarchical PSO
SSO	Squirrel search optimizer
ST-HDE	Selftuning hybrid differential evolution
ST-IRDPSO	Self-adaptive mechanism-Improved random drift PSO
SWT-PSO	Stochastic weight trade-off PSO
WCA	Water cycle algorithm
WH	The location of the water hole
WHOA	Wild horse optimizer algorithm

Nomenclature

F_T	Total fuel cost for all operating units
$F_i(P_i)$	The fuel cost of the ith generating unit in $/hr
ai, bi, ci	Cost factors of the ith unit
ei , fi	Valve-point loading effect coefficient of the ith unit
P_i	The power generation by the ith unit in MW
P_i^{min}	Maximum power capacity of ith unit
P_i^{max}	Minimum power output of ith unit
$P_{i,1}^{l}$	Lower power output within the kth prohibited zone for the ith generator unit
P_{i,z_i}^{u}	Upper power output within the kth prohibited zone for the ith generator unit
UR_i	Up-ramp limits of the ith generator unit
DR_i	Down-ramp limits of the ith generator unit
P_D	Load demand of the grid
P_L	Total power loss for load transmission line
B_{ij}, B_{0i} , B_{00}	Transmission loss coefficients
N	Population size
PS	Percentage of stallions
PC	Crossover percentage
G	The number of horse groups
$\overline{X_{\imath,G}^{\jmath}}$	Current position of a group member
$X_{i,G}^{j}$	New position of the group member
R	Uniform random number from the interval [−2, 2]
Z	Adaptive mechanism
$\overrightarrow{R_1}$, $\overrightarrow{R_3}$	Random vectors uniformly distributed in the range [0, 1]
R_2	Random number ranging between 0 , 1
IDX	The indices of the random vector
$\overrightarrow{R_1}$	Satisfy the condition (P == 0)
TDR	Adaptive parameter
iter	The current number of iteration
Maxiter	The maximum iterations
$X_{G,k}^{P}$	The position of horse p departing from group k
$X_{G,i}^{q}$	The position of the foal q originally from group i
$X_{G,j}^{z}$	Foal q mates with horse z positioned after reaching maturity
$\overline{\mathrm{Stall\imath on}_{G_\imath}}$	The anticipated next position of the leader of group i
$\mathrm{Stallion}_{G_i}$	The current position of the leader of group i

1. Introduction

Central to decision-making across diverse domains, such as engineering and economics, is the quest for optimization. Optimization theory and its established methodologies attempt to identify the optimal solution within a set of feasible conditions. This optimal solution minimizes or maximizes a predefined objective function, which quantifies the desired outcome. In recent years, optimization algorithms have gained significant popularity. This rise can be attributed to their straightforward nature, versatility, non-restrictive approach, and ability to circumvent local optima, setting them apart from traditional optimization techniques. These benefits stem from the algorithms' inherent randomness, allowing them to tackle complex, high-dimensional problems efficiently. Often drawing inspiration from biological processes, animal behaviors, or physical principles, these meta-heuristic optimization algorithms excel in resolving intricate challenges within minimal time frames [1], [2].

The economic dispatch (ED) problem is a vital optimization topic in modern power grids, focused on determining the optimal generation levels to minimize costs while satisfying various inequality, and equality constraints. A basic method might model the cost curve to be quadratic and continuous [3], [4]. However, in real-world thermal power plants display non-smooth and non-convex cost curves because of the valve-point loading effects (VPLE) and discontinuities caused by POZs [5], [6] .Classical methods are inadequate for solving ED problems with this level of complexity. While dynamic programming can address these complications, it suffers from the dimensionality and limited optimality [7]. In the category of the classic methods we can mention the interior point [8], quadratic programming [9], linear programming [10], Lagrangian relaxation algorithm [11], dynamic programming [12], and lambda iteration [13]. Metaheuristic methods have become popular due to their effectiveness in handling the complexities of the ED problem. These methods encompass a variety of techniques, including Genetic Algorithm (GA) [14], Particle Swarm Optimization (PSO) [15], Evolutionary Programming (EP) [16], neural networks [17], Differential Evolution (DE) [18], oppositional invasive weed optimization (OIWO) [19], and squirrel search optimizer (SSO) [20].

It should be noted that the more advanced versions of the ED problem, can be known as the economic emission dispatch problem (E2DP), combined heat and power economic dispatch problem (CHPEDP), and combined heat and power economic emission dispatch problem (CHPE2DP) [21], [22]. The more complicated topics in modern power grid studies, which are beyond the scope of this work.

Examining the previous proposed methods in relation to the ED problem shows that the proposed methods are all aimed at finding the optimal solution of the problem, i.e., finding the minimum value of the objective function while respecting the problem constraints. In this regard, many meta-heuristic algorithms have been applied to the ED problem and are still being used. The innovation of the methods used in this field is simply finding better solutions. Accordingly, the most important innovation of this research is the use of the WHOA in the ED problem for some of the best-known case studies and the comparison of the obtained results with previous works.

The wild horse optimizer algorithm (WHOA) is suggested based on modleing the social behaviors of wild horses [23]. This novel algorithm begins with an initial random population, which undertakes the search process over a predefined number of iterations. The search procedure is divided into two stages of exploitation and exploration. The distinctiveness of various optimization algorithms lies in the mechanisms they use to conduct the search and maintain a balance between these phases. The WHOA involves five main steps: first, create the initial population, forme horse groups, and selec the leaders; second, graze and matte of horses; third, leadership and group guidance by the stallion; fourth, exchange and select the leaders; and fifth, save the optimal solution. The simulation results of the WHOA method are then compared with those from other established artificial intelligence techniques.

This paper is structured as follow: section 2 discusses the formulation of the ED problem. Section 3 describes the WHOA in detail. The implementation of WHOA to solve the ED problem is addressed in section 4. Section 5 addresses the WHOA implementation for four different test systems and compares it with other algorithms. Finally, conclusions are provided in section 6.

2. The problem formulation of ED

The main goal of the economic dispatch (ED) problem is minimizing the fuel costs associated with operating thermal power units while meeting a specified demand. This objective must be achieved while adhering to a range of constraints.

2.1. Objective function

The objective function or cost of the ED problem is characterized by the quadratic fuel cost function for thermal power plants, and it is formulated as follows. [24]:

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

where N_g is the aggregate of generating units, $F_i(P_i)$ is fuel cost of the ith generating plant in \$/hr, P_i is the power generation by the ith unit in MW, and a_i, b_i and c_i are the cost factors of jth generator.

2.2. Fuel cost function consodering valve point loading effect (VPLE)

Fossil-fuel based power units, particularly those utilizing steam turbines, experience a phenomenon known as the VPLE. This effect introduces discontinuities or ripples into the relationship between a generator's output power and its associated fuel cost. These ripples are a consequence of the discrete nature of steam admission control valves within the turbine. Maintaining system active power balance necessitates adjustments to these valves, which in turn impact the plant's efficiency. Incorporating the VPLE into the objective function for economic dispatch problems introduces additional complexity and it is expressed as follows [25]:

$$F_T = \sum_{i=1}^{N_g} F_i(P_i) = \sum_{i=1}^{N_g} (a_i + b_i P_i + c_i P_i^2) + \left| e_i \, sin(f_i(P_i^{min} - P_i)) \right| \tag{2}$$

where e_i and f_i are the VPLE coefficients of the ith generator unit.

2.3 constraints

- *Prohibited operating zones (POZ)*

The safe and efficient operation of generators in power plants necessitates defining permissible operating zones. These zones delineate the acceptable range of power output for each generator while accounting for potential limitations. The opening and closing of steam admission control valves introduce discontinuities in the cost curve and can lead to efficiency drops. Operating at power levels near these valve transition points might be undesirable due to increased fuel consumption or reduced reliability. The permissible operating zones for the ith generator can be outlined as addressed in [26]:

$$P \in \begin{cases} P_i^{min} \le P_i \le P_{i,1}^{l} \\ P_{i,k-1}^{u} \le P_i \le P_{i,k}^{l} \quad k = 1, \dots, POZ_i \\ P_{i,z_i}^{u} \le P_i \le P_i^{max} \end{cases} \tag{3}$$

Where $P_{i,k}^{l}$ is represents the lower power output within the kth POZ for the ith generator. Operating below this value might be undesirable due to reasons such as excessive valve cycling or shaft vibration concerns. $P_{i,k}^{u}$ is signifies the upper power output within the kth POZ for the ith generator. Operating above this value might also be undesirable for similar reasons.

- *Ramp Rate Limits (RRLs)*

One of the unrealistic assumptions made in traditional economic dispatch problems is that power output adjustments occur instantaneously. However, in real-world scenarios, RRLs restrict the operation of all online units. Power unit may increase or decrease only within a specified range, thereby constraining the units due to these RRLs as follows [27]:

$$\begin{aligned} P_i - P_{i0} &\le UR_i \\ P_{i0} - P_i &\le DR_i \end{aligned} \tag{4}$$

After adjusting generation limits to account for RRLs constraints, the revised values are now specified as [28]:

$$\begin{aligned} \max(P_i^{min}, P_{i0} - DR_i) \le P_i \\ \le \min(P_i^{max}, P_{i0} + UR_i) \end{aligned} \tag{5}$$

where P_{i0} is the former output power, UR_i and DR_i are the up-ramp and the down-ramp limits of the ith generator.

- *Power balance constraint*

The total production power must be equal to the total demand, and total transmission power losses.

$$\sum_{i=1}^{N} P_i = P_D + P_L \tag{6-a}$$

$$P_i^{min} \le P_i \le P_i^{max} \tag{6-b}$$

where P_i denotes the output of the ith generating unit in megawatts (MW), P_D is the whole power demand in MW, P_i^{min} and $Pi^{\max}$ are the minimum power generation and maximum power generation limits of the ith generator, respectively. Additionally, P_L accounts for the line losses in MW. Which are calculated using B-coefficients, as follows [29]:

$$P_L = \sum_{i=1}^{Ng} \sum_{j=1}^{Ng} P_i B_{ij} P_j + \sum_{i=1}^{ng} B_{0i} P_i + B_{00} \tag{7}$$

where P_i and P_j denote the real power injection at ith and jth buses and B_{ij} is the loss coefficients which are typically considered constant during normal operational conditions.

3. Wild horse optimizer algorithm

The Wild Horse Optimizer Algorithm (WHOA) draws inspiration from the social dynamics observed in wild horse populations. In their natural habitat, horses organize into groups comprising a stallion, multiple mares, and their foals. These groups, known as harems, are cohesive and non-territorial, fostering stable family units. Additionally, there exist groups consisting solely of adult stallions and younger horses. Stallions maintain proximity to mares for communication and potential mating opportunities, which can occur year-round. Foals begin grazing within their first week of life and progressively increase their grazing activity as they mature. Male foals typically leave their natal groups before reaching sexual maturity to join bands of bachelor stallions, where they undergo maturation in preparation for breeding. Female foals, conversely, integrate into other family groups to mitigate the risks associated with inbreeding [23].

3.1 Creating an initial population

let N denote the population size, the number of horse groups is

$$G = [\, N \times PS \,] \tag{8}$$

where PS being the stallions percentage in the total population, serving as a pivotal control parameter for this algorithm. Consequently, the top G stallions are designated as leaders among the groups, while the remaining members (N–G) are evenly distributed across these groups.

3.2 Grazing behaviour

Foals typically spend the majority of their time grazing within their group. To simulate this grazing behavior, we model the stallion as the focal point of the grazing area, with group members dispersing around this central point to graze. The equation to simulate grazing behavior, as follows:

$$\begin{aligned} \overline{X_{i,G}^{J}} = 2Z \cos 2\pi RZ \times \left(Stallion^{j} - X_{i,G}^{j}\right) \\ + Stallion^{j} \end{aligned} \tag{9}$$

where $X_{i,G}^{j}$ represents the current position of a group member (foal or mare),Stallion^{j} denotes the position of the stallion (group leader), $X_{i,G}^{j}$ signifies the new position of the group member during grazing, R is a uniform random number drawn from the interval [−2, 2] contributing to the grazing behaviour by introducing variability in the angles at which horses graze around the group leader (spanning 360 degrees). Additionally, Z serves as an adaptive mechanism computed as follows:

$$\begin{aligned} &P = \overrightarrow{R_1} < TDR \;\; ; IDX = (P == 0) \; ; \\ &Z = R_2 \Theta \mathrm{IDX} + \overrightarrow{R_3}\, \Theta(\sim IDX) \end{aligned} \tag{10}$$

Here, P is a vector whose dimensions correspond 0 and 1 to those of the problem, $\overrightarrow{R_1}$ and $\overrightarrow{R_3}$ are random vectors uniformly distributed in the range [0, 1], while R_2 is a random number also ranging between 0 and 1, IDX represents the indices of the random vector $\overrightarrow{R_1}$ that satisfy the condition (P == 0). TDR serves as an adaptive parameter that initiates at 1 and gradually diminishes throughout the algorithm's execution, ultimately reaching 0 by the algorithm's completion, as outlined by the following equation:

$$TDR = 1 - iter \times (\frac{1}{Maxiter}) \qquad (11)$$

where iter is the current number of iteration and max iter is the maximum iterations of the algorithm.

3.3 Horse mating behaviour

Horses exhibit an unparalleled behavior where foals leave their family groups before reaching pubescence to prevent inbreeding. Male foals join a group of single horses, while female foals join another family group. This ensures they find unrelated mates. The process involves foals from different groups joining a temporary group where they can mate after puberty. Their offspring then leave this temporary group to join another group, continuing the cycle of departure, mating, and reproduction across various horse groups. To simulate this behavior, which is similar to the crossover operator of the mean kind, are proposed:

$$X_{G,k}^{P} = Crossover\left(X_{G,i}^{q}, X_{G,j}^{z}\right) \qquad (12)$$

$$i \neq j \neq k \qquad p = q = end \quad Crossover \, = \, Mean$$

In the context of group dynamics among horses, consider $X_{G,k}^{P}$ as the position of horse p departing from group k . This horse leaves the group, making room for a new horse. This new arrival is the offspring of two horses, which were previously in groups i and j have reached maturity, and are unrelated. These horses have mated and reproduced. The position of the foal q originally from group i , is denoted as $X_{G,i}^{q}$. After reaching maturity, this foal q mates with horse z positioned at $X_{G,j}^{z}$, who subsequently departs from group j.

3.4 Group leadership

The leader of the group is liable for guiding the group to an appropriate location, which define as the water hole. The group must travel toward this water hole. Similarly, other groups also move toward this water hole. The leaders of these groups compete for access to the water hole, with the dominant group gaining exclusive use of it. While the dominant group occupies the water hole, other groups are prohibited from using it. Therefore, group leaders must direct their groups to the water hole and utilize it if they achieve dominance. If another group is dominant, they must lead their group away from the water hole. The following calculated has been suggested:

$$\overline{Stallion_{G_i}} \qquad (13a)$$

$$= \begin{cases} 2Z\cos(2\pi RZ) \times (WH - Stallion_{G_i}) + WH \,; if \; R_3 \; > 0.5 \\ 2Z\cos(2\pi RZ) \times (WH - Stallion_{G_i}) - WH; \; if \; R_3 \; \leq 0.5 \end{cases} \qquad (13b)$$

where $\overline{Stallion_{G_i}}$ denotes the anticipated next position of the leader of group i, WH represents the location of the water hole, and $Stallion_{G_i}$ indicates the current position of the leader of group i.

3.5 Exchange and selection the leaders

To maintain the inherent randomness of the algorithm, leader selection is initially performed at random. Subsequently, a fitness-based approach is adopted for leader selection. If a member of the group exhibits a fitness level exceeding that of the current leader, their positions are swapped according to the following equation [23]:

$$Stallion_{G_i} \qquad (14)$$

$$= \begin{cases} X_{G,i} \quad if \quad \cos t\,(X_{G,i}) \; < \; \cos t\,(Stallion_{G_i}) \\ Stallion_{G_i} \,; \; if \;\; ;\cos t\left(X_{G,i}\right) > \; cos\,t\,(Stallion_{G_i}) \end{cases}$$

4. Implementation the WHOA to ED problem

To apply the WHOA to the ED problem, the primitive set of power generation vector ***P***=*[P*$P_1,P_2,\ldots,P_N$*]* specifies the output powers of the units, also the individuals of the population are generated by considering the Eq.6-b and for generating units with POZ, if the randomly generated value falls within the POZ, it is adjusted to the nearest boundary which is violated according to Eq.3. Subsequently, if a unit has RRLs, as per Eq.5, the power output is uniformly distributed between the effective lower and upper limits. This process is repeated to generate N members of the population or number of search agents and enter values stallions percentage (PS) and crossover percentage (PC) in this article we have considered PS = 0.2, PC = 0.13. The WHOA begins by generating a population of individuals. Through iterative processes, it continuously improves the solutions, ultimately converging to an optimal solution by effectively exploring the feasible search space. Figures 1 and 2 illustrate the flowchart and pseudo-code of the WHOA, demonstrating its application in solving the Economic Dispatch problem by thoroughly navigating the feasible search space.

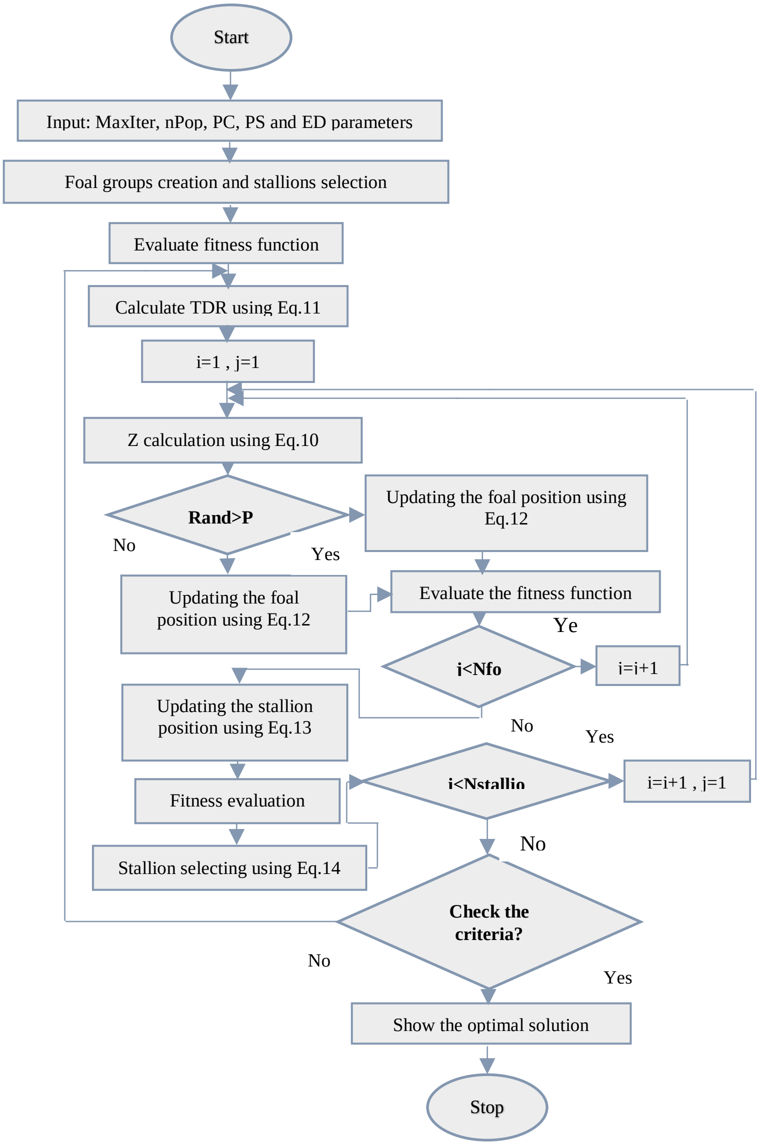
```
Initialize the first population of Horses randomly
Input WHOA parameters
Calculate the fitness of Horses
Create Foal groups and select Stallions
Find the best Horse as the optimum
While the end criterion is not satisfied
    Calculate TDR by Eq.11
    For number of Stallion
        Calculate Z by Eq.10
        For number of Foals of any group
            If rand > PC
                Update the position of the Foal by Eq.9
            Else
                Update the position of the Foal by Eq.12
            End
        End
        If rand > 0.5
            Update the position of the $\overline{Stallion_{G_i}}$ by Eq.13a
        Else
            Update the position of the $\overline{Stallion_{G_i}}$ by Eq.13b
        End
        If cost ($\overline{Stallion_{G_i}}$) < cost(Stallion)
            Stallion = $\overline{Stallion_{G_i}}$
        End
        Sort Foal of group by cost
        Select Foal with Minimum cost
        If cost (Foal) < cost (stallion)
            Exchange Foal and Stallion Position by Eq.14
        End
    End
    Update optimum
End
```

Figure 1. Pseudo-code of the WHOA for solving the ED problem [23], [30], [31]

4. Simulation results

To assess the efficacy of the WHOA in addressing the ED problem, four distinct case studies were undertaken. These studies incorporate considerations for transmission power losses and accommodate VPLE within the generators' cost functions. The algorithm was implemented in Matlab (R2018b) and run on a PC, Intel Core, i7-6700 CPU, 16 GB RAM. In evaluating the WHOA's performance, 50 independent trial runs were conducted for each case study. The optimal and average fuel costs were recorded and compiled into tables for analysis. These results were subsequently compared with findings from various methodologies documented in the literature, as referenced by their respective abbreviations in associated tables. Specifically, the first case study involves 6 generators, the second comprises 15 generators, the third consists of 40 generators, and the fourth case study pertains to the Korean system.

Figure 2. The used flowchart of the WHOA for solving the ED problem [23], [30], [32]



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5.1 Test system study 1

This test system comprises 6 units consist RRLs, POZs, and transmission power losses, with total power demand of 1263 MW [33]. The parameters of algorithm chosen as Number of search factors 70 and maximum of iterations 500. It should be noted that PS (stallions percentage), and PC (crossover percentage) are chosen equal to 0.2, and 0.13 respectively.

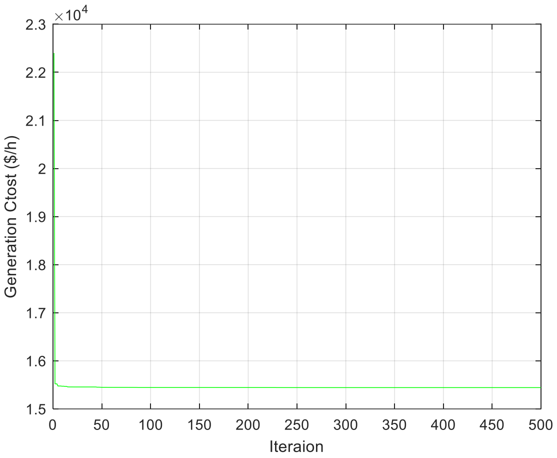

Figure 3. Convergence characteristic of the WHOA for the Test System 1

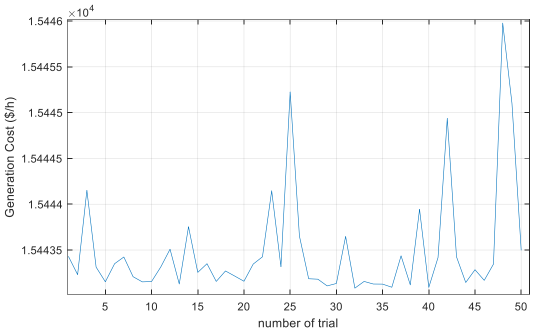

Figure 4. Total generation cost obtained for 50 trials in Test system 1

That the best results were obtained in 50 runs as depicted in Table. 1. They show the best cost of 15,443 ($/h) compared to other methods, which satisfying the demand. Also, the minimum power loss of 12.4324 is obtained. The results confirm the primogeniture of the WHOA over other methods for this case. The CPU time is 2.5 second. It is important to note that here the power loss calculations based on B-loss coefficients were performed exactly as reported in other references.

Table 1. Best solution for Test system 1

Generation (MW)	**PSO [33]**	**GA [33]**	**MTS [34]**	**BSA [35]**	**RCBA [36]**	**CBA [37]**	**WHOA**
P_1	447.4970	474.8066	448.1277	447.4902	444.7021	447.4187	447.2323
P_2	173.3221	178.6363	172.8082	173.3308	175.9130	172.8255	173.2464
P_3	263.4745	262.2089	262.5932	263.4559	256.3328	264.0759	263.4419
P_4	139.0594	134.2026	136.9605	139.0602	142.2861	139.2469	139.4826
P_5	165.4761	151.9039	168.2031	165.4804	169.9175	165.6526	164.9574
P_6	87.1280	74.1812	87.3304	87.1409	86.6873	86.7625	87.0717
Total Generation(MW)	1275.957	1275.94	1276.023	1275.9583	1275.84	1275.982	1275.4323
P_L(MW)	12.9584	17.0213	13.0205	12.9583	12.9266	12.9848	12.4324
Total generation cost($/h)	15,450	15,459	15,450.06	15449.8995	15449.61	15450.23	15,443.0836

Table 2. Best solution for Test system 1

Method	**Total generation cost($/h)**
CBA [37]	15450.23
MTS [34]	15,450.06
PSO [33]	15,450
NPSO-LRS [38]	15450.00
EPSO [39]	15449.94
MPSO-TVAC [40]	15449.91
MSSA [41], DHS [42], BSA [35], CMFA [43], MHS [44], MCSA [45], MABC [46], L-HMDE [47]	15449.90
ST-IRDPSO [48]	15449.89
LM [49]	15449.80
RCBA [36]	15449.61
GA [33]	15,459
WHOA	15,443.0836

5.2 Test system study 2

This test system comprises 15 units, which include RRLs, POZs, and transmission losses. The whole power demand for this system is 2630 MW [33]. The parameters of algorithm chosen as Number of search factors 90 and Maximum of iterations 1000. It should be noted that PS (stallions percentage), and PC (crossover percentage) are chosen equal to 0.2, and 0.13 respectively

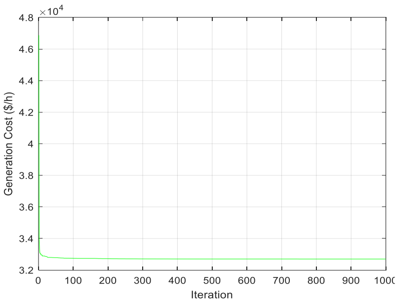

Figure 5. Convergence characteristic of the WHOA for the Test System 2 (15-generators).

The best total generation cost which was obtained in 50 runs is 32,697.8990 ($/h). Furthermore, the power losses are 30.08 MW, and CPU time is 1.45 second.

Table 3. Best solution for Test system 2

Generation(MW)	**GA [33]**	**PSO [33]**	**AIS [50]**	**SOH-PSO [15]**	**APSO [51]**	**GAAPI [52]**	**MTS [34]**	**SGA [53]**	**BSA [35]**	**ESSA [54]**	**WHOA**
P_1	415.3108	439.1162	441.1587	455.00	455.00	454.70	453.9922	455.00	455.0000	454.9995	455.00
P_2	359.7206	407.9727	409.5873	380.00	380.01	380.00	379.7434	380.00	380.0000	379.9996	380.00
P_3	104.425	119.6324	117.2983	130.00	130.00	130.00	130.0000	130.00	130.0000	130.0000	130.00
P_4	74.9853	129.9925	131.2577	130.00	126.5228	129.53	129.9232	130.00	130.0000	130.0000	130.00
P_5	380.2844	151.0681	151.0108	170.00	170.0131	170.00	168.0877	170.00	170.0000	170.0000	170.00
P_6	426.7902	459.9978	466.2579	459.96	460.00	460.00	460.0000	460.00	460.0000	460.0000	460.00
P_7	341.3164	425.5601	423.3678	430.00	428.2836	429.71	429.2253	430.00	430.0000	430.0000	430.00
P_8	124.7867	98.5699	99.948	117.53	60.00	75.35	104.3097	106.25	71.6368	70.1478	71.4488
P_9	133.1445	113.4936	110.684	77.90	25.00	34.96	35.0358	25.00	59.0234	60.2593	58.6314
P_{10}	89.2567	101.1142	100.2286	119.54	159.7893	160.00	155.8829	160.00	160.0000	159.9599	160.00
P_{11}	60.0572	33.9116	32.0573	54.50	80.00	79.75	79.8994	80.00	80.0000	79.9996	80.00
P_{12}	49.9998	79.9583	78.8147	80.00	80.00	80.00	79.9037	80.00	80.0000	79.9999	80.00
P_{13}	38.7713	25.0042	23.5683	25.00	33.7038	34.21	25.0220	25.00	25.0001	25.0007	25.00
P_{14}	41.9425	41.414	40.2581	17.86	55.00	21.14	15.2586	15.00	15.0001	15.0000	15.00
P_{15}	22.6445	35.614	36.9061	15.00	15.00	21.02	15.0796	15.00	15.0005	15.0009	15.00
Total Generation (MW)	2668.4	2662.4	2662.04	2662.29	2658.3226	2660.36	2661.36	2661.3	2660.6609	2660	2660.08
P_L(MW)	38.2782	32.4306	32.4075	32.28	28.3655	30.36	31.3523	31.258	30.6609	30.3679	30.0802
Total generation cost($/h)	33113	32858	32854	32751.39	32742.7774	32732.95	32716.87	32711	32704.4504	32701.21	32697.8990

Table 4. Best solutions for test system 2

Method	**Total generation cost($/h)**
GA [33]	33113
PSO [33]	32858
AIS [50]	32854
SOH-PSO [15]	32751.39
MTS [34]	32716.87
APSO [51]	32742.7774
GAAPI [52]	32732.95
SGA [53]	32711
IPSO [55]	32706.66
CSO [56]	32706.66
IJAYA [57]	32706.62
CACO-LD-AP [58]	32706.38
Jaya-SML [59]	32706.36
MDE [60]	32704.90
EPSO [39]	32704.83
SWT-PSO [61]	32704.45
WCA [62]	32704.45
BSA [35]	32704.45
CTPSO [63]	32704.45
L-HMDE [47]	32704.45
CLCS-CLM [64]	32704.45
ESSA [54]	32701.21
WHOA	**32697.8990**

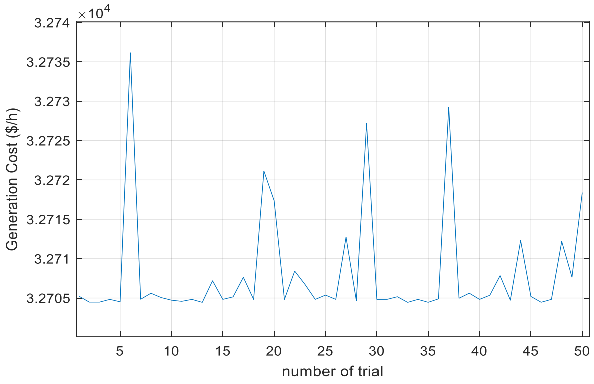

Figure 6. Total generation cost obtained for 50 trials in Test system 2

5.3 Test system study 3

This test system comprises 40 units consist VPLE without POZ, transmission losses, and RRLs. The demand is 10,500 MW [65]. The parameters of algorithm chosen as number of search factors 100 and maximum of iterations 1000. That the best solution was obtained in 50 runs 121,619.719 ($/h) total generation cost and CPU time 4.95 second.

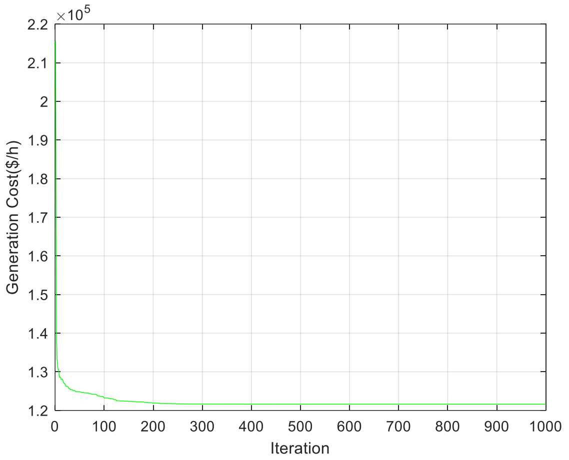

Figure 7. Convergence characteristic of the WHOA for the test system 3

Table 5. Best optimal generations and cost obtained by the WHOA for test system 3

Unit	Generation (MW)	Unit	Generation (MW)
1	114.00	21	523.2797
2	114.00	22	523.2796
3	199.9999	23	523.6596
4	179.7341	24	523.289
5	97.00	25	523.2797
6	140.00	26	523.2844
7	259.6413	27	10.00
8	285.3658	28	10.00
9	299.8966	29	10.00
10	130.0014	30	96.9976
11	94.00	31	190.00
12	168.7999	32	190.00
13	125.0002	33	190.00
14	304.5189	34	200.00
15	394.2791	35	200.00
16	394.2797	36	199.9999
17	489.2827	37	110.00
18	489.2795	38	110.00
19	511.2806	39	109.9999
20	511.2915	40	511.2793
Total generation cost($/h)	**121,619.719**		

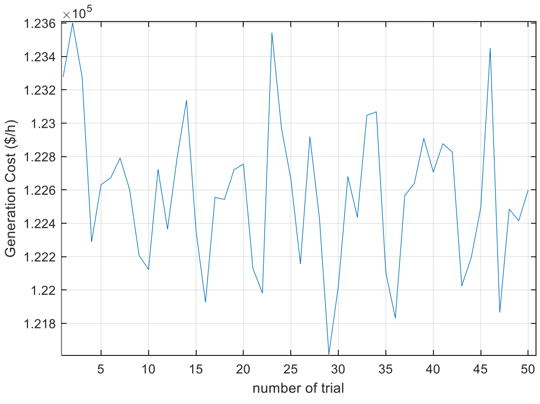

Figure 8. Total generation cost obtained for 50 trials in test system 3

Table 6. Best solution for test system 3

Method	Total generation cost($/h)
GSO [66]	124,265.3984
SCA [67]	122,713.6828
EP-SQP [68]	122,323.97
PSO [69]	122,252.265
PSO-SQP [70]	122,094.67
GA [71]	121,996.40
MILP [72]	121,986
ACO [72]	121,930.58
DE [73]	121,840
AA (Dist.) [74]	121,788.7
ST-HDE [75]	121,698.51
NPSO-LRS [38]	121,664.4308
WHOA	121,615.719

5.4 Test system study 4

This test system comprises 140 power units in Korean power grid consist VPLE and POZs, and RRLs are considered. The total power demand is 49,342 MW [63].

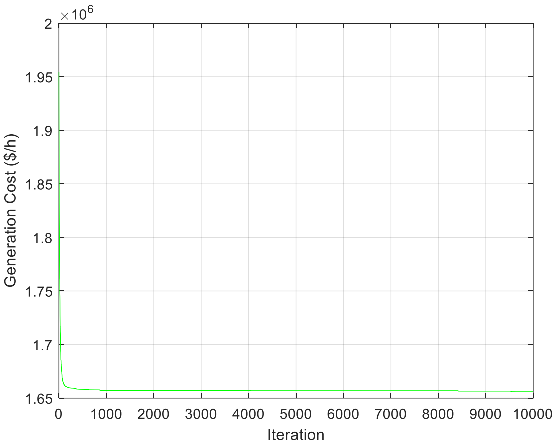

Figure 9. Convergence characteristic of the WHOA for the test system 4 (Korean system).

The parameters of algorithm chosen as number of search factors 1000 and maximum of iterations 10000. That the best solution was obtained 1,655,825.9333 ($/h) total generation cost and CPU time 1166 second.

Table 7. Best solution for Test system 4 (Korean system).

Method	Total generation cost($/h)
CTPSO [63]	1,657,962.7300
CSPSO [63]	1,657,962.7300
COPSO [63]	1,657,962.7300
CCPSO [63]	1,657,962.7300
MTLA [76]	1,657,951.9053
WHO	**1,655,825.9333**

5.5. Main findings

Based on what was reported in the simulation section, the proposed algorithm is able to provide better solutions than other related algorithms regarding the studied cases. Tables 6 to 9 respectively show the percentage of improvement of the objective function value obtained by using the algorithm compared to the values reported in other references.

- Based on the comparisons the total generation cost reductions (%) of WHOA for test system 1, are depicted in Table 8, from minimum 0.0423 to maximum 0.1031, compared to RCBA [36], and GA [33], respectively. Assuming the same annual load pattern for this case, the cost savings will be equal to $57171.264, $139427.664, respectively. For more detil see Table 8.

Table 8. Total generation cost reduction (%) of WHOA compared to other method for test system 1 (6-generators).

Method	Total generation cost reduction (%) of WHOA
CBA [37]	0.0463
MTS [34]	0.0452
PSO [33]	0.0448
NPSO-LRS [38]	0.0448
EPSO [39]	0.0444
MPSO-TVAC [40]	0.0442
MSSA [41], DHS [42], BSA [35], CMFA [43], MHS [44], MCSA [45], MABC [46], L-HMDE [47]	0.0441
ST-IRDPSO [48]	0.0441
LM [49]	0.0435
RCBA [36]	0.0423
Method	**Total generation cost reduction (%) of WHOA**

- For test system 2 (15-generators), the total generation cost reductions (%) of HOW, vary from 0.0101 (ESSA [54]) to 1.2695 (GA [33]). Assuming the same annual load pattern for this case, the cost savings will be vary from $29,004.34 to $3,636,284.76, respectively (see Table 9).

Table 9. Total generation cost reduction (%) of WHOA compared to other method for test system 2 (15-generators).

Method	Total generation cost reduction (%) of WHOA
GA [33]	1.2695
PSO [33]	0.4896
AIS [50]	0.4774
SOH-PSO [15]	0.1636
MTS [34]	0.0580
APSO [51]	0.1373
GAAPI [52]	0.1072
SGA [53]	0.0401
IPSO [55], CSO [56]	0.0268
IJAYA [57]	0.0267
CACO-LD-AP [58], JAYA-SML [59]	0.0259
MDE [60]	0.0214
EPSO [39]	0.0212
SWT-PSO [61], WCA [62], BSA [35], CTPSO [63], CTPSO [63], L-HMDE [47], CLCS-CLM [64]	0.0200
ESSA [54]	0.0101

- For test system 3 (40-generators), the total generation cost reductions (%) of WHOA, vary from 0.040054 (NPSO-LRS [38]) to 2.178731 (GA [33]). Assuming the same annual load pattern for this case, the cost savings will be vary from $426,715.4 to $23,211,192, respectively (see Table 10).

Table 10. Total generation cost reduction (%) of WHOA compared to other method for case 3 (40 generators with VPLE).

Method	Cost reduction (%)
GSO [66]	2.178731
SCA [67]	0.902814
EP-SQP [68]	0.582368
PSO [69]	0.523408
PSO-SQP [70]	0.393823
GA [71]	0.31302
MILP [72]	0.304468
ACO [72]	0.258898
DE [73]	0.184418
AA (Dist.) [74]	0.142236
ST-HDE [75]	0.068076
NPSO-LRS [38]	0.040054

- For test system 4 (Korean system), the total generation cost reductions (%) of WHOA, vary from 0.12839 (MTLA [76]) to 0.12904 (CTPSO, CSPSO, COPSO, CCPSO [63]). Assuming the same annual load pattern for this case, the cost savings will be vary from $26,383,3no12.52to $26,517,647.05, respectively (see Table 11).

Table 11. Total generation cost reduction (%) of HOW compared to other method for Test system 4 (Korean system).

Method	Cost reduction (%)
CTPSO, CSPSO, COPSO, CCPSO [63]	0.12904
MTLA [76]	0.12839

6. Conclusions

The increasing emphasis on environmentally friendly policies, combined with the competition among power generation companies and the rapidly emerging gap between energy demand and supply, necessitates the development of effective operational strategies for power generation utilities. Achieving this requires a precise mathematical formulation of the ED problem in the context of power system optimization and operation. This study considers all practical constraints and demonstrates the applicability of the proposed WHOA for solving non-convex, complex, and non-continuous ED problems in different scales of power grids. For this purpose, four different scale test systems were implemented to show the effectiveness of WHOA, with varying sizes and complexities. The results indicated that the WHOA reduces the optiml cots for 6, 15 ,40 and 140 generating units by at least 0.0423 %, 0.0101%, 0.040054%, and 0.12839 % compared to the optimal results of RCBA, emended salp swarm algorithm (ESSA), new PSO- simple local random search (NPSO-LRS), and modified MTS (MTLA) algorithms, respectively. Among the suggestions for the future work in this field, using the combination of WHOA with other techniques include mathematical-, or metaheuristic-based techniques to enrich the algorithm performancefor solving the ED problem can be addressed. Furthermore, applying some modifications, or improvements on WHOA can be mentioned as a challenging issue. Also, applying the WHOA to other relevant complex optimization problems of power grids, such as the E2DP, CHPEDP, CHPE2DP can be considered.

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