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Article

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Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Tehzeeb-ul-Hassan; Alquthami, Thamer; Butt, Saad; Tahir, Muhammad Faizan; Mehmood, Kashif (2020) : Short-term optimal scheduling of hydro-thermal power plants using artificial bee colony algorithm, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, pp. 984-992,
<https://doi.org/10.1016/j.egy.2020.04.003>

This Version is available at:

<https://hdl.handle.net/10419/244095>

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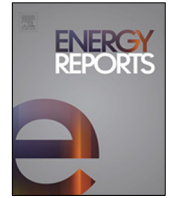
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Research paper

Short-term optimal scheduling of hydro-thermal power plants using artificial bee colony algorithm

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ARTICLE INFO

Article history:

Received 25 October 2019

Received in revised form 9 February 2020

Accepted 2 April 2020

Available online xxxx

Keywords:

Short-term scheduling

Hydro-thermal

Artificial bee colony algorithm coordination

ABSTRACT

This research paper reports the implementation of short-term scheduling of hydro-thermal power plants by using an artificial bee colony algorithm. Short-term hydro-thermal scheduling is a type of economic dispatch problem in which thermal power plants are dispatched at the optimized operating point to reduce the fuel cost and to achieve in parallel the maximum cost-benefit from hydel power plants. The power system, considered in this study, is assumed to run optimally and the transmission losses have also been taken into account. The artificial bee colony algorithm proves itself to be most suited for this particular problem as it results in the minimum cost in the shortest time compared with those obtained from previously applied techniques.

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1. Introduction

Hydro-thermal scheduling is an optimization problem in which the dispatch of hydel and thermal plants is accomplished to ensure that the fuel cost for thermal power plants is minimized (Hossain and Shiblee, 2017). Hydrothermal scheduling is a very vital issue in the power system operations and economics as the power system is mostly comprised of hydel and thermal power plants. Moreover, high costs of thermal power plants and intermittency of renewable energy sources (Tahir et al., 2019a,b) shift more focus towards hydro-thermal scheduling (Padmini et al., 2015).

For the short-term scheduling problem, the capacity of a hydro unit, the electrical load, hydraulic inflows at starting, discharge limits of a reservoir, and the reservoir volumes at starting and ending have to be known (Das et al., 2018). The functioning of a hydro-electric power system is based on the stability between the thermally generated power, hydro-electrically generated power and the electrical load. The economic operation and scheduling of a power system is a challenge because of ensuring water discharge to suit all hydraulic limitations and meeting the load

demand (Øyn Naversen et al., 2019). The short-term scheduling problem has already been implemented using different techniques which include Lagrange multiplier (Wood Allen et al., 1996; Rodrigues et al., 2012), gradient search approach (Zhang et al., 2017), evolutionary programming (Sinha and Lai, 2006; Hota et al., 1999), fast evolutionary programming (Sinha et al., 2003; Türkay et al., 2011), hybrid evolutionary programming (Nallasivan et al., 2006; Fang et al., 2014), simulated annealing (Wong and Wong, 1994; Wong, 2001), genetic algorithm (Sinha and Lai, 2006; Kumar and Mohan, 2011) and particle swarm optimization (Samudi et al., 2008; Yu et al., 2007).

However, aforementioned algorithms have different limitations such as infeasibility of the dual solution in case of Lagrange multiplier, low convergence rate and complexity in parameters setting in simulated annealing and slow convergence in multimodal optimization when dealing with evolutionary algorithms. Moreover, genetic algorithms suffer inferior search performance, particle swarm optimization faces premature convergence. To overcome the issues of the above deterministic and heuristic methods for short term hydrothermal scheduling, Artificial Bee Colony (ABC) algorithm is proposed in this work. This optimization technique is based on the foraging behaviour of the honey bee swarm (Karaboga and Akay, 2009) and outperforms the existing optimization techniques especially in terms of low execution time (Karaboga, 2005). ABC algorithm has already been used for different purposes such as training the feed-forward neural networks (Karaboga et al., 2007), optimal reactive power flow (Ayan

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and Kiliç, 2012), dynamic economic dispatch for units with valve-point effect (Hemamalini and Simon, 2011), and real and reactive power tracing in deregulated power systems (Sulaiman et al., 2012).

Moreover, this problem has been tried to be solved using a variant of particle swarm optimization, i.e. fully-informed particle swarm optimization in reference (Nayak et al., 2009). However, it has been mentioned with deep remorse that the implementation had a flaw in it which was not noticed. The main contributions of the paper are:

i. Hydro-thermal power plants economic scheduling is conducted in this study and transmission losses are also taken into account while determining the optimum solution.

ii. Thermal power plants are optimized in terms of reducing fuel cost while hydel power plants optimization proves to be cost-effective. This economic scheduling is carried out by using ABC algorithm

iii. Proposed algorithm comparison in finding least cost solution with other deterministic and heuristic techniques are made.

Rest of the paper is organized as follows. Section 2 elaborates ABC algorithm while Section 3 explains problem formulation by using the proposed algorithm. Section 4 demonstrates results discussion and Section 5 concludes the study.

2. Hydrothermal scheduling problem formation

Hydrothermal scheduling problem lies under the context of power system operation and control. In this problem, the ultimate goal is to dispatch the generating power of hydro and thermal power plants to the distribution centres so that the dispatch cost is minimized, which is primarily the fuel cost of the generating units. The objective function, to be minimized, is given by the following expression:

$$\min(f) = \sum_{n=1}^N F_n \quad (1)$$

where, n is interval. F_i is the operating cost of the i^{th} interval. In hydrothermal scheduling problem the water discharge rate is the main concern for the irrigation system. Therefore the water discharge constraint (q) considered is given by Eq. (2).

$$q_{\text{tot}} = \sum_{n=1}^N q_n \quad (2)$$

The second constraint is about the balancing of power generation between the load demand (P_{load}), transmission losses in the system (P_{loss}), Hydro power generation (P_{hydal}) and thermal power generation (P_{thermal}) which can be expressed as shown in Eq. (3).

$$P_{\text{load}} + P_{\text{loss}} = P_{\text{hydal}} + P_{\text{thermal}} \quad (3)$$

The hydropower generation losses are the function of the output power; $P_{\text{loss}}=f(P_{\text{hydal}})$ while the hydropower generation is the function of discharge rate for the i^{th} interval; $P_{\text{hydal}}=f(q_j)$. The discharge rate, thermal power plant and the hydro power plant must follow the following inequality constraints in the economic dispatch of the power system as expressed in Eq. (4).

$$\begin{cases} q_n \min \leq q_n \leq q_n \max \\ P_{\text{thermal},\min} \leq P_{\text{thermal},n} \leq P_{\text{thermal},\max} \\ P_{\text{hydal},\min} \leq P_{\text{hydal},n} \leq P_{\text{hydal},\max} \end{cases} \quad (4)$$

The first inequality in Eq. (4) represent water discharge limits, second inequality represent thermal power generation limits and the third inequality represents hydropower generation limits.

The volume of the water in the reservoir is a function of inflow rate, discharge rate and spillage rate in the i^{th} interval as follows.

$$V_n = V_{n-1} = (R_n - q_n - S_n) \quad \text{where } V_{n\min} < V_n < V_{n\max} \quad (5)$$

where, V_i , R_i , q_i and S_i represents inflow rate, discharge rate and spillage rate in the i^{th} interval respectively.

The main goal is to minimize the generation cost of hydrothermal power plants along with the fulfilment of hydro and thermal generating units constraint as described above.

3. Artificial bee colony algorithm

The ABC algorithm is based on the foraging behaviour of the honey bee swarm. There are three important components of the foraging selection as described in reference (Karaboga and Akay, 2009).

3.1. Food source

The richness and concentration of energy of the food source describe the value of it.

3.2. Employed foragers

The bees associated with a particular food source are called employed foragers. These foragers have information about the location and value of the food source.

3.3. Unemployed foragers

These bees are on the look for a food source and are stationed at the hive and are of two types; scouts and onlooker bees.

The exchange of information about the value and location of the food source is done at the dancing area of the hive. The onlooker bee at the dancing area selects the food source based on the highest probability of the value and goes to it. If the new food source is rich in value more than the previous one, the new food source is saved in the onlooker bee's memory. This is the greedy selection. The scout bee, on the other hand, waits so that an employed bee abandons a food source and becomes an unemployed bee. This scout bee then goes out and searches for a new food source. In an ABC algorithm the bees employ four different selection processes, as mentioned in Karaboga and Akay (2009):

- (1) A global probabilistic selection process (used by onlooker bee)
- (2) A local probabilistic selection process (used by employed and onlooker bees)
- (3) Greedy selection process (also used by employed and onlooker bees)
- (4) Random selection process (used by scouts)

4. Solution of hydrothermal scheduling problem using ABC algorithm

In this section, the process to solve the hydro-thermal problem in Section 2, using the ABC algorithm, is discussed in details. For solving the short-term scheduling problem a single equivalent thermal plant and also a single equivalent hydro plant are considered.

4.1. Constraints of hydro-thermal generation systems

- (1) Constraint for balancing power

The total power generated including hydal and thermal must be equal to the sum of the load (P_L) and the losses (P_{LOSS}) in the system (transmission lines), also called equality constraint (Nayak et al., 2009) as expressed in Eq. (6).

$$\sum_{i=1}^N P_i = P_{\text{hydal}} + P_{\text{thermal}} = P_{\text{load}} + P_{\text{loss}} \quad (6)$$

(2) Constraints for thermal generation units

The power from a thermal generator unit is limited between upper power limit (generally the rated power) and lower power limit (needed for stable boiler operation). These are inequality constraints which are shown in Eq. (7).

$$P_{thermal,min} \leq P_{thermal,i} \leq P_{thermal,max} \tag{7}$$

(3) Constraints for hydro generation unit

The scheduling of hydro generation has four controlling parameters as listed below.

(a) Water discharge in an interval

The water discharge rate in an interval is also characterized by the maximum ($q_{n,max}$) and minimum ($q_{n,min}$) limits at the end of the interval

$$q_{n,min} \leq q_n \leq q_{n,max} \tag{8}$$

(b) Volume of the reservoir

The volume of a reservoir has also upper ($V_{n,max}$) and lower ($V_{n,min}$) limits, also an inequality constraint

$$V_{n,min} \leq V_n \leq V_{n,max} \tag{9}$$

(c) Hydropower produced in the interval

This is the constraint which tells us about the maximum ($P_{n,max}$) and minimum ($P_{n,min}$) power that can be produced in an interval

$$P_{n,min} \leq P_n \leq P_{n,max} \tag{10}$$

(d) Total load

This is the description of total load (P_{Ln}) in an interval which is defined at the start of problem formulation.

The proposed implementation of the hydro-thermal scheduling problem through ABC algorithm uses the discharge rate per interval as the controlling parameter for the algorithm and fine-tunes the controlled parameter. ABC algorithm fine-tunes more than one solution simultaneously to avoid local optima and to provide truly divergent solutions. The total population of bees is given by N_p . At a particular time, half the bees are the employed bees while the other half are onlooker bees and is given as $\frac{N_p}{2}$. The number of simultaneous solutions is equal to $\frac{N_p}{2}$.

Let the set of simultaneous solutions be represented by Q_c and shown in Eq. (11).

$$Q_c = \begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_{\frac{N_p}{2}} \end{pmatrix} \tag{11}$$

A single solution of Q_c is represented as an individual M-dimensional vector Q_n expressed in Eq. (12).

$$Q_n = \{q_{n1}, q_{n2}, \dots, q_{nm}\} \tag{12}$$

Here n represents the solution number or the bee number as represented in Eq. (13)

$$n = \left\{ 1, 2, \dots, \frac{N_p}{2} \right\} \tag{13}$$

m is the number of parameters of the solution. In this specific case, M will represent the number of intervals given in the problem. A single parameter of Q_n will be given as q_{nm} where m represents the parameter number or interval number as expressed in Eq. (14).

$$m = \{1, 2, \dots, M\} \tag{14}$$

4.2. Initialization

In the initialization phase, the first step is the initialization of collection Q_c . The initialization process for each vector Q_n is carried out in a sequential manner starting from the first dimension using Eq. (15).

$$q_{nm} = \text{unif}(q_{nmMin}, q_{nmMax}) \tag{15}$$

$\text{unif}(a_{nm}, b_{nm})$ represents a continuous uniform probability distribution of the random variable q_{nm} between q_{nmMin} and q_{nmMax} as shown in Eqs. (16) and (17).

$$q_{nmMin} = \max(q_{nmMinH}, q_{nmMinT}, q_{nmMaxV}) \tag{16}$$

$$q_{nmMax} = \min(q_{nmMaxH}, q_{nmMaxT}, q_{nmMinV}) \tag{17}$$

q_{nmMinH} is the minimum discharge required by a hydel plant to fulfil its power constraints. It can be represented as in Eq. (18):

$$q_{nmMinH} = a + b * Ph_{min} \tag{18}$$

where, a and b are the hydel plant's constants and Ph_{min} is the minimum power constraint of the plant.

q_{nmMinT} is the minimum discharge required by a thermal plant to fulfil the power requirements. It can be represented as shown below:

$$q_{nmMinT} = a + b * Ph_{minReq} \tag{19}$$

Ph_{minReq} is the minimum hydel power required for the load in that interval and is represented in Eq. (20).

$$Ph_{minReq} = Pl_m + Ploss_m - Pt_{max} \tag{20}$$

$Ploss_m$ are the transmission losses in the m th interval, Pl_m is the load in m th interval and Pt_{max} is the maximum producible thermal power.

q_{nmMaxV} is the discharge required to ensure that the reservoir does not violate its maximum volume constraint. This can be represented as demonstrated in Eq. (21).

$$q_{nmMaxV} = V_s - \sum_{e=1}^{m-1} q_{ne} + \sum_{f=1}^m i_{nf} - V_{max} \tag{21}$$

where, V_s is the start volume of the reservoir, i_{nf} is the inflow in f th interval and V_{max} is the maximum bound of the reservoir.

In Eq. (22), q_{nmMaxH} is the maximum discharge required by the hydel plant to fulfil its power constraints.

$$q_{nmMaxH} = a + b * Ph_{max} \tag{22}$$

where, Ph_{max} is the maximum power constraint of a hydel power plant.

q_{nmMaxT} is the maximum discharge required by a thermal plant to fulfil the power requirements as expressed in Eq. (23).

$$q_{nmMaxT} = a + b * Ph_{maxReq} \tag{23}$$

where, Ph_{maxReq} is the maximum hydel power required for the load in that interval and is represented as

$$Ph_{maxReq} = Pl_m + Ploss_m - Pt_{min} \tag{24}$$

where, Pt_{min} is the minimum thermal power producible.

q_{nmMinV} is the discharge required to ensure that the reservoir does not violate its minimum volume constraint as represented in Eq. (25).

$$q_{nmMinV} = V_s - \sum_{e=1}^{m-1} q_{ne} + \sum_{f=1}^m i_{nf} - V_{min} \tag{25}$$

V_{min} is the minimum bound of the reservoir.

The second step is the evaluation of the cost of each solution and finding the minimum cost. For this process, we define C_n as the cost of the n th solution. The cost is calculated by Eq. (26).

$$C_n = c + d * Pt_{nm} + e * Pt_{nm}^2 \tag{26}$$

where, Pt_{nm} and Ph_{nm} can be computed as:

$$Pt_{nm} = Pl_{nm} + Ploss_{nm} - Ph_{nm} \tag{27}$$

$$Ph_{nm} = \frac{q_{nm} - a}{b} \tag{28}$$

The successive unsuccessful tries for a solution is represented as T_n and is initialized to zero. The maximum number of successive failed tries for a solution is represented as T_{Max} .

4.3. Employed bee:

In this phase, a new random process P is created as:

$$P = (X_1, X_2) \tag{29}$$

where, X_1 and X_2 are both discrete random variables with uniform distribution.

$$X_1 \in \{1, 2, \dots, M\} \tag{30}$$

And has the probability,

$$P(X_1) = \frac{1}{M} \tag{31}$$

Also,

$$X_2 \in \{1, 2, \dots, M\} \tag{32}$$

And has the probability,

$$P(X_2) = \begin{cases} \frac{1}{M-1} & \text{if } X_2 \neq X_1 \\ 0 & \text{else} \end{cases} \tag{33}$$

The second step is to evaluate new values for each solution. We represent the new solutions as Q'_n and is the same type as Q_n . Only two parameters will be adjusted in this phase so that the total discharge is not affected. These parameters are taken as X_1 and X_2 . It can be represented as represented in Eq. (34).

$$q'_{nm} = \begin{cases} q_{nm} + Y & \text{if } m = X_1 \\ q_{nm} - Y & \text{if } m = X_2 \\ q_{nm} & \text{else} \end{cases} \tag{34}$$

Y is a continuous random variable with uniform distribution, $q_{nX_1} + Y$ and $q_{nX_2} + Y$ have the constraints defined in Eqs. (11) and (12).

The next step is to evaluate the cost of the new solutions. The cost is defined as shown in Eq. (35).

$$C'_n = c + d * Pt'_{nm} + e * Pt'^2_{nm} \tag{35}$$

where, Pt'_{nm} can be computed the same way as in Eq. (27).

In the next step, we will replace those solutions which have improved and increment the number of successive unsuccessful tries on the others.

$$Q_n = \begin{cases} Q'_n & \text{if } C'_n < C_n \\ Q_n & \text{else} \end{cases} \tag{36}$$

and,

$$T_n = \begin{cases} 0 & \text{if } C'_n < C_n \\ T_n + 1 & \text{else} \end{cases} \tag{37}$$

Next the probability of each solution is computed as under:

$$P(Q_n) = 1 - \frac{C_n}{\sum_{l=1}^{\frac{Np}{2}} C_n} \tag{38}$$

Table 1
Load pattern of three days.

Time (Days)	Time (Hours)	Load (MW)
Day one	2400 hr–1200 hr	1200 MW
	1200 hr–2400 hr	1500 MW
Day two	2400 hr–1200 hr	1100 MW
	1200 hr–2400 hr	1800 MW
Day three	2400 hr–1200 hr	950 MW
	1200 hr–2400 hr	1300 MW

4.4. Onlooker bee:

Onlooker bee works on positive feedback so the greater the probability of a solution the greater is the chance that the onlooker bee will be attracted to it. To model this behaviour a new random variable Z is introduced and can be described as represented in Eq. (39).

$$Z = unif(0, 1) \tag{39}$$

Eq. (39) describes Z as a continuous random variable with a uniform distribution between 0 and 1. If Z is lower than the probability of the solution than it will be reevaluated for improvement otherwise this phase will be skipped for that solution. In this phase, from Eqs. (29)–(37) will be reapplied for improvement.

4.5. Scout bee:

If a bee has reached the limit T_{max} , it would abandon its previous solution and would search for a new solution. The process of selecting a new solution will be the same as described in Eqs. (15) through (28). If the new solution is better than the previous one the bee will cling to the new solution.

After the scout bee phase, the best solution (the one having the highest probability) will be saved as the global minimum for the collection.

The whole process from the employed bee will be repeated over and over again until the stopping criteria is fulfilled.

4.6. Stopping criteria:

The algorithm will stop if the maximum number of iterations criteria is achieved which is started from zero and is incremented after each cycle. Once the stopping criterion is achieved the most optimum solution will be displayed as shown in Pseudocode (given below) and flowchart (Fig. 1).

1. Calculate maximum and minimum possible change in reservoir volume per interval, ΔV_{Max} and ΔV_{Min} .
2. Initialize foods with random values such that each value is between ΔV_{Max} and ΔV_{Min} , and the volume for interval is between minimum and maximum reservoir volume, V_{Min} and V_{Max} .
3. Initialize the number of employed bees N , and the number of maximum unsuccessful iterations for individual bee P .
4. While (iterations < i).
5. For all foods (food number < N).
6. Select the solution associated with the particular food number and randomly change two of its parameters such that the reservoir constraints are not violated.
7. Evaluate the cost of the new solution.
8. If the cost of a new solution is smaller than the last solution replacing the previous solution with the new one else increment the number of unsuccessful iterations for the solution.
9. End for.

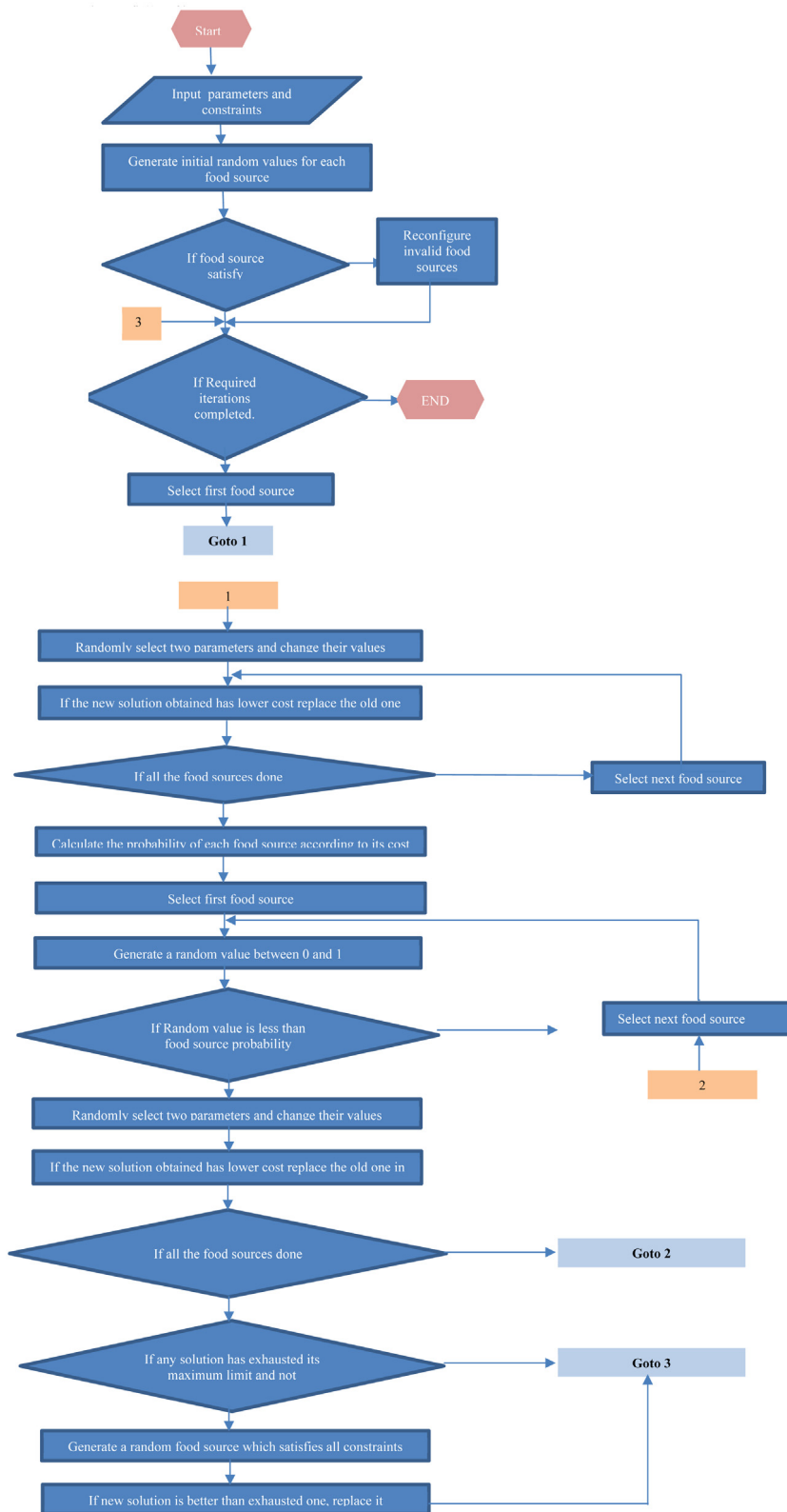


Fig. 1. Flowchart of the proposed ABC algorithm.

- 10. Calculate the probability for each food source. $p = (1 - \frac{\text{cost}}{\text{total cost}})$.
- 11. For N times.
- 12. Select a random number within 0 and 1.

- 13. If the number selected randomly is smaller to the probability of the food source reevaluate the food source the same way as in employed bee phase else skip the iterations.
- 14. End for.
- 15. For N times.

Table 2
Results for MCN = 10.

Intervals	Volume of reservoir (acre ft)	Discharge of water (acre ft/h)	Total load (MW)	Hydel power (MW)	Thermal power (MW)	Cost (\$)
1	101528.0	1872.66	1200	310.39	889.60	693798.8
2	77604.57	3993.61	1500	737.14	762.85	
3	101604.6	0	1100	0	1100.0	
4	60871.91	5394.38	1800	1018.99	781.00	
5	84871.91	0	950.0	0	950.00	
6	60000.00	4072.65	1300	753.05	546.94	

Table 3
Results for MCN = 100.

Intervals	Volume of reservoir (acre ft)	Discharge of water (acre ft/h)	Total Load (MW)	Hydel power (MW)	Thermal power (MW)	Cost (\$)
1	96151.70	2320.69	1200	400.54	799.45	693431.1
2	75259.06	3741.05	1500	686.32	813.67	
3	99259.06	0	1100	0	1100.0	
4	60010.03	5270.75	1800	994.11	805.88	
5	84010.03	0	950.0	0	950.00	
6	60000.00	4000.83	1300	738.59	561.40	

Table 4
Results for MCN = 250.

Intervals	Volume of reservoir (acre ft)	Discharge of water (acre ft/h)	Total load (MW)	Hydel power (MW)	Thermal power (MW)	Cost (\$)
1	96598.68	2283.44	1200	393.04	806.95	693427.10
2	75249.22	3779.12	1500	693.98	806.01	
3	99249.22	0	1100	0	1100.0	
4	60000.00	5270.76	1800	994.11	805.88	
5	84000.00	0	950.0	0	950.00	
6	60000.00	4000.00	1300	738.43	561.56	

The minimum value found out to be \$ 693427.10.

Table 5
Comparison of results with previous techniques.

Sr. no.	Authors	Optimization technique	Minimum cost (\$)
1	A.J. Wood [1]	Gradient Method	709877.38
2	N. Sinha et al [3]	Fast Evolutionary Programming	709862.05
3	W.K. Patel [5]	Simulated Annealing	709874.36
4	N. Sinha et al [2]	Genetic AF	709863.70
5	N. Sinha et al [2]	Classical EP	709862.65
6	N. Sinha et al [2]	Fast EP	709864.59
7	N. Sinha et al [2]	Particle Swarm Optimization	709862.048
8	D.S. Suman et al [4]	Hybrid Evolutionary Programming	703180.26
9	Samudi et al [6]	Particle Swarm Optimization	696002.30
10	This Study	Artificial Bee Colony Algorithm	693427.10

Table 6
Stochastic results of PSO (Samudi et al., 2008).

Max. cost (\$)	Min. cost (\$)	Avg. cost (\$)	Avg. time (s)
706817.96	693428.5	696002.3	13.343

16. If the number of unsuccessful iterations is equal to or greater than the maximum number of unsuccessful iterations get an entirely new solution and replace the exhausted one.
17. End for.
18. Save the minimum cost and its parameters.
19. Increment iteration number.
20. End while.

5. Results

The problem used for implementation of the short-term scheduling is given below.

Equivalent steam system:

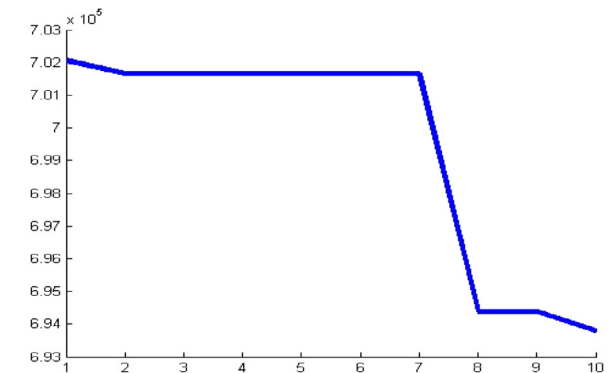


Fig. 2. Cost vs. cycle number curve for MCN = 10.

$$H = 500 + (8.0 \times P_{thermal}) + (0.0016 \times P_{thermal}^2) \text{ (MBtu/h)}$$

Fuel cost = 1.15 (\$/MBtu)
 Min power = 150 MW
 Max power = 1500 MW

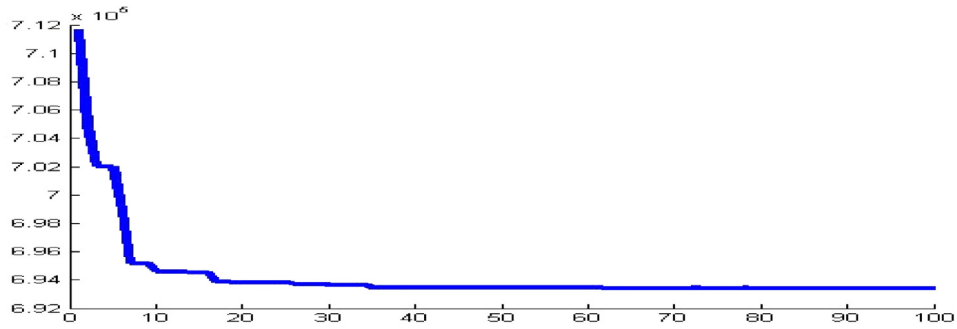


Fig. 3. Cost vs. cycle number for MCN = 100.

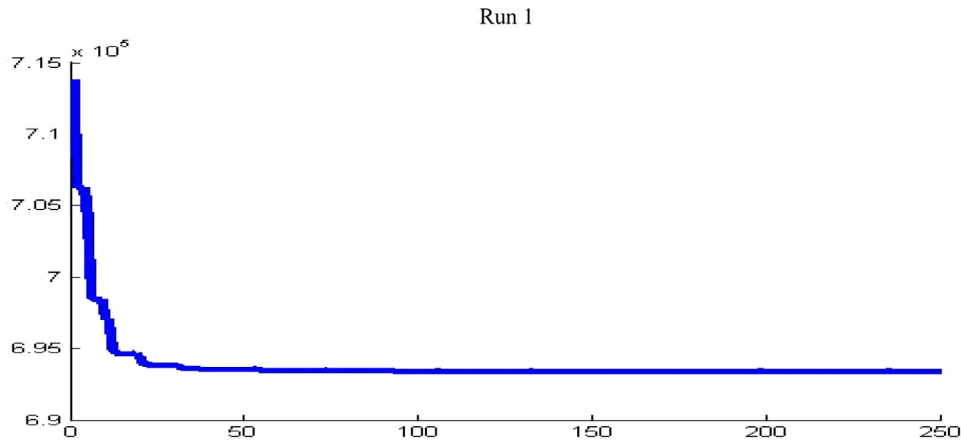


Fig. 4. Results for MCN=250 (run1).

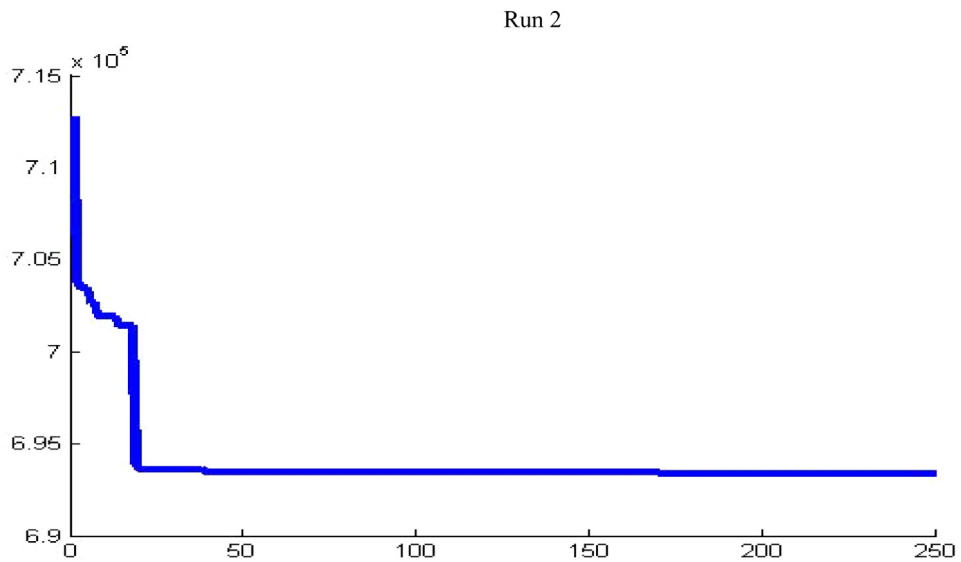


Fig. 5. Results for MCN = 250 (run 2).

Table 7
Stochastic results of this study using ABC algorithm.

Max. cost (\$)	Min. cost (\$)	Avg. cost (\$)	Max. time (s)	Min. time (s)	Avg. time (s)
693427.1	693427.1	693427.1	0.37288	0.36733	0.3701

Hydro plant system:

$$q = 330 + (4.97 \times P_{hyadal}) \text{ acre.ft/h}$$

Min power = 0
 Max power = 1000 MW
 Load pattern is given in Table 1.

Hydro-reservoir:

1. Starting volume 100,000 acre-ft.
2. Ending volume 60,000 acre-ft.
3. Volume of reservoir limited to:

a Lower limit : 60000 acre.ft

Table 8

Results for MCN = 250 considering transmission losses.

Intervals	Volume of reservoir (acre ft)	Discharge of water (acre ft/h)	Total load (MW)	Hydel power (MW)	Thermal power (MW)	Losses (MW)	Cost (\$)
1	96598.68	2283.44	1212.35	393.04	806.95	12.35	693433.60
2	75249.22	3779.12	1538.52	693.97	806.02	38.52	
3	99249.22	0	1100	0	1100	0	
4	60000	5270.76	1879.09	994.10	805.89	79.05	
5	84000	0	950	0	950	0	
6	60000	4000	1343.61	738.41	561.58	43.62	

b Upper limit : 120000 acre.ft

4. An inflow stream of 2000 acre-ft/h into the reservoir for the whole period.

Now, consider the parameters of ABC algorithm.

Population of bees = 50

Limit = 200.

5.1. For maximum cycle number (MCN) = 10

The cost vs. MCN curve and resultant values are shown in Fig. 2 and Table 2.

5.2. For maximum cycle number (MCN) = 100

The curve and values are given in Fig. 3 and Table 3.

MCN = 250

The results are shown in Figs. 4, 5 and Table 4

This clarifies that the answer converges at the minimum cost of running thermal plants to meet the load (Table 4)

5.3. Comparison with previous (research) results

Table 5 gives a comparison of the results of this study and those of the previous research, obtained by other techniques.

As it is clear that the proposed ABC algorithm is much better than the techniques already used. Now let us compare the results of previous best technique, particle swarm optimization, with the ABC algorithm to check for run time. Table 6 shows the scholastic results of PSO.

Now, run stochastic test on ABC algorithm: the results are shown in Table 7.

Considering transmission losses, which is considered as a function of the hydropower as in reference (Hossain and Shiblee, 2017), $P_{LOSS} = 0.00008 \times P_h^2$. The curve for MCN = 250 and the respective values of the scheduling are shown in Fig. 6 and Table 8.

The stochastic test results are shown in Table 9.

6. Conclusion

In this work, the ABC algorithm is employed for the short-term hydro-thermal scheduling problem. Inspired by observing the amazing behaviour of honey bees for gathering food, the application of ABC algorithm proves to be the best solution to the short-term scheduling problem. The transmission losses have also been considered for finding a realistic optimum solution. By employing the suggested technique, the results demonstrate that the running cost of the thermal power plants is considerably lower than those calculated by previous researchers using other techniques. Moreover, after careful consideration and comparison with other techniques, it has also been found that the average time for the search of the optimum solution is the least. The proposed technique demonstrates the highest convergence speed.

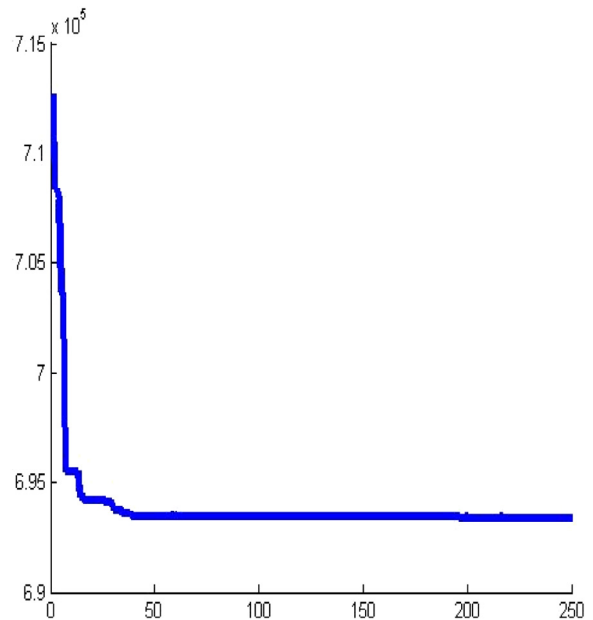


Fig. 6. Results for MCN = 250 considering transmission losses.

Table 9

Stochastic Test results considering transmission losses.

Max. cost (\$)	Min. cost (\$)	Avg. cost (\$)	Max. time (s)	Min. time (s)	Avg. time (s)
693433.60	693433.60	693433.60	0.41884	0.3736	0.39622

CRedit authorship contribution statement

Saad Ehsan Butt, Muhammad Faizan Tahir and Kashif Mehmood did the simulation work and wrote the manuscript. Thamer Alquthami provides funding acquisition. Tehzib-ul-Hassan supervise the project and proofread the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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