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Chaotic Sea-Horse Optimizer for Profit-Based Unit Commitment to Maximize the Profit of GENCOs in Restructured Power System Considering Reserve Allocation

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Abstract

Objectives: The primary objective of this research work is to solve the Profit Based Unit Commitment (PBUC) problem in Power Generation Companies (GENCOs) in the competitive Electricity market. The energy and spinning reserve allocation are considered to maximize the profit of power generation companies. **Methods:** A new and recently developed optimization technique of Chaotic Sea-Horse Optimizer (CSHO) is planned for an optimal solution PBUC problem. The control parameters of CSHO are the number of Population is 50, the Chaotic map parameter is 4, the dimensions are 10, and the maximum number of iterations is 100 are considered to achieve the global optimal solutions. The competitive study with standard golden approaches of the LR method and other soft computing techniques such as GA, PSO, etc. are considered for performance evaluations of CSHO. The proposed CSHO is mainly based on the natural behavior of Sea-Horse in the ocean. The MATLAB 15.0 platform is utilized for the expected problem. **Findings:** The CSHO was tested on a standard IEEE-39 bus system (10 generators and 24 hours) with reserve allocation. The CSHO technique improves the total profit of GENCOs with various test loads and reserve demand. The simulation results like Optimal UC schedule, power generation of thermal plants, fuel cost, startup cost, revenue, and profit are displayed. The percentage of total profit of 29.76% is improved when compared with the mathematical approach of the LR method with 102 second time period. **Novelty:** The CSHO has currently developed an effective algorithm that easily reaches the global optimal solutions. The CSHO mimics the movement, hunting, and breeding behavior of sea-horses in nature. Implementation of chaotic maps helps to improve the convergence speed of the proposed method.

Keywords: Deregulation; Profit Based Unit Commitment; Energy and Reserve Allocation; Cost Minimization; Profit of GENCOs; Chaotic Sea-Horse Optimizer

1 Introduction

In electric power systems, the Unit Commitment (UC) plays a major role in minimizing fuel cost, start-up, and environmental emission levels of regulated power systems. The rules and regulations of the classical UC are not applicable in the modern unbundled power sectors[1]. Under a commutatively deregulated environment, the PBUC problem provides more difference than the classical unit commandment. It not only minimizes the operating cost and emission level but also maximizes the profit of power generation companies (GENCOs). Here, the generated power of thermal, wind, solar, and PEV units is not necessary to meet system demand in all time intervals[2].

The PBUC scheduling process, calculation of economic operation, and emission reduction are optimized by various intelligent and soft computing approaches like GA, PSO, DE, ACO, ABC, etc. These algorithms sometimes provide premature solutions due to the selection of control parameter values and more dimensions of the problem. The proposed CSHO has a minimum number of parameters, so the searching ability is higher, and chaotic behavior helps to improve the accuracy of the expected solutions with a short execution period.

The researchers documented different classical, heuristic, and metal-heuristic algorithms to solve the PBUC problem, considering various sources. A classical mixed integer programming approach with CPLEX solver (software package)[3] has been applied in PBUC considering air energy storage and solar PV units. Revenue and profit were analyzed with different case studies, but reserve power allocation was not considered. Kumar.V.et al. applied a Monarch Butterfly Optimization[4] and considered the valve-point loading effect, ramp rate limits, and reserve probability in the PBUC problem. The emissions, RES, and EVs are not taken into account. A general algebraic modeling system software package[5] has been used to analyze the profit in both power and reserve allocation. The package contained three different software such ANTIGONE, COUENNE, and BARON. The BARON provides the best solution.

Hossein Lotfi and Mohammad Hasan Nikkhah have proposed a modified shuffled frog leaping algorithm[6] and considered the RES and energy storage units. Here, the impacts of emission reduction and EVs are not reported. The same problem has been analyzed by Kamalanathan. V and Asokan. K using a Corona Virus Herd Immunity Optimizer[7]. The authors determine the profit of GENCOs under reserve allocations and emission limitations. A solution to the UC problem has been discussed under-regulated and deregulated environments. A hybrid binary Sine-Cosine optimization algorithm with an optimal priority list algorithm[8] was applied to minimize the overall cost and profit considering the RES only.

Many researchers applied RES and PEVs to a classical UC problem to reduce the total operating cost of the system. Jian Pan and Tingzhang Liu have evaluated the cost of a thermal, wind, and solar integrated system. They also estimate the charging and discharging costs of EVs using enhanced-interval linear programming[9]. Here, reserve allocation and emission limitations are not considered. A chaotic zebra optimization algorithm[10] has been implemented on the same UC problem to reduce the overall cost of consistent systems. The Chaotic Arithmetic Optimization algorithm[11] was investigated for different 10-, 20-, 40-, and 100-unit systems. The approach also examines the security of the system.

The limited literature only analyzes the impact of EVs, PEVs, HEVs, and RES on the PBUC problem under a competitive open energy and auxiliary service market. Side Vasiyullah S. F and Bharathidasan S.G have applied a mathematically improved pre-prepared demand table with an analytical hierarchy process[12] to improve the profit of DISCOs. Here, 10 thermal units with equivalent wind, solar, and PEVs were considered for the solution. Intensify Harris Hawks Optimizer[13] has been used in PBUC and analyzed the impact of battery electric vehicles, hybrid electric vehicles, and plug-in electric vehicles. The power generation was evaluated in winter and summer. Here, electricity market revenue and profit were not displayed.

A software package of BARON solver[14] was used to solve PBUC considering the RES with battery storage system, and PEVs. The mathematical modeling of RES, battery storage units, and PEVs has been developed and analyzed for the uncertain nature of wind speed, solar irradiance, and PHEVs. The same software has been proposed for a solution of 10 thermal units with RESs (wind and solar) and EVs under deterministic and stochastic environments[15]. A chaotic map with the Harris Hawks Optimizer, Sine Cosine Algorithm, and Slime Mould Algorithm[16] has been implemented to analyze the profit of GENCOs under the summer and winter seasons. Here, 10, 40, and 100 thermal units with RES and PEVs were considered to test the projected methodology. A security-constrained generation maintenance scheduling[17,18] is also proposed to improve the GENCOs performance and profit under a deregulated environment.

In this research work, we developed a practical and well-established soft computing tool, the Chaotic Sea-Horse Optimizer for the solution of the spinning reserve constrained PBUC problem. The algorithm evaluates the profit of GENCOs in various test cases. The proposed CSHO provides the best solutions under nonlinear and uncertain load conditions. The performance of CSHO is experienced using an IEEE-39 bus test system with 10 thermal units for 24 hours. The outcomes of the PBUC schedule, energy and reserve allocation, total operating cost, revenue, profit, and computational time are represented with a comparative study. Chaotic behavior helps to improve the accuracy of expected solutions with a short execution period.

2 METHODOLOGY

2.1 Sea-Horse Optimizer (SHO)

The SHO is the nature-inspired, population-based optimization methodology developed by Zhao, S et. Al. in the year 2023.[19–21] The SHO is based on the natural life cycle of a sea horse searching for prey, movement, and breeding behavior in the sea. The solution to the optimization problem is mainly based on the four behaviors of SHO, such as

- Movement Behavior
- Foraging Behavior and
- Breeding Behavior

The performance of SHO was evaluated on 23 well-known functions and CEC2014 benchmark functions compared with six state-of-the-art meta-heuristic algorithms. Finally, five real-world engineering problems are utilized to test the effectiveness of SHO. The mathematical modeling of the initialization function, creating of populations, current positions, updating of search agents, and representation of searching agents are clearly described in the following sections.

The initial population of the SHO algorithm is mathematically represented as follows:

$$Sh = \begin{bmatrix} x1,i & \dots & x1,Dim-1 & x1,Dim \\ x2,i & \dots & \dots & x2,Dim \\ \vdots & \vdots & \vdots & \vdots \\ xN & \dots & xN,Dim-1 & xN,Dim \end{bmatrix} \tag{1}$$

$$Sh_{ij} = Randx(UB_j - LB_j) + LB_j \tag{2}$$

$$Sh_{elite} = (f(X_i)) \tag{3}$$

The mathematical representations of Movement Behavior, Foraging Behavior, and Breeding Behavior are clearly represented[19]. The flow diagram of CSHO-based solution to the PBUC problem is presented in Figure 1.

2.2 Chaotic Sea-Horse Optimizer (CSHO)

Chaotic maps play a critical role in optimization problems. Avoid local optima, improve convergence, speed up convergence, and improve the searching behavior of SHO[20]. In this article, the logistic type chaotic map is used to replace the *rand* in the SHO algorithm. The mathematical equation of the logistic-type chaotic map is as follows:

$$(i+1) = a \times (i)(1 - y\log(i)) \tag{4}$$

Where α is 4. So, the chaotic map variable with range [0,1] is obtained. So, the movement of SHO is represented as follows.

$$\theta = y \log \times 2\pi \tag{5}$$

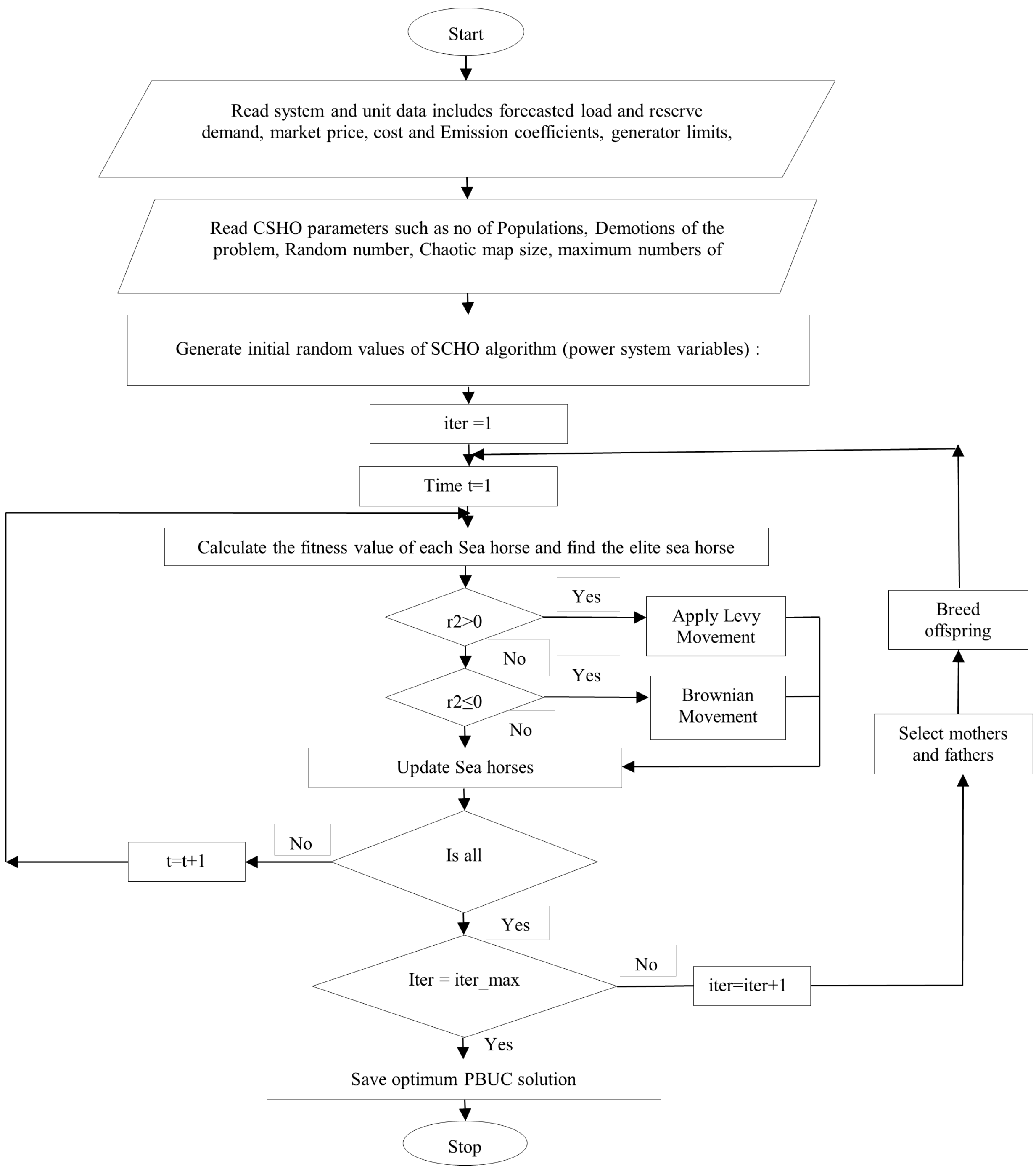

Fig 1. Flow chart of proposed CSHO algorithm for the solution of PBUC problem

2.3 Objective Function of GENCOs

The objective of the proposed work is to determine the appropriate scheduling of thermal generators for maximizing the profit of GENCOs considering the reserve allocation subject to the standard system constraints. The difference between the revenue obtained from the sale of energy at market price and the total operating cost of the generating company is mentioned as the profit of GENCOs. The MCP is used to sell both energy and reserve power in the competitive joint energy and reserve market. The value of MCP varied with different time periods.

The PBUC can be mathematically represented by the following equations.

$$Maximize\ PF = RV - TC \tag{6}$$

$$RV = \sum_{i=1}^{N}\sum_{t=1}^{T} P_{it} SP_t X_{it} + r\sum_{i=1}^{N}\sum_{t=1}^{T} RP_r R_{it} X_{it} \tag{7}$$

$$TC = (1-r)\sum_{i=1}^{N}\sum_{t=1}^{T} F(P_{it}).X_{it} + r\sum_{i=1}^{N}\sum_{t=1}^{T} F(P_{it}+R_{it})X_{it} + ST_t.X_{it} + SD_t.X_{it} \tag{8}$$

The total operating cost over the entire scheduling period is the sum of the production cost and start-up/shutdown cost of all the units. The shutdown cost is assumed to be equal to zero for all the units. The production cost of the committed units is mentioned by quadratic Equation (9).

$$MinF_{it}(P_{it}) = a_i + b_i P_{it} + c_i {P^2}_{it} \tag{9}$$

2.4 Standard Operating Constraints

The power balance, spinning reserve, generator, and reserve power limits, minimum ON/OFF time, and emission constraints are considered to solve the PBUC problem with emission limitations.

- Power balance constraint

$$\sum_{i=1}^{N} P_{it} X_{it} \le P_{Dt} \tag{10}$$

- Spinning reserve constraint

$$\sum_{i=1}^{N} R_{it} X_{it} \le SR_t \tag{11}$$

The power balance and spinning reserve constraints differ from the traditional UC problem because if GENCO acquires a greater profit, it can now select to produce the demand and reserve less than or equal to the forecasted level.

- Generator and Reserve power limits constraint

$$Pi_{imax_{imin}} \tag{12}$$

$$0 \le R_i \le Pimin_{imax}\ \ 1 \le i \le N \tag{13}$$

$$P_i + R_i\ \le P_{imax}\ \ 1 \le i \le N \tag{14}$$

- Minimum up/down time constraints

$$Ton_i \geq Tup_i \tag{15}$$

$$Toff_i \geq Tdown_i \tag{16}$$

- Emission constraint

$$\sum^{T}{}_{t=1} \sum^{N}{}_{i=1} E(P_{it})X_{it} \leq EM_t \tag{17}$$

2.5 Implementation of CSHO For Spinning Reserve Constrained PBUC problem

The spinning reserve-constrained PBUC optimization is accomplished using the CSHO by taking the following steps:

- Read system and unit data including forecasted load and reserve demand, market price, cost and emission coefficients, generator limits start-up and showdown cost, etc.
- Read CSHO parameters, such as population size, problem demotions, system variables, and maximum numbers of iterations, etc.
- Generate initial random values of shares (power system variables) for all shareholders: Xij (j=1, 3,…m, i=1, 2,…n).
- Compute the feasible units for forecasted load and reserve or market price for each population.
- Calculate the objective function using CSHO (real and reserve power generation, total operating cost, revenue, etc.).
- Calculate the profit (fitness) of each population (solutions) using the CSHO approach.
- Check the time interval for 24 hours. If satisfied, go to the next step; otherwise, go to step 4.
- Evaluate the fitness values of objective functions (maximum profit and minimum emission level) of the PBUC problem.
- Verify whether an optimal solution is reached. If all constraints are satisfied, go to the next step; otherwise, go to step 3.
- Save the best simulation results and stop.

3 Results and Discussion

Energy and Spinning reserve constrained optimal self-scheduling problems are solved using Chaotic Sea-Horse Optimizer. The validity and performance of the proposed CSHO are illustrated on the IEEE-39 Bus test system. The test system consists of 39 buses, 54 lines, and 10 thermal generating units. The generator data includes maximum/minimum generating limits cost and emission coefficients, hot and cold startup cost, minimum up/down time, and initial status of generators taken from reference[12]. The system data of forecasted load demand, forecasted reserve demand, and market price are taken from the same reference. In the IEEE-39 bus test system, reserve demand is considered to be 10% of actual load demand. The following values of control parameters of the CSHO algorithm were considered by trial-and-error method and displayed in Table 1.

Table 1. Control parameters of proposed SCHO

Parameters	Value
Population size	50
Demotions of the problem	10
Random number	0 to 1
Maximum number of iterations	100

Under a deregulated environment, power and reserve generation are not necessary to meet the system load and reserve demand. So, the power and reserve generation are less than or equal to the forecasted values. The proposed CSHO efficiently computes the feasible units, and the comparison of committed units of the proposed PBUC and classical CBUC is given in Figure 2. The power generation and reserve allocation of 10 units are reported in 24-hour duration using the CSHO approach. Here, the reserve power is obtained at 10 hours only the remaining hour is zero because the GENCOs are operated from the profit point of view. The graphical representation of power generation and reserve allocation with respect to load and reserve demand is displayed in Figure 3 and Figure 4.

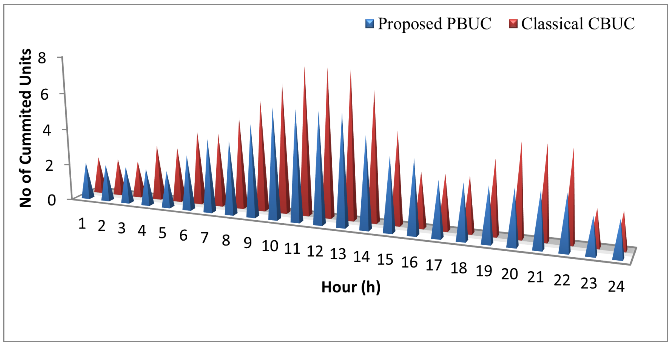

Fig 2. Comparison of Committed units of proposed PBUC and classical CBUC

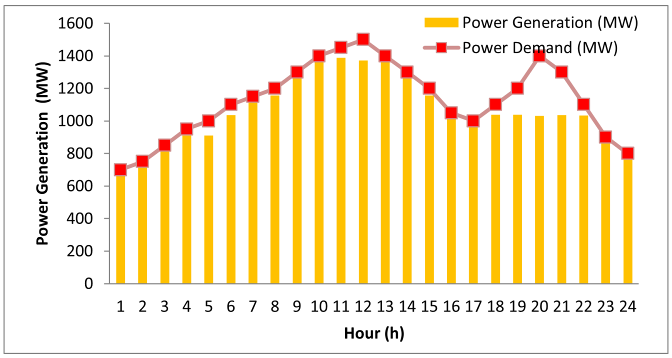

Fig 3. Comparison of Power Demand and Power Generationby proposed CSHO

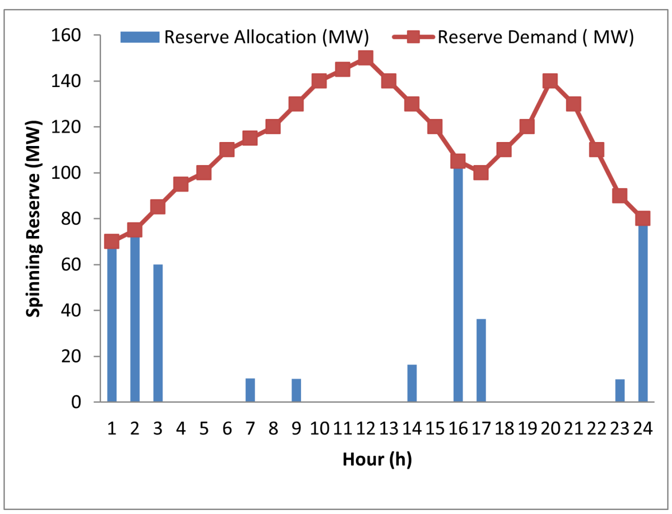

Fig 4. Comparison of Reserve Demand and Reserveallocation by proposed CSHO

Table 2. Simulation Results of proposed IEEE-39 bus test system using proposed CSHO

H (h)	Demand (MW)	Revenue ($)	Operating Cost ($)	Profit ($)
1	700	17776.5	14903.5	2873.02
2	750	18816	15864.5	2951.54
3	850	20966.1	17090.2	3875.86
4	950	20611.3	17353.1	3258.15
5	1000	21157.5	17353.3	3804.19
6	1100	23843.3	20195.1	3648.21
7	1150	26215.6	22939.4	3276.18
8	1200	25877.3	23075.8	2801.54
9	1300	29970.6	26431.9	3538.72
10	1400	40137.1	28199.3	11937.9
11	1450	41341	28260.6	13080.4
12	1500	43702.7	28457.8	15244.9
13	1400	33851	28378	5473
14	1300	32433.1	26575.1	5858
15	1200	26009.1	22863.4	3145.62
16	1050	27150.9	22848.6	4302.3
17	1000	23353.5	20149.2	3204.3
18	1100	22880.1	20172.8	2707.34
19	1200	23069.5	20199.6	2869.94
20	1400	23507.9	20176.7	3331.15
21	1300	24017.8	20209.3	3808.47
22	1100	23854.4	20203.6	3650.75
23	900	20778.9	17352.5	3426.34
24	800	20606.4	16827.3	3779.08
Total Profit ($)				**115847**

Table 2 explains the simulation results of the IEEE 39 bus system by the proposed CSHO approach. It includes load demand, operating cost, revenue, and profit of GENCOs. The total profit and computational time are $115847 and 102 seconds. The revenue, fuel costs, and profit of the proposed test system are efficiently improved. The results are from optimized values of real and reserve power allocation thermal units by the CSHO approach. The profit of GENCOs is improved by considering the reserve power generation. The reserve power is sold in the reserve or auxiliary service market with more market clearing prices. Therefore, the profit is improved by selling both energy and reserve power in the electricity market.

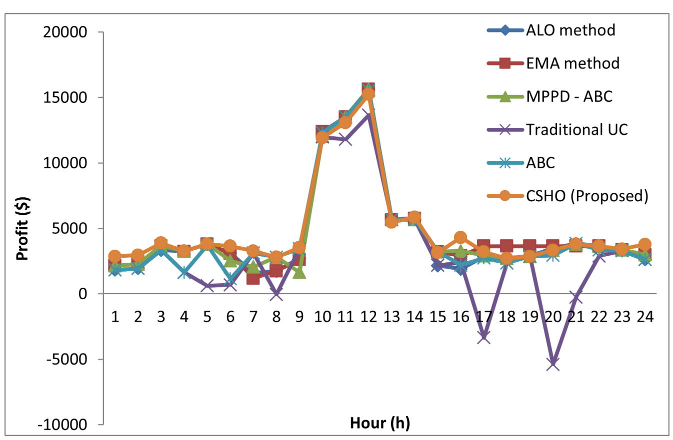

Fig 5. Comparison of profit of proposed method with the Existing methods for 24 hours

Table 3. Comparison of Total profit of proposed method with the Existing methods

Methods	Total Profit of GENCOs ($/24hr)			Computational time (s)
	Best profit	Average profit	Worst Profit	
Traditional UC [22]	81365.65	-	-	187
GA [22]	99058	-	-	152
Muller Method [7]	103296	-	-	150
ICA [23]	104,328	-	-	110
SFLA [23]	105442.4	-	-	124
MPPD – ABC [7]	105446.60	105205.50	105110.25	112
EMA approach [23]	105869.7	1005102.22	104952.50	118
ALO [23]	106266.60	106005.50	105525.22	115
GA-AIS [7]	107317.6	-	-	113
CVHIO [7]	107350.50	107253	107110	101
IALO [22]	111205.9	110552.56	109748.75	110
CSHO (Proposed)	**115847**	**115689.50**	**115590.99**	**102**

The comparative study was also done to evaluate the effectiveness of the proposed CSHO. The simulation results (total profit and computational time) are compared with other optimization methods and shown in Table 3. The profit from reserve power generation for 24 hours is compared with other available methods such as and graphically represented in Figure 5. From Table 3, the proposed CSHO approach provides maximum profit with less computational time when compared with existing methods. The CSHO algorithm mimics the movement, hunting, and breeding behavior of sea horses in nature. Chaotic maps are effectively used to improve the performance of meta-heuristic algorithms by avoiding the local optimum and increasing the speed of convergence

4 Conclusion

This study proposes an intelligent computational algorithm of CSHO to enhance the profit of GENCOs in a day-ahead energy and reserve market. In this research work, two major issues are handled simultaneously, such as power generation and reserve allocation. So, this problem is considered a bi-objective optimization function and solved by CSHO. A numerical case study with the IEEE 39-bus (10 units 24-hour test system) test system is considered to analyze the performance of the CSHO. The spinning reserve of the proposed test system is 10% of the forecasted load demand. The chaotic map behavior and searching ability of SHO effectively optimize the thermal variables and determine the best solutions for power dispatch, reserve allocation, fuel cost, revenue, and profit of GENCOs. The best profit with the computational time of the CSHO is $115847 and 102 seconds, respectively. The total profit of GENCOs improved by 29.76 % compared to the Traditional UC approach, and 4% was maximized compared to the other existing standard algorithm of the IALO approach. From the comparison, the proposed algorithm effectively improves the total profit of GENCOs in a competitive energy and reserve market. It is recommended that the proposed CSHO approach is a powerful meta-heuristic approach for solving complex, multi-objective nonlinear security-constrained UC, optimal bidding strategy problem, and reasonable energy with EV-constrained PBUC problems.

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