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A Study on Comparison between Thermal and Hydro-thermal ELD Using Metaheuristics Technique

Dipankar Santra[1], Anirban Mukherjee[2] and Subrata Mondal[3]

ABSTRACT

This paper presents for the first-time, application of Moth Flame Optimization and Bat Algorithm (MFO-BA) for optimal scheduling of thermal and hydro-thermal systems in a simulated environment. Results of three test systems (4-unit, 5-unit and 6-unit) comprising seven test cases as different combinations of fixed-head hydro units and thermal units with and without losses are presented to demonstrate the performance of the hybrid MFO-BA algorithm. The test results comprehensively establish the advantage and overall effectiveness of the hydro-thermal system over thermal-only system in terms of load dispatch and economy of generation cost and transmission loss. The present study can help find the most economic scheduling of hydro-thermal generating units using hybrid soft computing approach.

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1. INTRODUCTION

'Economic hydro-thermal load dispatch' is an optimization problem of electrical power generation systems where both hydro-power and thermal-power units are used to meet power demand. Proper scheduling of power generation is necessary with optimal combination of hydro and thermal power units to satisfy a given load. Fossil fuel becoming costlier day by day, it is high time to use renewable energy sources like flowing water or wind for cheaper generation of power. Operating cost of hydro-power units is significantly low compared to the that of the thermal-power units. On the other hand, availability of water, which is the source of hydro-power, is likely to suffer seasonal variation (water level depletion during summer time). Therefore, a hybrid system like hydro-thermal is a realistic solution that can keep the generation level steady irrespective of geo-climatic conditions.

A hydro-thermal system is, however, technically more complex in comparison to an all-thermal system owing to additional water-related constraints; to name a few are the time coupling effect of the flow of water in a predefined time interval that affects the discharge capability at a later period of time, the cascaded nature of the hydraulic network, the physical limitations on the reservoir storage and turbine flow rate and the varying hourly reservoir inflows.

This paper focuses on how economic hydro-thermal load dispatch approach can be applied to minimize the thermal operating cost, balancing the hydro-power generation in tandem with managing the different constraints of water during a given period of operation. The authors highlight the comparison between thermal and hydro-thermal economic dispatch problems. Typical case study of thermal and hydro-thermal systems with a total of four, five and six number generating units, is done in a simulated environment to show the efficacy of real-time power generation in a hybrid mode.

In the simplest form, the cost function of 'economic load dispatch (ELD)' problem is represented by a smooth quadratic equation, which is continuous and differentiable in nature [1]. Several classical methods, e.g., Newton's method, gradient method, dynamic programming (DP) method [2] have been widely used to solve hydro-thermal scheduling problems. Among these methods, DP appears to be the most popular one. However, one major disadvantage of the classical methods is the drastic increase of computational requirements and dimensional constraints with in-

[1,2] The authors are the Department of EE and IT, RCC Institution of Information Technology, Kolkata, West Bengal, India, E-mail: santra.dipankar@gmail.com, anirbanm.rcciit@gmail.com
[3] The author is the Department of PE Jadavpur University, Kolkata, West Bengal, India, E-mail: sub.mondal@gmail.com
[1] Corresponding author: santra.dipankar@gmail.com

creasing system size and operational time. Stochastic search algorithms such as Differential Evolution (DE) [3], Modified Differential Evolution [4], Genetic Algorithm (GA) [5], Moth-Flame Optimization (MFO) [6] and Artificial Bee Colony (ABC) with the BAT algorithm (ABC-BAT) [7] have been successfully used lately to solve thermal and hydro-thermal scheduling problem, though each method has shown its deficiency in terms of either premature convergence or stagnation.

After studying and experimenting with several hybrid algorithms previously applied by the present authors and other researchers in economic load dispatch of thermal power generation systems, the authors have finally selected the Moth Flame Optimization-Bat Algorithm (MFO-BA) and applied a customized version of it for optimal scheduling of a hydro-thermal system. In this application, fixed-head hydro plants are considered whose water discharge rate curves are formed as quadratic functions of the hydro-generations; thermal units are considered with smooth fuel cost function (no valve point loading effect) and the scheduling period is divided into four numbers of subintervals, each having a particular load demand.

The primary motivation behind conducting this study is the fact that not many experiments concerning ELD of hydro-thermal power system using hybrid soft computing approach are documented in the literature compared to that done for thermal power system. In real world scenario, where natural resources like fossil fuel is scarce and water availability varies with geo-climatic conditions, dynamic switching between thermal and hydro-thermal systems is necessary at different times of the year (even at different times of the day). Hence, different combinations of thermal and hydro units need to be checked for optimum scheduling, which has been taken up in this study. Synergistic integration of two of the most modern soft computing methods namely, MFO and BA has been done and subsequently applied in a relatively simple hydro-thermal system in expectation of exciting results. It is found that the individual soft computing methods, in hybrid mode, do not behave in conflicting manner but rather behave complimentary to one another and thus produce very good results in terms of load scheduling and generation cost and time as expected. The hybrid method successfully mitigates many of the challenges of classical optimization techniques and stochastic search algorithms.

The proposed MFO-BA method is validated by applying it to three test cases with involvement of total four, five and six number generating units, each having different combinations of hydro and thermal units as listed below.

Test Case 1: 4-unit system without transmission loss

i) 4-unit thermal power system
ii) 3-unit thermal with 1-unit hydro-power system (combined)

Test Case 2: 5-unit system with transmission loss

i) 5-unit thermal power system
ii) 3-unit thermal with 2-unit hydro-power system (combined)

Test Case 3: 6-unit system with transmission loss

i) 6-unit thermal power system
ii) 4-unit thermal with 2-unit hydro-power system (combined)
iii) 3-unit thermal with 3-unit hydro-power system (combined)

The Rest of this paper is organized as follows. In Section 2 the basic ELD problem formulation is discussed along with various linear and non-linear constraints. Section 3 briefly highlights the basic features of Moth Flame Optimization (MFO) and Bat Algorithm (BA). This section also describes the customized hybrid algorithm MFO-BA applied in the present study. In Section 4, the results of simulation experiments for three different test cases (including seven sub-test cases) are presented in details with data tables and graphs and finally the comparison of results for different power demand conditions is put up. The overall result analysis is discussed in Section 5. The paper is concluded in Section 6 with the achievement, limitation and future scope of the present study.

2. ELD PROBLEM FORMULATION

Hydro-thermal scheduling problem with N_H number of hydro units and N_T number of thermal units over M time intervals is described under 2.1 through 2.3:

2.1 Model for Thermal Generation:

The problem here is to minimize the fuel cost function. The total fuel cost function F for thermal power plant, is expressed as a quadratic function as shown in Eq. (1).

$$F = \sum_{m=1}^{M} \sum_{i=1}^{N_T} t_m \left[a_{T_i} + b_{T_i} P_{T_{im}} + c_{T_i} P_{T_{im}}^2 \right] \tag{1}$$

where a_{T_i}, b_{T_i} and c_{T_i} denotes cost coefficients of the i^{th} thermal unit. $P_{T_{im}}$ is the actual power output of the i^{th} thermal unit during subinterval m subject to the following constraints.

■ **Power Balance Constraints:**

$$\sum_{i=1}^{N_T} P_{T_m} - P_{D_m} - P_{L_m} = 0 \qquad m \in M \quad (2)$$

where P_{T_m} is actual power output of the i^{th} thermal unit during subinterval m. P_{D_m} is the load demand during subinterval m and P_{L_m} is power loss during subinterval m.

$$P_{L_m} = \sum_{l=1}^{N_H+N_T} \sum_{r=1}^{N_H+N_T} P_{l_m} B_{l_r} P_{r_m} \qquad m \in M \quad (3)$$

P_{L_m} is the transmission loss during subinterval m. B_{l_r} is the set of loss coefficients.

■ **Generation Limits:**

$$P_{T_i}^{\min} \leq P_{T_{im}} \leq P_{T_i}^{\max} \qquad i \in N_T, m \in M \quad (4)$$

where $P_{T_i}^{\max}$ and $P_{T_i}^{\min}$ are respectively the upper and lower limits of generation of the i^{th} thermal unit.

2.2 Model For Hydro Generation:

In hydro-power generation model, fuel cost is not related to power generation. As per Glimn-Kirchmayer model [8,9], input or output characteristics of a hydro-power generating unit are formulated by the rate of water discharge, which is expressed in terms of effective (reservoir's) water head and active power output in Eq. (5).

$$Q_j(t) = \eta\psi(h_j)\phi(P_{Hj}(t)) \quad (5)$$

where $Q_j(t)$ is the rate of water discharge for the j^{th} reservoir at time t, $P_{Hj}(t)$ is the hydro-power generated by the j^{th} unit at time t.
ψ , ϕ are independent functions, and η is the constant of proportionality.
For a fixed-head reservoir, where the effective head is considered constant, the function $\psi(h_j)$ is constant, and hence, Eq. (5) becomes:

$$Q_j(t) = \eta(h_j)\phi(P_{Hj}(t)) \quad (6)$$

For the scheduling period, the quantity of water accessible by each hydro-power unit is bound by a particular quantity V_j:

$$\int_0^T Q_j(t)dt = V_j \quad (7)$$

The objective function F_j is characterized by Eq. (8) and is subject to several constraints, the description of which follows in Section 2.2.1.

$$F_j\left(P_{H_{jm}}\right) = a_j P_{H_{jm}}^2 + b_j P_{H_{jm}} + c_j \quad (8)$$

$P_{H_{jm}}$ is the actual power output of j^{th} hydro-power unit during subinterval m.

2.2.1 Constraints

■ **Load Balance Equation:**

The total power generated must meet the total load demand including the transmission loss $P_L(t)$ beyond the scheduling period $P_D(t)$. This is expressed by the equality constraint i.e., Eq. (9)

$$\sum_{j=1}^{N_H} P_{H_{jm}} - P_{D_m} - P_{L_m} = 0 \qquad m \in M \quad (9)$$

where $P_{H_{jm}}$ is actual power output of the j^{th} hydro unit during subinterval m.

■ **Generation limits:**

$$P_{H_j}^{\min} \leq P_{H_{jm}} \leq P_{H_j}^{\max} \qquad j \in N_H, m \in M \quad (10)$$

Here $P_{H_j}^{\min}$ and $P_{H_j}^{\max}$ are respectively the lower and upper generation limits of j^{th} hydro unit.

■ **Water availability:**

$$\left[\sum_{m=1}^{M} t_m (a_{H_j} P_{H_{jm}}^2 + b_{H_j} P_{H_m} + c_{H_j})\right] - W_{H_j} = 0 \qquad j \in N_H \quad (11)$$

Here a_{H_j}, b_{H_j} and c_{H_j} are the coefficients for water discharge rate function of the j^{th} hydro unit. W_{H_j} is the predetermined volume of water availability for power generation by the j^{th} hydro unit during the scheduling period.

2.3 Model For Hydro-Thermal Generation:

The combined objective function is given by Eq. (12).

$$F_{HT} = \sum_{k=1}^{M_m} \sum_{i=1}^{N_{HT}} n_m F_i(P_{HT_i}) \quad (12)$$

■ **Capacity Limits:**

The maximum and minimum powers of the thermal and hydro units are represented as boundary constraints given by inequality (13) & (14).

$$P_{Ti}^{\min} \leq P_{Ti}(t) \leq P_{Ti}^{\max}(t) \quad (13)$$

$$P_{H_j}^{\min} \leq P_{H_j}(t) \leq P_{H_j}^{\max}(t) \quad (14)$$

where, $P_{Ti}^{\min}$= minimum power generation for the i^{th} thermal unit
$P_{Ti}^{\max}$ = maximum power generation for the i^{th} thermal unit
$P_{H_j}^{\min}$ = minimum power generation for the j^{th} hydro unit

$P_{H_j}^{\max}$ = maximum power generation for the j^{th} hydro unit

■ **Transmission Losses:**

The transmission power loss is expressed by the Kron's B-coefficients loss formula i.e., Eq. (15).

$$\mathrm{P}_L(t) = \sum_{i=1}^{M_H+N_T}\sum_{j=1}^{M_H+N_T} P_i(t)B_{ij}P_j(t) + \sum_{i=1}^{Ng} B_{i0}P_i(t) + B_{00} \quad (15)$$

where $P_i(t)$ can be either the power generation of hydro units or thermal units, and B_{ij} values are the B-loss coefficients.

■ **Load Balance Equation:**

$$\sum_{i=1}^{N_T} P_{T_m} + \sum_{j=1}^{N_H} P_{H_{jm}} - P_{D_m} - P_{L_m} = 0 \quad (16)$$

Here, P_{Tim} is the actual power output of i^{th} hydro unit during subinterval m.

$P_{H_{jm}}$ is actual power output of the j^{th} hydro unit during subinterval m.

$P_{D_m}$is the load demand during subinterval m and P_{L_m} is the transmission loss during subinterval m.

■ **Water Availability Limits:**

$$\sum_{m=1}^{N_m} n_m Q_{jm} = V_j \quad (17)$$

where Q_{jm} is the rate of water discharge of the j^{th} hydro plant at the time interval m. A typical equation of the discharge rate Q_{jm} is Eq. (18).

$$Q_{jk} = \alpha_j P_{H_{j_k}}^2 + \beta_j P_{H_{j_k}} + \gamma_j \quad (18)$$

where, α_j, β_j and γ_j are the coefficients of discharge rate for the j^{th} hydro unit.

3. OPTIMIZATION STRATEGY

3.1 Moth Flame Optimization

In 2015, S. Mirjali [10] introduced bio-inspired algorithm named Moth Flame Optimization (MFO) based on Moth flocking. At night, moths generally navigate at a particular angle with respect to the moon's location. This nature of the moth inspired implementation of the MFO algorithm for optimum solution following the best path of the moth out of its crosswise movement around the flame. The basis of the MFO technique is that every moth finds its way around the flame while in quest of a solution path. This natural technique becomes most effective in investigating the search space and updating the current position. This is formulated by Eq. (19), and the distance between the moth and flame (d) is calculated using Eq. (20).

$$S(M_i, F_j) = d_i e^{bn}\cos(2\pi n) + F_j \quad (19)$$

$$d_i = |F_j - M_i| \quad (20)$$

Here, F_j = position of j^{th} flame,
M_i = position of i^{th} moth,
d = the distance between the moth and flame,
b = constant of the shape of a logarithmic spiral,
n = random number between -1 and 1.

The number of flames is renewed iteratively by removing the poor solution made by flame by using Eq. (20).

$$F = round\left[F_{\max} - Ite \times \frac{F_{\max} - Ite_{\max}}{Ite_{\max}}\right] \quad (21)$$

Here, F = Number of flames,
$F_{\max}$ = maximum number of flames,
Ite = current number of iterations,
$Ite_{\max}$ = maximum number of iterations.

3.2 Bat Algorithm

The Bat algorithm was developed by Xin-She Yang [11] in 2010. This algorithm is one of the population-based metaheuristic algorithms for global optimization. This algorithm evolved inspired by the echolocation behavior of microbats, with varying pulse rates of emission and loudness. [12][13].

The microbats apply the reflected sound (echo) to locate their quarry as well as the precise position of the concerned quarry.

In the algorithm, the optimum solution of the objective function depends on bat's position; the fitness of the objective function, computed from bats' position, denotes the generation cost. The bat's position is obtained by frequency and velocity parameters. The formulation of Bat algorithm is expressed through Eqs. (22-24).

$$f_i = f_{\min} + (f_{\max} - f_{\min})\beta \quad (22)$$

$$v_i^t = v_i^{t-1} + (x_i^t - x_*)f_i \quad (23)$$

$$x_i^t = x_i^{t-1} + v_i^t \quad (24)$$

where f, v and x are frequency, velocity and position of bat respectively and β is a random number.

The loudness (L) and pulse rate (P) of bat algorithm are updated iteratively following Eq. (25) and (26).

$$L_i^{t+1} = \alpha L_i^t \quad (25)$$

$$P_i^{t+1} = P_i^0[1 - e^{(-\gamma t)}] \quad (26)$$

with the condition that $0 < \alpha < 1$ and $\gamma > 0$;

where α and γ are constants, α controls the rate of convergence of Bat algorithm.

3.3 Hybridization of Moth Flame Optimization and Bat Algorithms

Bat algorithm is quite effective in exploiting the best solution region but it has the disadvantage of being susceptible to getting stuck at local optima. On the contrary, the Moth Flame Optimization (MFO) is a well-built algorithm for good exploration of the entire search space, thereby having the possibility of finding better than the best local solutions but at the same time having limited capability of exploiting the regions around the local best solutions. The objective of hybridization of MFO and BA is to exploit the strengths of both the algorithms and achieve a good balance of exploration and exploitation in search mechanism, which is the requirement to find an excellent optimum solution.

In the hybrid MFO-BAT algorithm, BA is adjusted into exploitation mode [14] by fine-tuning the weight of pulse rate and loudness while MFO is tuned into complete exploration mode by adjusting the value of the distance between moth and flame.

Hybrid MFO-BA steps based on hydro-thermal economic load dispatch

Step 1: Define the following:

I. load demand and generators' power limits power limits(max and min)
II. the objective function and equality constraints based on power balance
III. the generators' power in terms of moths' and bats' positions
IV. the dimensions of searching agents concerning the number of generating units
V. the population
VI. the frequency (max and min), loudness, and pulse rate of bats.

Step 2: Initialize the following:

I. frequency and velocity of bats
II. the moths' position based on the generators' limits(max and min)

Step 3: While taking into account the equality constraints, compute the power losses and evaluate the fitness of the objective function using moths' position
Step 4: Select the global best value
Step 5: Set iteration to 1
Step 6: Update the number of flames using Eq.(21)
Step 7: If the number of iterations is equal to 1, perform the sorting of moths' positions and assign them as sorted population (F_j)
Step 8: If the number of iterations is greater than 1, perform the sorting of moths' positions based on the previous iteration and current iteration and assign them as sorted population (F_j)
Step 9: Calculate 'α','t' and 'd' using Eqs. (27),(28) and (20) respectively

$$\alpha = (-1 + Ite) \times \left[\frac{-1}{Ite_{\max}}\right] \tag{27}$$

$$t = (\alpha - 1) \times rand + 1 \tag{28}$$

Compute the distance of the moth with respect to the corresponding flame using Eq.(20)
Step 10: Update moths' positions by using Eq.(19)
Step 11: Check the inequality constraints by using generator power limits for bringing back the moths that are outside the search space
Step 15: Calculate the power losses and then evaluate the objective function by using bats' positions while satisfying the equality constraints, Update local best values, Update the global best fitness and global best position
Step 16: Repeat steps 6-15 until the maximum iteration is attained.
Step 17: Display the global best fitness of the objective function (total generation cost) and global best position (power generated in each unit)

The flowchart representing pseudo code of the hybrid MFO-BA algorithm is depicted in Fig. 1.

4. SIMULATION OUTCOME AND ANALYSIS

The problem formulation and corresponding data modeling and analysis is done in Matlab platform using Matlab2016a version using PC processor of Intel(R) Core(TM) i3-5020U CPU@2.20GHz with 4.00GB RAM. The values of the input parameters of the algorithm are depicted in Table 1.

Table 1: *Settings of the Hybrid MFO-BA parameters.*

Parameter	Value	Parameter	Value
b : constant of the shape of a logarithmic spiral	1 to 5	**P**: Pulse rate	0.001
n: Random number	[-1,1].	**f**: Frequency range	[+0.32, -0.34]
L: Loudness	0.9	**N**: Population size	50

The simulation results obtained for four test cases are described below:

Test Case 1: 4-Unit System without Transmission Loss Sub Case 1.1: 4-Unit Thermal Power System

This experiment has been done with four thermal power units considering quadratic cost function and no transmission loss. The generator capacity, operating limits, and cost coefficients are given in Table 2. The total load demand is P_D=500 MW, the load demands for different sub-intervals are shown in Table 3. The simulation result including generator-wise load dispatch and the best cost of generation are depicted in Table 4.

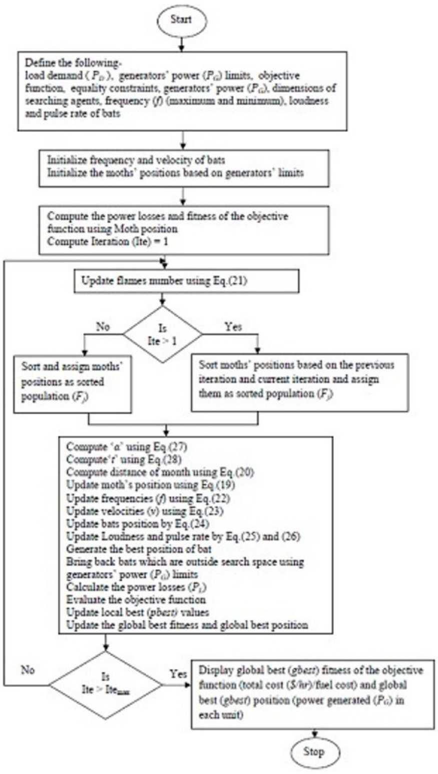

Fig.1: *Flowchart of Hybrid MFO-BA.*

Table 2: *4-unit all-thermal system-cost coefficients and generator limits [15].*

Unit	a_{Ti} ($/h)	b_{Ti} ($/MW h)	c_{Ti} ($/MW^{2}h)	P_{min} (MW)	P_{max} (MW)
P_1	684.74	16.83	0.0021	75	300
P_2	585.62	16.95	0.0042	60	250
P_3	213	20.74	0.0018	25	80
P_4	252	23.6	0.0034	20	60

Table 3: *Sub-intervals with load demand.*

Sub-interval	Duration (Hr)	P_D(MW)
1	6(12:00am-6:00am)	500
2	6(6:00am-12:00noon)	600
3	6(12:00 noon -6:00pm)	700
4	6(6:00pm-12:00am)	800

Table 4: *Simulation result of the 4-unit all-thermal.*

Unit	Result using MFO-BA
U_{T1}	264.7977 MW
U_{T2}	190.2023 MW
U_{T3}	25.0000 MW
U_{T4}	20.0000 MW
P_D=500 (MW)	500.0000 MW
Best Cost ($/hr)	10708.0099

Sub Case 1.2: 4-unit hydro-thermal system comprising one hydro unit and three thermal units

This case study has been done with hydro-thermal system comprising three thermal units and one hydro unit. The objective function modeling data (coefficients etc.) are given in Table 5. The load demands are shown in Table 3. The total water volume of the hydro unit is 25,000 m^3 and the fuel cost is 1 $/MBtu. The simulation result including generator-wise load dispatch and best cost of generation is depicted in Table 6.

Table 5: *4-unit hydro-thermal system-cost coefficients and generator limits [1], [16].*

System	Unit	a_H (acre-ft/h)	b_H (acre-ft/MWh)	c_{H^2} (acre-ft/(MW)^{2}h)	$P_{Hi,min}$ (MW)	$P_{Hi,max}$ (MW)
Hydro plant	U_{H1}	0.0000 4864	0.01621	0.1135	10	100
System	**Unit**	a_{Ti} ($/h)	b_{Ti} ($/MW h)	c_{Ti} ($/MW^2 h)	$P_{Ti,min}$ (MW)	$P_{Ti,max}$ (MW)
Thermal plant	U_{T1}	0.00156	7.92	561	150	600
	U_{T2}	0.00194	7.85	310	100	400
	U_{T3}	0.00482	7.97	78	50	200

Table 6: *Simulation result of the 4-unit hydro-thermal system.*

Unit	Result using MFO-BA
U_{H1}	10.0000 MW
U_{T1}	196.9458 MW
U_{T2}	97.5448 MW
U_{T3}	195.5094 MW
P_D = 500 MW	500.0000 MW
Best Cost ($/hr)	1744.9666

Based on the simulation experiments done for Cases 1.1 and 1.2, the output of 4-unit all-thermal and hydro-thermal systems are compared in Table 7. The differences in unit-wise dispatch and total generation cost of the two systems are graphically illustrated in Fig. 2 and Fig. 3.

Table 7: *Comparison between 4-unit all-thermal and hydro-thermal systems.*

Unit	4-unit thermal	4-unit hydro-thermal (1-unit hydro and 3-unit thermal)
U_1	264.7977	196.9458
U_2	190.2023	97.5448
U_3	25.0000	195.5094
U_4	20.0000	10.0000
Best Cost ($/hr)	10708.0099	1744.9666

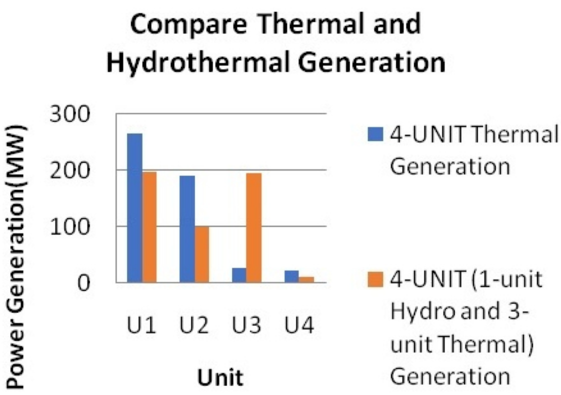

Fig.2: *Graphical comparison of unit-wise load of the 4-unit all-thermal and hydro-thermal systems.*

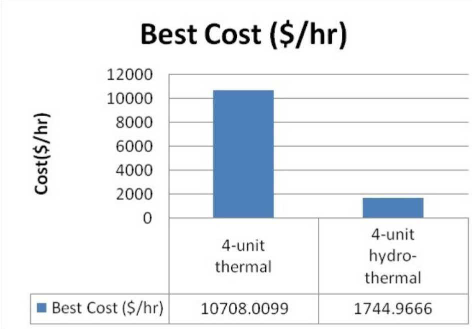

Fig.3: *Graphical comparison of best generation cost of the 4-unit all-thermal and hydro-thermal systems.*

Test Case 2: 5-Unit System with Transmission Loss

Sub Case 2.1: 5-Unit All-Thermal System with Transmission Loss

This experiment has been done with five thermal units considering quadratic cost function and transmission loss. The generator capacity, operating limits, and cost coefficients are given in Table 8. The total load demands (P_D) are 400 MW and 550 MW. The B-loss coefficient matrix is shown in Table 9. The simulation result including best cost of generation (out of 100 trials) is depicted in Table 10; the convergence characteristics for 400MW demand is illustrated in Fig.4.

Table 8: *5-unit all-thermal system-cost coefficients and generator limits.*

Unit	a_{Ti} ($)	b_{Ti} ($/MW)	c_{Ti} ($/MW)^2	P_{imin} (MW)	P_{imax} (MW)
U_{T1}	0.00375	2.0	0.0	50	250
U_{T2}	0.0175	1.75	0.0	20	160
U_{T3}	0.0625	1.0	0.0	15	100
U_{T4}	0.0834	3.25	0.0	10	70
U_{T5}	0.025	3.0	0.0	10	60

Table 9: *B-loss coefficient of a 5-unit all-thermal system [17].*

$$B = \begin{bmatrix} 0.0005 & 0 & 0 & 0 & 0 \\ 0 & 0.0003 & 0 & 0 & 0 \\ 0 & 0 & 0.0004 & 0 & 0 \\ 0 & 0 & 0 & 0.0005 & 0 \\ 0 & 0 & 0 & 0 & 0.00025 \end{bmatrix}$$

Table 10: *Simulation result of the 5-unit all-thermal system.*

Unit	Result using MFO-BA P_D=400MW	Result using MFO-BA P_D=550MW
Total Power Generation(MW)	420.6945	582.8981
Transmission loss(MW)	20.6945	32.8981
Best Cost ($/hr)	1286.448	2155.6484

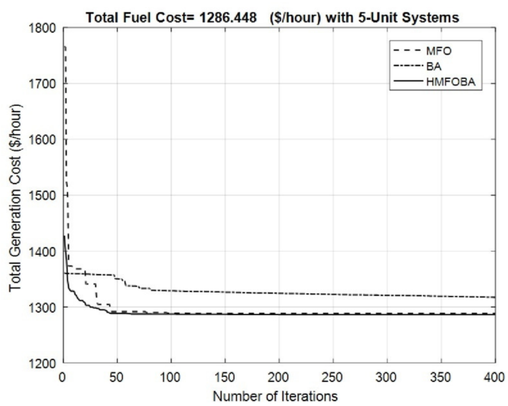

Fig.4: *Convergence characteristics - Test Case 2.1 for P_D=400MW.*

Sub Case 2.2: 5-Unit Hydro-Thermal System comprising 2 Hydro Units and 3 Thermal Units

This case study has been done with a hydro-thermal system comprising three thermal units and two hydro units. The objective function modeling data (coefficients etc.) are given in Table 11. The B-Loss coefficients are shown in Table 12. The total water volume of the hydro units is 25,000 m^3, and the fuel cost is 1 $/MBtu. The simulation result including generator-wise load dispatch and best cost of generation (out of 50 trials) along with transmission loss for load demands of 400 MW and 500 MW are depicted in Table 13 and further illustrated in Fig.5 and Fig.6. The convergence characteristics for load demand 550MW is illustrated in Fig.7.

Based on the simulation experiments done for Cases 2.1 and 2.2 the output of the 5-unit all-thermal and 5-unit hydro-thermal systems are compared in

Table 11: *5-unit hydro-thermal system-cost coefficients and generator limits [17] and [18].*

System	Unit	a_H (acre-ft/h)	b_H (acre-ft/MWh)	c_{H^2} (acre-ft/(MW)^{2}h)	$P_{Hi,min}$ (MW)	$P_{Hi,max}$ (MW)
Hydro plant	U_{H1}	1.423	0.187	0.00001829	12	126
	U_{H2}	1.714	0.198	0.0000203	20	180
System	**Unit**	a_{Ti} (\$/h)	b_{Ti} (\$/MW h)	c_{Ti} (\$/MW^2 h)	$P_{Ti,min}$ (MW)	$P_{Ti,max}$ (MW)
Thermal plant	U_{T3}	561	7.92	0.001562	150	600
	U_{T4}	310	7.85	0.00194	100	400
	U_{T5}	78	7.97	0.00482	50	200

Table 12: *B-Loss co-efficient of 5-unit hydro-thermal systems [17], [18].*

$$B = 0.001^* \begin{bmatrix} 0.0212 & 0.0085 & 0.0069 & 0.0002 & 0.0002 \\ 0.0085 & 0.0188 & -0.0062 & 0.0051 & 0.0002 \\ 0.0069 & -0.0062 & 0.4817 & -0.1333 & -0.1604 \\ 0.0002 & 0.0051 & -0.1333 & 0.2180 & -0.0251 \\ 0.0002 & 0.0002 & -0.1604 & -0.0251 & 0.1406 \end{bmatrix}$$

Table 14. It reflects the economic advantage gained by replacing two thermal units with two hydro units. The comparison of transmission loss for both the cases against the given two power demands of 400 MW and 550 MW is shown in Table 15. Fig.5 and Fig.6 graphically illustrates the result of Table 14.

Table 13: *Simulation result for the 5-unit hydro-thermal system for P_D=400 and 550MW.*

Unit	P_D=400MW	P_D=550MW
U_{H1}	125.9997	126.0000
U_{H2}	172.9352	180.0000
U_{T3}	50.0000	106.8174
U_{T4}	40.0000	53.8335
U_{T5}	30.0000	110.0478
Generation (MW)	418.9350	576.6986
P_Loss (MW)	18.9349	26.6986
Best Cost (\$/hr)	509.8376	753.5225

Table 14: *Cost comparison between 5-unit all-thermal and hydro-thermal systems.*

Power Demand (P_D)MW	**5-Unit Thermal**	**5-Unit Hydro-Thermal** (2-unit Hydro and 3-unit Thermal)
400	1286.448	509.8376
500	2155.6484	753.5225

Table 15: *Comparison of transmission loss for the 5-unit all-thermal and hydro-thermal systems.*

Power Demand (P_D)MW	**5-Unit Thermal**	**5-Unit Hydro-Thermal** (2-unit Hydro and 3-unit Thermal)
400	20.6945	18.9349
500	32.8981	26.6986

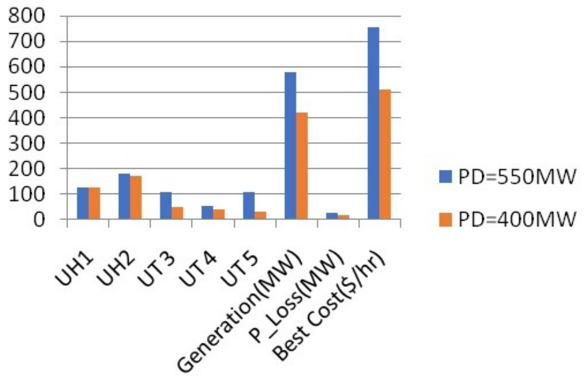

Fig.5: *Graphical comparison of unit-wise load, total loss, and best cost for the 5-unit all-thermal and hydro-thermal systems.*

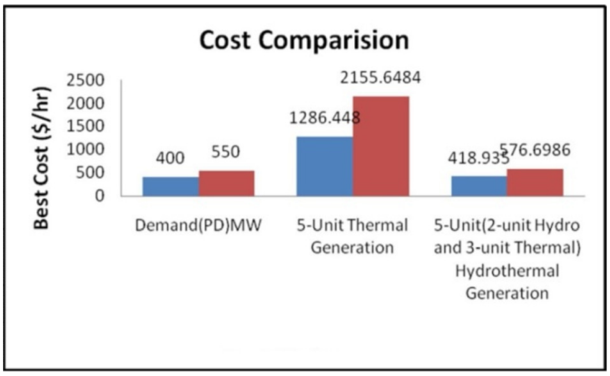

Fig.6: *Graphical comparison of best generation cost for the 5-unit all-thermal and hydro-thermal systems.*

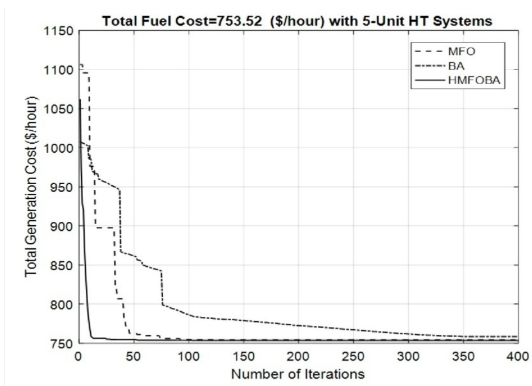

Fig.7: *Convergence characteristics - Test Case 2.1 for P_D=550MW.*

Test Case 3: 6-Unit System with Transmission Loss

Sub Case 3.1: 6-Unit All-Thermal System with Transmission Loss

This experiment has been done with six thermal units considering quadratic cost function and transmission loss. The generator capacity, operating limits, and cost coefficients are given in Table 16. The load demands for the four different sub-intervals are shown in Table 17. The B-loss coefficients are given in Table 18. The simulation result including best cost of generation (out of 100 trials) for four different sub-intervals with load demands of 570 MW, 600 MW, 700 MW, and 800 MW are depicted in Table 19.

Table 16: *6-unit thermal system - cost coefficients and generator limits [19].*

Unit	a_i (\$)	b_i (\$/MW)	c_i (\$/MW)^2	P_{imin} (MW)	P_{imax} (MW)
U_{T1}	249	7	0.0070	100	500
U_{T2}	200	10	0.0095	50	200
U_{T3}	220	8.5	0.0090	80	300
U_{T4}	200	11	0.0090	50	150
U_{T5}	220	10.5	0.0080	50	200
U_{T6}	120	12	0.0075	50	120

Table 17: *Hour-wise load demand.*

Sub-interval	Duration (hr)	P_D (MW)
1	6 (12:00 am - 6:00 am)	570
2	6 (6:00 am - 12:00 noon)	600
3	6 (12:00 noon - 6:00 pm)	700
4	6 (6:00 pm - 12:00 am)	800

Table 18: *B-Loss coefficient for a 6-unit thermal system [15].*

$$B = \begin{bmatrix} 0.000140 & 0.000017 & 0.000015 & 0.000019 & 0.000026 & 0.000022 \\ 0.000017 & 0.000060 & 0.000013 & 0.000016 & 0.000016 & 0.000020 \\ 0.000015 & 0.000013 & 0.000065 & 0.000017 & 0.000024 & 0.000019 \\ 0.000019 & 0.000016 & 0.000017 & 0.000071 & 0.000030 & 0.000025 \\ 0.000026 & 0.000015 & 0.000024 & 0.000030 & 0.000069 & 0.000032 \\ 0.000022 & 0.000020 & 0.000019 & 0.000025 & 0.000032 & 0.000085 \end{bmatrix}$$

Table 19: *Simulation result of the 6-unit all-thermal system with transmission loss.*

Unit	P_D=570 (MW)	P_D=600 (MW)	P_D=700 (MW)	P_D=800 (MW)
U_{T1}	234.1446	248.0652	277.8699	306.3008
U_{T2}	59.2125	71.9067	99.1646	116.4223
U_{T3}	140.3194	144.4958	176.7691	190.1809
U_{T4}	50.0002	50.0030	50.0000	65.4806
U_{T5}	50.9026	51.6636	67.6280	99.0386
U_{T6}	50.0000	50.0541	50.0000	50.0001
Generation (MW)	584.5793	616.1885	721.4316	827.4232
P_Loss(MW)	14.5793	16.1881	21.4316	27.4232
Best Cost (\$/hr)	6973.5903	7316.3214	8501.3319	9740.8917

Sub Case 3.2: 6-Unit Hydro-Thermal System Comprising 2 Hydro Units and 4 Thermal Units

This case study has been done with a hydro-thermal system comprising four thermal units and two hydro units. The generator capacity, operating limits, and cost coefficients are given in Table 20. The load demands for four different sub-intervals are shown in Table 17. The B-Loss coefficients are given in Table 21. The total water volume of the hydro plant is 25,000 m^3, and the fuel cost is 1 \$/MBtu. The simulation result including best cost of generation (out of 50 trials) along with transmission loss for the four different subintervals with load demands of 570 MW, 600 MW, 700 MW, and 800 MW are depicted in Table 22. The convergence characteristics for 800 MW load demand has been illustrated in Fig.8.

Table 20: *6-unit hydro-thermal system - cost coefficients and generator limits [20].*

System	Unit	a_H (acre-ft/h)	b_H (acre-ft/ MWh)	c_H^2 (acre-ft/ (MW)^2 h)	W_H (acre-ft)	P_{Hmin} (MW)	P_{Hmax} (MW)
Hydro plant	U_{H1}	260	8.5	0.00986	125000	0	250
	U_{H2}	250	9.8	0.00986	28600	0	500
System	Unit	a_{Ti} (\$/h)	b_{Ti} (\$/MW h)	c_{Ti} (\$/MW^2 h)		P_{Timin} (MW)	P_{Timax} (MW)
Thermal plant	U_{T3}	10	3.25	0.0083		20	125
	U_{T4}	10	2.00	0.0037		30	175
	U_{T5}	20	1.75	0.0175		40	250
	U_{T6}	20	1.00	0.0625		50	300

Table 21: *B-Loss coefficients for a 6-unit hydro-thermal system [1].*

$$B = \begin{bmatrix} 0.0005 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.00003 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.00004 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.00004 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.00002 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.000025 \end{bmatrix}$$

Table 22: *Simulation result for the 6-unit hydro-thermal system for P_D=570MW, 600MW, 700MW, 800MW.*

Unit	P_D=570 (MW)	P_D=600 (MW)	P_D=700 (MW)	P_D=800 (MW)
U_{H1}	20.0250	32.2412	73.5965	114.5328
U_{H2}	0	5.8964	28.4599	76.2578
U_{T3}	125.0000	125.0000	125.0000	125.0000
U_{T4}	175.0000	175.0000	175.0000	175.0000
U_{T5}	195.1774	201.7293	237.4962	240.1351
U_{T6}	61.1370	67.1206	70.0818	81.7486
Generation (MW)	576.3394	606.9875	709.6344	812.6744
P_Loss(MW)	6.3394	6.9875	9.6344	12.6744
Best Cost (\$/hr)	3046.3709	3325.5551	4314.8638	5405.5833

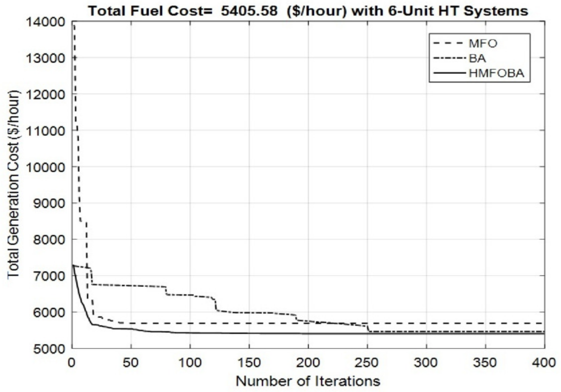

Fig.8: *Convergence characteristics- Test Case3.2, P_D=800MW.*

Sub Case 3.3: 6-Unit Hydro-Thermal System Comprising 3 Hydro Units and 3 Thermal Units

This case study has been done with a hydro-thermal system comprising four thermal units and two hydro units. The generator capacity, operating limits, and cost coefficients are given in Table 23. The load demands in four different sub-intervals are shown in Table 17. The B- Loss coefficients are given in Table 21. The total water volume of the hydro plant is 25,000 m^3, and the fuel cost is 1 $/MBtu. The simulation result including generator-wise load dispatch and best cost of generation (out of 50 trials) along with transmission loss for four different subintervals with load demands of 570 MW, 600 MW, 700 MW, and 800 MW are depicted in Table 24.

Table 23: *6-unit hydro-thermal system - cost coefficients and generator limits [1], [18].*

System	Unit	a_i ($)	b_i ($/MW)	c_i ($/MW^2)	$P_i min$ (MW)	$P_i max$ (MW)
Hydro Generation	U_{H1}	1.423	0.187	0.00001829	12	126
	U_{H2}	1.714	0.198	0.0000203	20	180
	U_{H3}	1.055	0.149	0.0000192	30	240
Thermal Generation	U_{T1}	50	0.1	0.01	50	200
	U_{T2}	40	0.1	0.02	40	170
	U_{T3}	30	0.1	0.01	30	215

Based on the simulation experiments done for Case 3.1 (all-thermal), 3.2 (2 hydro + 4 thermal), and 3.3 (3 hydro + 3 thermal) the results have been compared in Table 25 and 26, which reflects the economic advantage gained in introducing one or more hydro units along with thermal units. The comparison of generation costs is shown in Table 25. Table

Table 24: *Simulation result for the 6-unit hydro-thermal system for P_D= 570MW, 600MW, 700MW, 800MW.*

Unit	P_D=570 (MW)	P_D=600 (MW)	P_D=700 (MW)	P_D=800 (MW)
U_{H1}	61.0872	81.1916	126	126.0000
U_{H2}	153.9481	165.3835	180	180.0000
U_{H3}	240.0000	240.0000	240	240.0000
U_{T4}	50.0000	50.0000	60.7842	104.4792
U_{T5}	40.0000	40.0000	40	54.2950
U_{T6}	30.0000	30.0000	61.529	107.2228
Generation (MW)	575.0353	606.5751	708.3133	811.9970
P_Loss (MW)	5.0353	6.5751	8.3133	11.9970
Best Cost ($/hr)	2825.123	2886.625	3452.4480	5318.9300

26 gives the comparison of transmission loss for the three cases against the given four power demands. Fig.9 and Fig.10 graphically illustrates the result of Table 25 and Table 26 respectively. The convergence characteristics of the hydro-thermal system for 800 MW load demands is illustrated in Fig.11.

Table 25: *Cost comparisons between 6-unit all thermal and hydro-thermal systems.*

Power Demand(P_D) MW	**6-unit Thermal Generation**	**6-unit Hydro-thermal** (2-unit Hydro and 4-unit Thermal)	**6-unit Hydro-thermal** (3-unit Hydro and 3-unit Thermal)
570	6973.5903	3046.3709	2825.1230
600	7316.3214	3325.5551	2886.6250
700	8501.3319	4314.8638	3452.4480
800	9740.8917	5405.5833	5318.9300

Table 26: *Comparison of transmission loss between 6-unit all-thermal and hydro-thermal systems.*

Power Demand(P_D) MW	**6-unit Thermal Generation**	**6-unit Hydro-thermal** (2-unit Hydro and 4-unit Thermal)	**6-unit Hydro-thermal** (3-unit Hydro and 3-unit Thermal)
570	14.5793	6.3394	5.0353
600	16.1881	6.9875	6.5751
700	21.4316	9.6344	8.3133
800	27.4232	12.6744	11.9970

5. RESULT ANALYSIS

Going through the simulation results using customized MFO-BA in Section 4, we find distinct improvements in generation cost for all the cases. Firstly, in test case 1 (i.e., 4-unit system), the introduction of one unit of hydro-power system along with

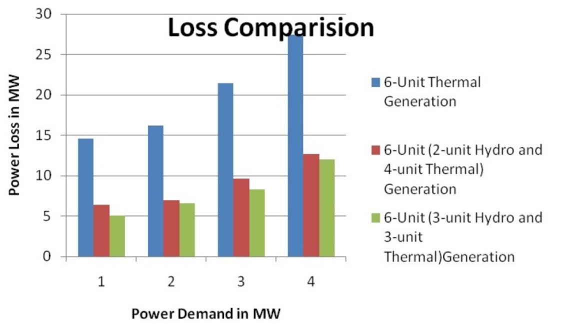

Fig.9: *Graphical cost comparison between 6-unit all-thermal and hydro-thermal systems.*

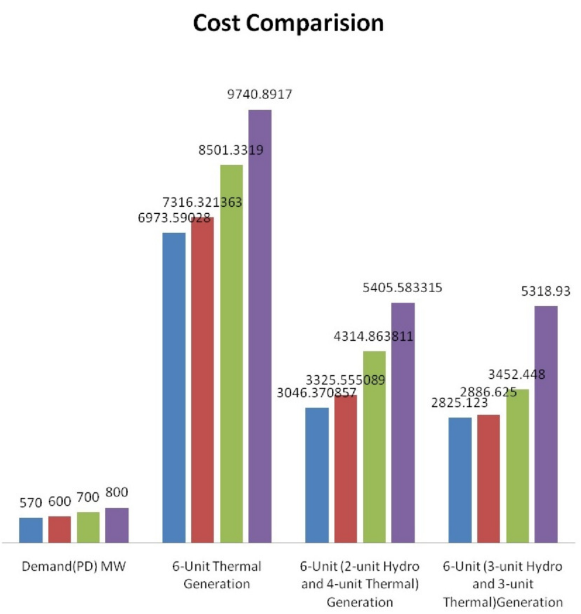

Fig.10: *Graphical loss comparisons between 6-unit all-thermal and hydro-thermal systems.*

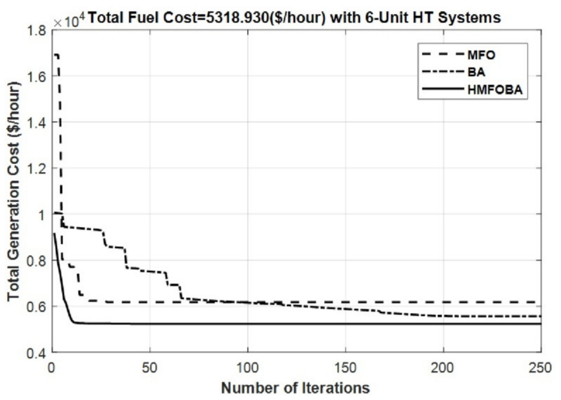

Fig.11: *Convergence characteristics- Test Case 3.3, P_D=800 MW.*

three unit of thermal power system (hydro to thermal ratio **1:3**) reduces the 500 MW power generation cost by **6.14** times (1744 $/hr vis-à-vis 10708 $/hr), which is a considerable advantage given the operational feasibility of a hydro-power system. Secondly, in test case 2 (i.e., 5-unit system), when two units of hydro power system replaces two units of thermal power system making hydro to thermal unit ratio 2:3 i.e., **1:1.5**, the generation cost reduces by factors of **2.49** (510 $/hr vis-à-vis 1268 $/hr) and **2.86** (754 $/hr vis-à-vis 2155 $/hr) for 400 MW and 550 MW power generation respectively. At the same time transmission loss also reduces, though not significantly. Thirdly, in test case 3 (i.e., 6-unit system), if equal number (three each) of hydro and thermal units are used instead of all six thermal units thereby making hydro to thermal ratio **1:1**, then the generation cost reduces by a factor of **1.83** (on an average) vis-à-vis cost reduction by a factor of **1.80**(on an average) when hydro to thermal ratio is **1:2**. The average is taken over the variation of cost with variation of power demand from 570 MW to 800 MW throughout 24 hours of a day. Besides generation cost, transmission loss is also reduced by **2.16** and **2.29** for 1:1 and 1:2 ratio respectively. It is thus observed that for higher number of units lesser economy is achieved in power generation cost but more economy is achieved in transmission loss if hydro units replace thermal units and MFO-BA technique is applied for economic load dispatch.

It appears from the convergence characteristics graphs that MFO-BA reaches optimum value much earlier than MFO or BA when applied separately. In some of the test cases the convergence curve of MFO-BA is highly steep implying sharp fall in objective function value with iterations. Moreover, in most cases, the stable optimum value i.e., the minimum value obtained by applying MFO-BA is less than that found by applying MFO or BA separately. Hence, from the run-time efficiency graph, MFO-BA emerges as a better algorithm in comparison to MFO and BA individually, although in few test cases BA shows better result against particular load demands.

6. CONCLUSION AND FUTURE SCOPE

The main aim of this study was to find the most economical and effective combination of hydro and thermal units as a trade-off between uncertainties of geo-climatic conditions (availability of water used as a resource for hydro-power generation with its characteristic constraints) and the ever-increasing cost of fossil fuel (used as a resource for thermal power generation). In this study three test systems and seven test cases were taken up in a simulation bed for applying a relatively new hybrid soft computing technique that is never used before in hydro-thermal economic load dispatch.

As expected, the hydro-thermal system proved to be more economical and effective over equivalent thermal system; it produces quite significant reduction in generation cost and transmission loss (in some test cases). The performance of the hybrid optimization algorithm MFO-BA has been compared with MFO and BA separately; the hybrid emerged more effective in terms of quick convergence (in less number of iterations) and yield of minimum generation cost. The combined power of MFO and BA in exploitation and exploration of search space accounted for the improved performance of the hybrid.

Besides the two-fold gain of the study in terms of effectiveness of MFO-BA in hydro-thermal load dispatch and economy of hydro-thermal systems over all-thermal systems, the other potential advantage of hydro-thermal system is economic emission as hydro power is cleaner and more environment-friendly. This remains a scope for future study.

Moreover, the study can be extended for medium-scale and high-scale hydro-thermal systems where different constraints of hydro-unit may be considered; such constraints may include cascaded nature of the hydraulic network, the varying hourly reservoir inflows, and different physical limitations on the reservoir storage. The loss coefficients also need to be determined for large-scale power generation systems.

Though by assuming fixed head hydro units the present study avoids complexities in ELD modeling, its novelty lies in the fact that no such indicative study has been done so far for hydro-thermal load dispatch problem using hybrid soft computing techniques. It may go a long way in finding even better solutions of nonlinear non-convex hydro-thermal load dispatch problem with dynamic switching between hydro and thermal units as per varying load demand at different hours of the day. That may well be one of the viable future options of power generation in a country like India.

AUTHOR CONTRIBUTIONS

DS and AM performed the literature survey and based on analysis of different hybrid metaheuristic components finally selected the hybrid MFO-BA approach for the present application duly considering the characteristic constraints of hydro-thermal systems. Both the authors revisited the work in view of the reviewer's comments and added necessary changes, graphs, etc.; DS developed the MATLAB coding of the hybrid MFO-BA, executed trials by altering the parameters of the programs and reported the results; DS and SM analyzed and interpreted the results and critically reviewed the economic advantage gained in introducing one or more hydro units along with thermal units.

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Dipankar Santra received his Bachelor's in Electrical Engineering from Jadavpur University in 2002 and MTech in Electrical Engineering (Electrical Power) from the University of Calcutta, West Bengal, India in 2009. He has done his PhD at Jadavpur University in 2021. Currently, he is Associate Professor of Electrical Engineering at RCC Institute of Information Technology, Kolkata, India. His areas of interest are power system, economic load dispatch and soft computing applications to different power system problems and electrical machines.

Anirban Mukherjee did his Bachelors in Civil Engineering in 1994 from Jadavpur-University, Kolkata and PhD from Indian Institute of Engineering, Science and Technology (IIEST), Shibpur. He is currently a Professor in the Department of Information Technology at RCC Institute of Information Technology, Kolkata, India where he has 24 years of experience in teaching engineering and management subjects and more than 14 years of experience in academic administration including accreditation of academic programs. His research interests include Computer Graphics, Computational Intelligence, Optimization and Digital Pedagogy. He has co-authored 2 UG engineering (CSE) textbooks and 18 books on Distance Learning Programs of BBA/MBA/BCA/MCA courses of different Universities across India. Besides authoring several papers/chapters published in journals, books and conferences he is the co-editor of 8 edited books published by international publishers. He is a life member of the Computer Society of India and Fellow of Institution of Engineers (India) and Science Association of Bengal (SAB).

Subrata Mondal has joined as an Assistant Professor of Power Engineering Department, Jadavpur University in 2016. He completed his BE in Mechanical Engineering from Jadavpur University in 2004. He completed his MTech in Mechanical Engineering from IIT Kanpur in 2007 and completed his PhD (Engg.) from the School of Laser Science and Engineering from Jadavpur University in 2013. Having some industrial experience, he is in teaching and research for twelve years. He has published 25 national and international journal papers He has reviewed 18 international journal papers. His research area includes soft computing techniques, laser machining, thermal energy, solar energy etc.