ISSN: 2633-4828 Vol. 5 No.4, December, 2023

International Journal of Applied Engineering & Technology

SHORT-TERM HYDROTHERMAL GENERATION SCHEDULING USING HYBRID SNAKE OPTIMIZER

Avneet Kaur[1], J.S. Dhillon[2] and Manmohan Singh[3]
[1]Department of Electrical and Instrumentation Engineering, Sant Longowal Institute of Engineering and Technology, Punjab, India
[2,3]Professor, Department of Electrical and Instrumentation Engineering, Sant Longowal Institute of Engineering and Technology, Punjab, India
[1]avneetdhaliwal2@gmail.com, [2] jsdhillonp@yahoo.com and [3] singh_manmohan@msn.com

ABSTRACT
The hybrid snake optimizer (HSO) is proposed for optimal generation scheduling of short-term hydrothermal systems over a day's time horizon. The work aims to minimize the operating fuel cost of thermal units by utilizing the water for hydro units to its fullest extent. Direct heuristics based on proportional sharing independently handle the active power balance and water volume equality constraints. The parameter-tuning, exploration, and exploitation tactics profoundly affect the stochastic algorithms' overall solution precision and rate of convergence. The HSO hybridizes the simplex search technique with a snake optimization algorithm based on real-world snake mating processes to improve the premature convergence behaviour of the snake optimization algorithm. The proposed algorithm successfully solves the practical short-term hydrothermal power generation scheduling problem. The results, convergence curve, and Whisker box plot justify the proposed HSO's efficacy.

Keywords: Hydrothermal generation scheduling, Snake optimization algorithm, simplex search method, Metaheuristics optimization, Optimization problem.

1. INTRODUCTION
The national power policy aims to increase per capita energy consumption while ensuring that consumers have a reliable and cost-effective supply of electricity. A modern power system typically includes a mix of thermal (fossil fuel-based) and hydropower plants connected through a transmission network. The primary goal is to use all available energy sources as efficiently as possible. This approach ensures the most profitable and environmentally sustainable use of energy resources. The main sources of electric energy are hydrothermal systems, which involve the coordinated utilization of hydropower and thermal power generation. Hydro units are preferred for their low marginal operating costs. Multiple factors play a role in shaping decisions regarding power generation, encompassing considerations like maximizing thermal unit performance on an hourly basis and managing the water usage of hydro units. These decisions are subject to limitations imposed by power balance requirements and specific criteria related to water storage. Factors pertaining to water, such as water head, the reservoir's required water volume, and generation constraints, also contribute significantly to these decisions. The process of scheduling power generation in a hydrothermal system is framed as an NP-hard optimization problem. This means that it's a computationally challenging task to find the optimal solution, considering various constraints and objectives. The optimization problem must satisfy load demand requirements and adhere to constraints related to water volume, ensuring a constant power supply while efficiently utilizing water resources [1].

Conventional optimization methods employed for addressing the hydrothermal generation scheduling (HTGS) problem are constrained when it comes to tackling the intricately complex and non-linear nature of the HTGS problem [2]. Metaheuristics, often referred to as intelligent optimization algorithms, obviate the need for calculating derivatives of any order for the objective function. Due to their advantages over conventional methods, heuristic pursuit methods have increased their popularity over the past few decades [3], gravitational search algorithm [4], firefly algorithm [5], couple-based particle swarm optimization [6], modified cuckoo search algorithm [7], grasshopper optimization algorithm [8], quasi-reflected symbiotic organism optimization [9], are applied for solving HTGS problem.

Incremental gravitational search algorithm (IGSA) [10] has been used to solve the two different short-term hydrothermal coordination problems (STHCP) with variable-head. The proposed method's primary flaw is its propensity to stick in a local minimum. Dhillon et al. [11] successfully addressed the HTGS problem by employing a real-coded genetic algorithm (RCGA). However, a significant challenge in RCGA lies in the accurate estimation of the penalty parameter, as it involves adhering to local solutions and necessitates the adjustment of numerous factors. A variable and fixed-head HTGS problem utilizing PPO was described by Narang et al. [12]. For PPO to be implemented successfully, many variables must be precisely calibrated.

The already published research work obtained the optimal power generation schedule, but there are further chances of enhancing the optimal results.

The primary features and capabilities of metaheuristic optimization algorithms include explorations of large solution domains, finding global solutions, and avoiding sticking to the local solution. Because of these significant advantages, metaheuristic methods are still often utilized in many engineering disciplines in contrast to other optimization techniques. While there are resemblances among these optimizers, nature-inspired optimization methods possess distinct characteristics that set them apart in terms of their unique search strategies. Hashim et al. [13] proposed the nature-inspired metaheuristic snake optimization algorithm (SOA) to address the global solution of an optimization problem. SOA is based on the snakes' mating habits. Each snake fights to have the best mate if the available food is sufficient and the temperature is low. The SOA has a solid balance between exploration and exploitation and a consistent and quick convergence rate that draws writers to use it to sum up these commonalities. SOA has been used in various fields, such as feature selection, quantum physics, and the medical field. Khurma et al. [14] proposed a binary snake optimizer for feature selection problems. Al-Shourbaji et al. [15] presented the snake optimizer to determine the optimal feature offset.

The proposed hybrid snake optimizer to solve hydrothermal generation scheduling (HTGS) avoids the chances of being stuck in local minima and maintains a balance between exploration and exploitation. Like other heuristic techniques, SOA also tends to stagnate, which leads to inaccurate results and takes a long time to converge. To overcome this problem, The local simplex search technique is hybridized with SOA. The simplex search technique avoids local stagnation and slow convergence, improving the results and convergence of basic SOA. It is found that the proposed technique is effective regarding exploration-exploitation balance and convergence speed. The contribution of the paper is outlined below:

- The Hybrid Snake Optimizer is utilized to address a hydrothermal generation scheduling (HTGS) problem characterized by high constraints and non-linearity.
- The proportional sharing heuristics used to handle load demand and available water volume constraints of HTGS optimization problem.
- A hydrothermal electric power test system is used to verify the efficacy of the proposed algorithm.
- Statistical significance checks verified the robustness of the proposed HSO algorithm.

Six sections constitute the rest of the paper.

2. HYDROTHERMAL GENERATION SCHEDULING PROBLEM

The hydrothermal generation scheduling problem aims to optimize the power output of different hydrothermal units to minimize the total operating cost, J by utilizing available water volume to its fullest extent while satisfying various operational constraints of the power system. Each hydro unit is also bound by the amount of water that can be drawn down throughout the planning period, T, which is one of the equality constraints. A power comprising 'm' hydro units and 'n' thermal units is considered. The discrete mathematical model is presented as follows [12]:

2.1Thermal Model

The primary goal is to determine cost-effective thermal power generation throughout the planning duration [11]. The objective is to make the most efficient use of the accessible water resources throughout the scheduled timeframe in order to lower the operational expenses of thermal power plants, as illustrated below:

$$J = \sum_{t=1}^{T}\left(\sum_{i=1}^{n} t_t\left(a_i + b_i P_{ti} + c_i P_{ti}^2 + |d_i sin(e_i(P_i^L - P_{ti}))|\right)\right) \; (\$) \qquad (1)$$

where, $P_t = [P_{t1}, \dots, P_{t,n_t}]^T$ and a_i, b_i, c_i, d_i and e_i are fuel coefficients of i^{th} generating unit having (\$/h), (\$/MWh), $(\$/MW^2h)$, $(\$/h)$, and (rad/MW) units, respectively.

2.2 Hydro Model

The input-output characteristics of a hydro generator are the variation in water discharge as a function of power output, P_{tk} and net head, w_{tj}^h, respectively. The Glimn-Kirchmayer model [17] calculates the j^{th} hydro unit's discharge rate (q_{tj}) for the t^{th} subinterval as follows:

$$q_{tj} = K_j \, \emptyset(P_{tk}) \Psi(w_{tj}^h) \; (j \in [1, m]; k = j + n; t \in [1, T])(2)$$

where K_j is the proportional constant. The functions $\emptyset(P_{tk})$ and $\Psi(w_{tj}^h)$ represent generation of hydro units and water head of reservoir, respectively, and are defined as:

$$\emptyset(P_{tk}) = x_j P_{tk}^2 + y_j P_{tk} + z_j$$

$$(j \in [1, m]; k = j + n; t \in [1, T]) \; (3)$$

$$\Psi(w_{tj}^h) = \alpha_j (w_{tj}^h)^2 + \beta_j w_{tj}^h + \gamma_j \; (j \in [1, m]; t \in [1, T]) \; (4)$$

where $x_j (m^3/MW^2h)$, $y_j (m^3/MWh)$ and $z_j (m^3/h)$ are coefficients of water discharge for the j^{th} hydro generator, $\alpha_j (m^{-2})$, $\beta_j (m^{-1})$ and γ_j (unitless) are head variation coefficients of the j^{th} hydro unit.

The reservoir of the j^{th} hydro unit is assumed to have vertical sides and a finite capacity in order to compute the effective head. Spillage only occurs when the reservoir's storage capacity (determined by surface area of the reservoir, SA_j) is exceeded. The equation for effective head continuity

$$w_{tj+1}^h = w_{tj}^h + \frac{t_t}{SA_j}(I_{tj} - q_{tj}) \; (j \in [1, m]; k \in [1, T]) \; (5)$$

where w_{tj}^h (m) is effective head, t_t(h) is time interval, and I_{tj} (m^3/h) is water inflow.

2.3 Constraints

The short-term HTGS problem is subject to the following set of constraints:

(i) *The water availability limits*: The cumulative discharge, q_{tj}, for each individual hydro unit over the planning period is restricted to a predefined reservoir water volume, denoted as Vo_j. Since the constant value, $Vo_j (m^3)$ represents the predefined water volume determined by the reservoir management strategy and the water discharge, $q_{tj} (m^3/h)$, is a function of the hydropower output, $P_{tj} (MW)$.

$$\sum_{t=1}^{T} t_t \, q_{tj} = Vo_j \qquad (j \in [1, m]) \qquad (6)$$

(ii) *Energy balance equation:* The total power generation from hydro and thermal units must satisfied the energy balance equation at each sub-interval while considering the power network's transmission losses.

$$\sum_{i=1}^{n+m} P_{ti} = P_t^D + P_t^{Loss} \quad (t \in [1,T]) \quad (7)$$

$$P_t^{Loss} = \left(B_{00} + \sum_{i=1}^{n+m} B_{0i} P_{ti} + \sum_{i=1}^{n+m} \sum_{j=1}^{n+m} P_{ti} B_{ij} P_{tj} \right)$$

where $P_{ti}\ (MW)$ is active power output of i[th] generator and $P_t^D\ (MW)$ is power demand during t[th] interval. B_{00} (MW), B_{0i}, $B_{ij}\,(MW^{-1})$ represents the loss coefficients evaluated by performing a.c. load flow analysis [11].

(iii) *Inequality constraints:* The power generation of hydro and thermal units must lie within maximum and minimum limits and is described as follows:

$$P_i^L \le P_{ti} \le P_i^U \quad (i \in [1, n+m]; t \in [1,T]) \quad (8)$$

where P_i^L (MW) and $P_i^U\,(MW)$ are the minimum and maximum power generation limits of hydro and thermal generators, respectively.

The hydrothermal generation scheduling optimization problem is stated as below:

Minimize operating cost given by Eq.(1)

Subject to Eq.(6), Eq. (7) and Eq. (8)

3. CONSTRAINTS HANDLING PROCEDURES

This section discusses the approach used to manage constraints in the HTGS problem for each specific constraint.

3.1 Inequality Constraints handling

Throughout the search process, a replacement technique is employed to confine power generation within the operational limits of the i^{th} generator [21].

$$P_{ti} = \begin{cases} P_{ti} & ; (P_i^L \le P_{ti} \le P_i^U) \\ P_i^L & ; (P_{ti} < P_i^L) \\ P_i^U & ; (P_{ti} > P_i^U) \end{cases} \quad (i \in [1, n+m]; t \in [1,T]) \ (9)$$

3.2 Utilization of Available Water

An iterative repair technique is employed to provide a feasible solution for handling equality limits. The following equation shows the difference E_j^v, between total reservoir volume and total hydro unit discharge.

$$E_j^v = Vo_j - \sum_{t=1}^{T} t_t q_{tj} \quad (j \in [1,m]) \quad (10)$$

When the value of $|E_j^v| \le \epsilon$ the reservoir's overall storage is utilized to its greatest potential; otherwise, power generation is updated to increase or decrease its value using the following equation.

$$P_{t,j+n} = \begin{cases} P_{t,j+n} + X_1 & ; (E_j^v > 0) \\ P_{t,j+n} - X_2 & ; (E_j^v < 0) \end{cases}$$

$$(j \in [1,m]; t \in [1,T]) \, (11)$$

where

$$X_1 = \min\left((P_j^U - P_{t,j+n}) r_j,\ \left(\frac{|E_j^v|}{\sum_{t=1}^{T} q_{tj}} \right) P_{t,j+n} \right)$$

$$X_2 = \min\left(\left(P_{t,j+n} - P_j^L\right) r_j ,\ \left(\frac{|E_j^v|}{\sum_{t=1}^{T} q_{tj}} \right) P_{t,j+n} \right)$$

r_j is a random number between o and 1.

3.3 Power Balance Constraint Handling

To handle the power balance equality constraint, the difference between total power generation by hydrothermal units and total power demand plus transmission losses (P_t^{Loss}) is calculated for t[th] time interval and is denoted by E_t^{PD}, which is given below

$$E_t^{PD} = P_t^D + P_t^{Loss} - \sum_{i=1}^{n+m} P_{ti} \quad (t \in [1, T]) \qquad (12)$$

When the value of $|E_t^{PD}| \le \epsilon$ the power generated is within the feasible range, and there is no need to repair the solution. Within generation limits, the solution is repaired using the following equation based on proportional sharing of unmet demand to each generator.

$$P_{ti} = \begin{cases} P_{ti} + Y_1 & ;(E_t^{PD} > 0) \\ P_{ti} - Y_2 & ;(E_t^{PD} < 0) \end{cases} (i \in [1, n+m]; t \in [1, T]) \ (13)$$

where

$$Y_1 = \min\left((P_i^U - P_{ti}) r_i ,\ \left(\frac{|E_t^{PD}|}{\sum_{i=1}^{n_g} P_{ti}} \right) P_{ti} \right)$$

$$Y_2 = \min\left((P_{ti} - P_i^L) r_i ,\ \left(\frac{|E_t^{PD}|}{\sum_{i=1}^{n_g} P_{ti}} \right) P_{ti} \right)$$

r_i is uniform random number $\in [0,1]$. The detail of finding feasible solution by satisfying Eqs. (6-8).

4. HYBRID SNAKE OPTIMIZER (HSO)

This paper explores constrained short-term hydrothermal generation scheduling problem using the proposed hybrid snake optimizer (HSO). The basic snake optimization algorithm is hybridized with the simplex search technique to improve its performance. HSO's core idea centers around real-world observations related to the mating behavior of snakes [16].

4.1Initialization

An initial population of snakes(P_{kti}) is produced randomly within the specified hydrothermal power generation output limits as follows:

$$P_{kti} = P_i^L + (P_i^U - P_i^L) r_{kti}$$

$$\left(i \in [1, n_g]; t \in [1, T];\ k \in [1, n_s]\right) \ (14)$$

n_s represents population of snakes and n_g=n+m represents total number of hydro and thermal generators. To intialize the optimization algorithm, a matrix $P_k(g)$ of size $(n_s \times T \times n_g)$ is generated randomly as:

$$\begin{bmatrix} P_{k11}(g) & P_{k12}(g) & \cdots & \cdots & P_{k1n_g}(g) \\ P_{k21}(g) & P_{k22}(g) & \cdots & \cdots & P_{k2n_g}(g) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ P_{kT1}(g) & P_{kT2}(g) & \cdots & \cdots & P_{kTn_g}(g) \end{bmatrix}_{T \times n_g} \qquad (k \in [1, n_s])$$

The objective function $F_k(g)$ of k[th] snake during g[th] movement can be calculated as:

$$F_k(g) = J(P_k(g)) \qquad (k \in [1, n_s]) \qquad (15)$$

4.2 Categorization of Male and Female Snakes

The total population is divided into two equal groups: males and females. The population of snakes, n_s is equally divided into males, n_l and females, n_o. The male, $X_k(g)$ and female, $Y_k(g)$ population and corresponding objective function of male $F_k^X(g)$ and female, $F_k^Y(g)$ are represented as vector of snakes as $P_k(g) = [X_k(g) \vdots Y_k(g)]^T$ and $F_k(g) = [F_k^X(g) \vdots F_k^Y(g)]^T$, g represents the iteration counter.

4.3 Temperature and Food Quantity

The mating of snakes depends on the temperature, T_{tp} and quantity of food, Q available.

$$T_{tp} = exp\left(\frac{-g}{G^{max}}\right) \qquad (16)$$

$$Q = C_1 exp\left(\frac{g - G^{max}}{G^{max}}\right) \qquad (17)$$

where g and G^{max} refers to the current iteration and the maximum number of iterations. C_1 is constant and is set equals to 0.5.

4.4 Exploration Phase

The exploration phase is modelled as follows if $Q < 0.25$, to update position of snakes during next iteration.

$$P_{kti}(g+1) = \begin{cases} Y_{uti}(g) \pm Z_1 & ;(r < 0.6) \\ X_{uti}(g) \pm Z_2 & ;(r \geq 0.6) \end{cases}$$

$$(i \in [1, n_g]; t \in [1, T]; k \in [1, n_s]) \quad (18)$$

where

$$Z_1 = C_2\left(exp\left(\frac{F_u^Y(g)}{F_k^X(g)}\right)\right)\left((P_i^L - P_i^U)r_i + P_i^L\right)$$

$$Z_2 = C_2\left(exp\left(\frac{F_v^X(g)}{F_k^Y(g)}\right)\right)\left((P_i^U - P_i^L)r_i + P_i^L\right)$$

where $P_{kti}(g+1)$ is the k[th] snake position, $X_{uti}(g)$ *and* $Y_{uti}(g)$ represents the random positions of male and female snakes, respectively during the $(g+1)^{th}$ movement and $v \in [1, n_l]$ and $u \in [1, n_o]$ are random integers. C_2 is a constant and set equals to 0.05. r_0 is uniform random number $\in [0,1]$. $F_v^X(g)$ and $F_u^Y(g)$ refers to the fitness of random male and female snakes, respectively.

4.5 Exploitation Phase

In case the food quantity is greater than the threshold value (Q>threshold), i.e., food exists, this is called the exploitation phase, as represented by the following equation:

$$P_{kti}(g+1) = P_{uti}(g) \pm C_3 T_{tp}\left(P_{ti}^{best} - P_{kti}(g)\right) r_i$$

$$(i \in [1, n_g]; t \in [1, T]; k \in [1, n_s]) \qquad (19)$$

where P_{ti}^{best} refers to the position of the best snake and C_3 is a constant equal 3.u is random integer $\in [1, n_s]$.

Mathematically, the fighting mode and the mating mode for male and female snakes is stated below:

Fighting mode

$$X_{kti}(g+1) = X_{kti}(g+1) \pm C_3\left(exp\left(\frac{-F_Y^{best}}{F_k^X(g)}\right)\right)tp$$

$\left(i \in [1, n_g]; t \in [1, T]; k \in [1, n_l]\right)$ (20)

$$Y_{kti}(g+1) = Y_{kti}(g+1) \pm C_3\left(exp\left(\frac{-F_X^{best}}{F_k^Y(g)}\right)\right)tq$$

$\left(i \in [1, n_g]; t \in [1, T]; k \in [1, n_o]\right)$ (21)

$$tp = f_{FM}\left(QY_{ti}^{best} - X_{kti}(g+1)\right)r_i$$

$$tq = \left(QX_{ti}^{best} - Y_{kti}(g+1)\right)r_i$$

Mating mode

$$X_{kti}(g+1) = X_{kti}(g+1) \pm C_3 lp$$

$\left(i \in [1, n_g]; t \in [1, T]; k \in [1, n_l]\right)$ (22)

$$Y_{kti}(g+1) = Y_{kti}(g+1) \pm C_3 lq$$

$\left(i \in [1, n_g]; t \in [1, T]; k \in [1, n_o]\right)$ (23)

$$lp = \left(exp\left(\frac{-F_k^Y(g)}{F_k^X(g)}\right)\right)\left(QX_{kti}(g) - Y_{kti}(g+1)\right)r_l$$

$$lq = \left(exp\left(\frac{-F_k^X(g)}{F_k^Y(g)}\right)\right)\left(QY_{kti}(g) - X_{kti}(g+1)\right)r_l$$

where F_Y^{best} and F_X^{best} represents the fitness of the best female and male, respectively. F_k^X and F_k^Y represents the fitness of k[th] female and male agent, respectively. $F_k^X(g)$ and $F_k^Y(g)$ are the fitness of k[th] male and k[th] female agents, respectively.

Choose the worst male and female and replace them if the egg incubates

$$P_{kti}^{worst} = P_i^L + (P_i^U - P_i^L)r_i$$

$\left(i \in [1, n_g]; t \in [1, T]; k \in [1, n_o]\right)$ (24)

Where P_{kti}^{worst} represents the position of worst snake and is divided into two equal parts of worst male and femal position and is represented by P_l^{worst} and P_o^{worst}, respectively.

4.6 Simplex Search Method

The simplex method of Nelder and Mead, uses the geometric properties of the n-dimensional space in an n-dimensional space (n_g+1) points forms a simplex. Intially, determine the worst snake agent $(P_{l_1 t})$, the best agent $(P_{l_2 t})$ and next to worst agent $(P_{l_3 t})$ from the initial set of snake agents. Compute the centroid (P_{ti}^C) of all snake agents, as defined below:

$$P_{ti}^C = \frac{1}{n_s}\sum_{k=1, k\neq l_1}^{n_s+1} P_{kti} \quad \left(i \in [1, n_g]; t \in [1, T]\right) \quad (25)$$

The new reflected agent, P_{ti}^{R}, is computed as follow:

$$P_{ti}^{R} = 2P_{ti}^{C} - P_{l_1 ti} \quad \left(i \in [1, n_g]; t \in [1, T]\right) \qquad (26)$$

The new position of snake is computed as given below:

$$P_{ti}^{N} = \begin{cases} y_1 P_{ti}^{C} - \alpha P_{l_1 ti} & ; F(P^R) < F(P_{l_2}) \\ y_2 P_{ti}^{C} - \gamma P_{l_1 ti} & ; F(P^R) \geq F(P_{l_1}) \\ y_3 P_{ti}^{C} + \gamma P_{l_1 ti} & ; F(P_{l_3}) < F(P^R) < F(P_{l_1}) \\ P_{ti}^{R} & ; otherwise \end{cases}$$

$$\left(i \in [1, n_g]; t \in [1, T]\right) \quad (27)$$

A better one is selected, and a new simplex is formed. The process can be terminated if no improvement is observed in the objective function.

$$\sqrt{\left[\sum_{k=1}^{n_s+1} \frac{\left(F(P_{kti}) - F(P_{ti}^{C})\right)^2}{n_s + 1}\right]} \leq \epsilon \qquad (28)$$

where $y_1 = (1+\alpha), y_2 = (1-\gamma), y_3 = (1+\gamma)$, is and ϵ the termination parameter close to zero.

Number of function evaluations can be computed as: $NFE = N_S + G^{max}(N_S + 2G_s^{max})$. The complexity order is 2.

5. RESULTS AND DISCUSSIONS

The proposed hybrid snake optimization (HSO) approach has been implemented to solve a complex real-world engineering problems in hydrothermal generation scheduling (HTGS). In the proposed HSO, Maximum iterations, G^{max} are taken 100 and Maximum iteration, for simplex, G_s^{max} are taken 250. Control parameters, C_1, C_2, C_3 are taken 0.5, 0.05 and 3, respectively. To validate the global solution when implementing HSO, a total of 30 independent trial runs are conducted.

Test System-HTS1: The hydrothermal test system, HTS1, deals with the scheduling of two thermal and two hydro units in a variable-head hydrothermal generation context, spanning a 24-hour period without accounting for valve point loading effects [12]. Table 1 provides a comparative analysis of the total operating costs achieved by HSO and existing techniques found in the literature, specifically PPO [12]. The results indicate that HSO incurs $391.12 less in total operating costs than PPO, and its standard deviation is also lower than SOA method. Detailed generation schedules for both thermal and hydro units and water discharge rates for hydro units are available in Tables 2 and 3, respectively. From Tables 2 and 3, the power balance equality constraint $|E_t^{PD}|$ is less than 0.0001 and the volume constraint $|\Delta V_j|$ is almost 0. Both power balance equality constraints and volume constraints are met, hence the solutions are feasible.

Table1: Comparison of results (total operating cost) for HTS1

Method	Operating fuel cost ($/hr)			
	Min	Avg	Max	SD
PPO[12]	68379.73	NA	NA	NA
SOA	67989.29	67994.85	68001.65	2.580913
HSO	**67988.61**	**67992.93**	67999.38	2.153047

Table3 Water discharge rate (m^3/h) of hydro units for HTS1

Interval t	Q_{1t}	Q_{2t}	Interval t	Q_{1t}	Q_{2t}
1	92.414	45.5852	13	135.310	125.26
2	81.700	33.5884	14	140.584	139.718

3	70.788	24.2296	15	138.111	137.454
4	71.7	27.3892	16	139.583	146.678
5	71.327	26.7304	17	151.420	156.094
6	77.345	33.2422	18	159.731	189.387
7	93.311	37.5101	19	145.955	153.376
8	109.52	74.6798	20	137.532	141.163
9	136.48	138.005	21	130.688	118.531
10	138.60	140.136	22	121.140	95.8491
11	148.22	164.324	23	105.513	79.5369
12	153.33	163.255	24	99.6641	58.2735
Computed Volume(m^3)				**2850.0**	**2450**
Available Volume, (m^3)				**2850. 0**	**2450**
Error in Volume $\|\Delta V_j\|$, (m^3)				**0**	**0**

Whiskers box plots for the hydrothermal test system HTS1 of SOA and HSO are shown in Fig. 1. SOA has three outliers and a large quartile, whereas HSO has one outlier and a smaller quartile. which depicts that HSO gives competing results over SOA and performs better. The convergence behaviour of SOA and HSO is depicted in Fig. 2. It is observed that the convergence of HSO is better than that of SOA.

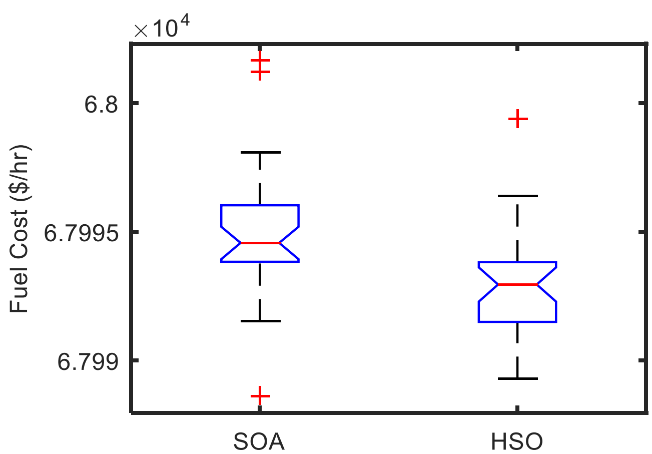

Fig. 1 Box plot for HTS1

The Wilcoxon signed-rank test is utilized to assess HTS1 systems. The findings reveal that the p-value acquired for HTS1 is 8.1200×10^{-04} which is statistically significant at a 5% significance level

Table 2: Total demand, transmission losses, thermal generation and hydro generation for HTS1

Interval t	P_t^D (MW)	P_t^{Loss} (MW)	Thermal generation (MW)		Hydro generation (MW)		$\|E_t^{PD}\|$ (MW)
			P_{1t}	P_{2t}	P_{3t}	P_{4t}	
1	800	22.34541	148.9333	349.1226	279.696	44.59339	7E-05
2	700	17.06078	138.9542	293.9328	251.4671	32.70661	6E-05
3	600	12.48562	122.0846	245.279	221.8102	23.31171	4E-05
4	600	12.52859	122.9435	238.7012	224.3765	26.50725	5E-05
5	600	12.51976	123.0883	240.1842	223.3949	25.85226	9E-05
6	650	14.68548	126.5023	265.8503	239.9279	32.4049	6E-05
7	800	22.36192	154.2752	348.9991	282.405	36.68248	7E-05
8	1000	35.4001	186.3705	452.2278	323.7801	73.02159	7E-05
9	1330	64.18528	237.2536	635.8605	389.1472	131.9239	8E-05

10	1350	66.2316	239.9974	647.9249	394.2587	134.0506	0.0001
11	1450	77.03507	260.9935	693.4947	416.7011	155.8456	9E-05
12	1500	82.77977	272.9733	726.089	428.5341	155.1833	8E-05
13	1300	61.20274	240.803	612.2086	386.9969	121.1942	7E-05
14	1350	66.23832	244.6971	637.4661	399.5113	134.5638	8E-05
15	1350	66.23627	241.4283	648.2123	393.8788	132.7168	8E-05
16	1370	68.39063	256.7586	642.8663	397.4752	141.2906	7E-05
17	1450	77.00815	260.669	691.3524	424.9806	150.0061	9E-05
18	1570	91.19235	281.5521	755.9092	443.9796	179.7514	6E-05
19	1430	74.79463	255.7301	688.1522	412.7806	148.1317	9E-05
20	1350	66.25828	246.0425	639.6293	393.3058	137.2806	9E-05
21	1270	58.24043	226.3741	608.082	377.2299	116.5543	0.00011
22	1150	47.29728	205.3919	542.3658	354.3106	95.229	3E-05
23	1000	35.38669	182.98	457.279	315.5661	79.56143	9E-05
24	900	28.45872	166.3414	402.7479	300.7232	58.64616	6E-05

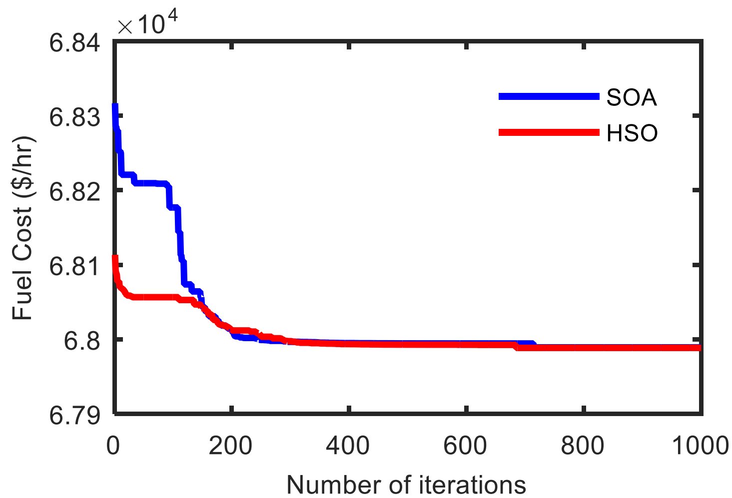

Fig. 2: Convergence graph for HTS1

6. CONCLUSIONS

This paper proposes a hybrid snake optimizer (HSO) to address the short-range variable head hydrothermal generation scheduling problem. The snake optimization algorithm is hybridized with the simplex search method to improve the performance of SOA by enhancing global solution accuracy, improving convergence rates, and avoiding premature convergence. An iterative repair approach is employed to manage the equality constraints, while a replacement method is employed to address the inequality constraints. The proposed HSO demonstrates a remarkable capacity to substantially decrease the overall operational expenses associated with thermal units. Specifically, it achieves the lowest cost among various heuristic techniques documented in the literature. The total saving in operating costs for 4 generating units is 391.12 $. A convergence curve is drawn to authenticate the results with a better convergence rate. A Wilcoxon signed-rank test has been performed to justify the robustness of HSO. Additionally, the proposed algorithm offers the potential for further customization through its integration with another nature-inspired algorithm.

The HSO is improved by the hybridization of the simplex search method with a basic snake optimizer. The HSO performs better in terms of rapid convergence, achieving the minimum operating cost value, and having the minimum standard deviation. The proposed HSO can be applied to solve practical problems like Speed Reducer Design, Welded Beam Design, Pressure Vessel Design, and Tension/ compression Spring Design.

7. ACKNOWLEDGMENTS

Our thanks to the institute for providing the resources and environment necessary to conduct this research.

REFERENCES

[1] Santos T.N., Diniz A.L., Lucia C., Borges T., A new nested benders decomposition strategy for parallel processing applied to the hydrothermal scheduling problem, IEEE Transactions Smart Grids 2017, 8 (3) 1504–1512.

[2] Zare K, Haque MT, Davoodi E. Solving non-convex economic dispatch problem with valve point effects using modified group search optimizer method. Electric Power Systems Research. 2012 Mar 1;84(1):83-9.

[3] Vieira, D. A. G.; Guedes, L. S. M. ;Lisboa, AC; Saldanha, RR. Formulations for hydroelectric energy production with optimality conditions. Energy Conversion and Management. 2015, v. 89, p. 781-788.

[4] Gouthamkumar N, Sharma V, Naresh R. Disruption-based gravitational search algorithm for short-term hydrothermal scheduling. Expert Systems with Applications. 2015 Nov 15;42(20):7000-11.

[5] Liaquat S, Fakhar MS, Kashif SA, Rasool A, Saleem O, Padmanaban S. Performance analysis of APSO and firefly algorithm for short term optimal scheduling of multi-generation hybrid energy system. IEEE Access. 2020 Sep 28; 8:177549-69.

[6] Wu Y, Wu Y, Liu X. Couple-based particle swarm optimization for short-term hydrothermal scheduling. Applied Soft Computing. 2019 Jan 1; 74:440-50.

[7] Nguyen TT, Vo DN. Modified cuckoo search algorithm for multi-objective short-term hydrothermal scheduling. Swarm and evolutionary computation. 2017 Dec 1; 37:73-89.

[8] Zeng X, Hammid AT, Kumar NM, Subramaniam U, Almakhles DJ. A grasshopper optimization algorithm for optimal short-term hydrothermal scheduling. Energy Reports. 2021 Nov 1; 7:314-23.

[9] Das S, Bhattacharya A, Chakraborty AK. Solution of short-term hydrothermal scheduling problem using quasi-reflected symbiotic organisms search algorithm considering multi-fuel cost characteristics of thermal generator. Arabian Journal for Science and Engineering. 2018 Jun;43(6):2931-60.

[10] Yaşar C, Özyön S. A modified incremental gravitational search algorithm for short-term hydrothermal scheduling with variable head. Engineering Applications of Artificial Intelligence. 2020 Oct 1;95:103845.

[11] Dhillon JS, Dhillon JS, Kothari DP. Real coded genetic algorithm for stochastic hydrothermal generation scheduling. Journal of Systems Science and Systems Engineering. 2011 Mar 1;20(1):87-109.

[12] Narang N, Dhillon JS, Kothari DP. Scheduling short-term hydrothermal generation using predator-prey optimization technique. Applied Soft Computing. 2014 Aug 1; 21:298-308.

[13] Hashim FA, Hussien AG. Snake Optimizer: A novel meta-heuristic optimization algorithm. Knowledge-Based Systems. 2022 Apr 22;242:108320.

[14] Khurma RA, Albashish D, Braik M, Alzaqebah A, Qasem A, Adwan O. An augmented Snake Optimizer for diseases and COVID-19 diagnosis. Biomedical Signal Processing and Control. 2023 Feb 17:104718.

[15] Al-Shourbaji I, Kachare PH, Alshathri S, Duraibi S, Elnaim B, Abd Elaziz M. An efficient parallel reptile search algorithm and snake optimizer approach for feature selection. Mathematics. 2022 Jul 5;10(13):2351.

[16] Feng ZK, Niu WJ, Zhou JZ, Cheng CT, Zhang YC. Scheduling of short-term hydrothermal energy system by parallel multi-objective differential evolution. Applied Soft Computing. 2017 Dec 1; 61:58-71.

[17] El-Hawary, ME, Ravindranath, KM (1988). Optimal operation of variable head hydrothermal systems using the Glimn-Kirchmayer model and the Newton-Raphson method. Electric power systems research. 1988, 14(1), 11-22.

Conflicts of Interest: The authors declare no conflict of interest.