AN IMPROVED TEACHING LEARNING BASED OPTIMIZATION ALGORITHM FOR OPTIMAL SCHEDULING OF SHORT-TERM HYDROTHERMAL SYSTEM CONSIDERING VALVE-POINT LOADING EFFECT

Baburao Pasupulati
Research Scholar
Dept. of Electrical Engineering,
Annamalai University
Annamalai Nagar, Chidambaram
Tamil nadu, India
pasupulatibaburao@gmail.com

Dr. R. Ashok Kumar
Professor
Dept. of Electrical Engineering
Annamalai University
Annamalai Nagar, Chidambaram
Tamil Nadu, India
ashokraj_7098@rediffmail.com

Dr. K. Asokan
Assistant Professor
Dept. of Electrical Engineering
Annamalai University
Annamalai Nagar, Chidambaram
Tamil Nadu, India
asokaneee@gmail.com

Abstract: *The power system is generally planned to meet the ever increasing load demand of the consumers at a reasonable tariff by properly handling the fuel cost. The short-term hydrothermal scheduling problem received the attention of researchers, in arriving the minimum fuel cost of power plants. It advocates the scheduling process of hydro and thermal plants with a view to minimise the fuel cost over the planning horizon by considering system constraints. The problem of scheduling of generation mixture of hydro and thermal problems involves non-linear, non-convex curves comprising valve-point loading effects with a set of equality and inequality constraints. The interpretation of hydrothermal plants with hydro dominance is seems to be complex than a hydro system. Hence, the conventional techniques may not yield the perfect solution for this kind of problem. In this article, a simple concept of improved teaching learning based optimization (ITLBO) algorithm for the solution of short-term hydrothermal scheduling has been presented. It is an exceptional distinct optimization algorithm stimulated by the effect of repercussion of a teacher on the productivity of learners in the domain. The proposed methodology has been applied on two standard test systems for 24 hours time period. The results are evolved in terms of water discharge, reservoir storage volume and fuel cost of thermal units with/without Valve-Point loading effects. The performance of the proposed method is validated by comparing with other methods available in the literatures. From the findings, it is evident that ITLBO based approach is able to provide a global optimal solution.*

Keywords—Hydrothermal Scheduling; Valve-point loading effect; Fuel cost; ITLBO algorithm.

1. Introduction

The short-term hydrothermal scheduling (STHTS) assumes significance in the field of power system engineering because of its complexity and operational task. The STHTS problem is considered to be a debatable subject for economical and reliable operation of system. The STHTS performs the hour-by-hour scheduling of hydro and thermal resources while fulfilling the hydraulic and thermal constraints over a predefined time horizon [1]. The intention is to utilize the water resources to the extent possible for minimizing the production cost of thermal plants [2]. A well modelled scheme of scheduling of generating units considerably reduces the production cost besides improving the system reliability. In STHTS problem, the hydraulic and thermal constraints are categorized as power balance, water balance, physical limitation of reservoir storage, turbine flow rate and loading limits. Moreover, the cascaded operation of hydro plants creates the interdependence among the performance of hydel plants. The impact of valve-point loading effect on the operating cost of thermal plants magnifies the non-convexity and non-linearity of the STHTS problem. Therefore, STHTS is a large scale, non-convex, non-linear and non-smooth optimization problem. The methodological change in the generation systems enforces the need for renewed formulation for the optimal scheduling of hydrothermal power plants.

Hydrothermal scheduling problem received much attention among researchers in recent years. Number of optimization methods has been proposed to evolve the solution for hydro thermal coordinated system. However, the problem is yet to be completely resolved in arriving the global optimal solution. Few of these optimization methods are Dynamic Programming (DP) [29], Lagrangian Relaxation (LR) [3,7], Mixed-Integer Programming (MIP) [4], Benders Decomposition [5], Newton's method [6,9], Non-Linear Programming (NLP) [8].

The DP method has been widely used among these techniques. Although the DP is capable of handling the subjects of scheduling problem, it is being suffered from the burden of dimensionality and increasing system size. Hence the method lacks behind large memory storage problem and extended computational time. Because of this reasons, the solutions are ended up with suboptimal solutions for a non-linear problem. Newton’s method has been mathematically viable and efficient in solving non-linear problems. Therefore it has a high regard in evolving solution for the optimization problem. Even though it is based on the constitution of jaccobian matrix, it encounters complication in reaching the solutions for large scale problem. Linear programming is only suitable for the problems, which have linear objective function and constraints. The non-linear programming method, lags from the problem of slow convergence and needs large memory space.

The fuel cost characteristics of thermal plants and the input-output curves of hydro plants are normally expressed in term of non-linear and non-convex curves. Hence much of the traditional methods do not yield the reliable solutions.

With the advent of evolutionary computation techniques, awareness has been turned towards the application of such techniques in handling the complicated Non-Linear problems. Stochastic search algorithm such as Simulated Annealing (SA) [10], Genetic Algorithm (GA) [11,12], Particle Swarm Optimization (PSO) [13], Improved PSO(IPSO) [14], Evolutionary Programming (EP) [15,16], Differential Evolution (DE) [17], Modified Differential Evolution (MDE) [18], Cuckoo Search Algorithm [19] and Teaching learning based optimization (TLBO) [20] have been suggested for the solution of optimal hydrothermal scheduling problem.

Although many optimization techniques were developed by researchers, the non-linear nature of this problem necessiates the development of an efficient algorithm for the solution of optimal scheduling. In this background, the basic endeavour of this study is to establish a constructive frame work for the optimal solution of STHTS problem.

This algorithm functions on the philosophy of the effect of influence of a teacher on the output of learners in a class and also learning by interaction between the class members. This process helps for the improvement of their grades. In some situations a teacher has to take more steps to improve the results, which results in slower convergence rate of optimization problem. Considering this experience, to upgrade the exploration and exploitation capacities, some reformation has been introduced in the TLBO algorithm by Rao and Patel. The idea of elitison is exercised in most of the algorithm where the inferior solution is replaced by the best solution.

In this article, a simple methodology of Improved Teaching Learning Based Optimization (ITLBO) algorithm is proposed for solving the optimization problem of STHTS with a view to obtain global optimal solution, best computational effort and high reliability. The suggested technique has been devised to minimize the total thermal generation cost of thermal units subject to power balance, spinning reserve, generation limit, minimum up and down time, water discharge and water storage volume constraints. The organization of the paper is summarized as follows. Section 2 of the paper elaborates the mathematical formulation of STHTS problem with mathematical model of hydro and thermal units. Section 3 describes the proposed Improved TLBO algorithm, with a short description of the algorithm implemented on the test system. Section 4 depicts the numerical results and its discussion. Finally the conclusion has been drawn in section 5.

2. Problem formulation

2.1 Objective function

The prime objective of STHTS is to identify the optimal generation scheduling of hydro and thermal units with a view to minimizing the total operation cost of the thermal plants while satisfying the system constraints.

Normally hydrothermal power plants comprise several units which has been modelled as an equivalent unit with cost characteristics as shown in Fig. 1. The fuel cost and power generation of thermal units are formulated as a quadratic equation.

$$\mathbf{F_i(P_{it}) = a_i P_{sit}^2 + b_i P_{sit} + c_i} \quad (1)$$

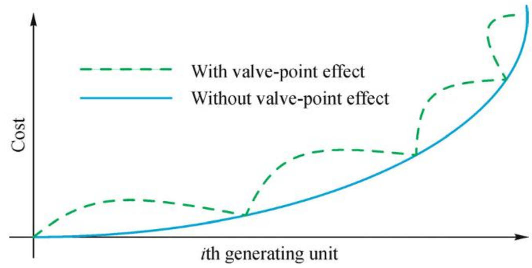

Fig. 1. Variation of cost function of generating unit

Practically, thermal power plants may have multiple steam admitting values. In order to have a perfect model, it is essential to include the effect of valve-point effect on the fuel cost parameter.

$$F_i(P_{it}) = \left\{a_i P_{sit}^2 + b_i P_{sit} + c_i + \left|d_i \times \mathrm{Sin}\left[e_i \times \left(P_{sit}^{min} - P_{sit}\right)\right]\right|\right\} \quad (2)$$

From equation (2), the fuel cost of thermal units is found to be non-smooth characteristics of the generated power.

The objective of STHTS is to minimise the total fuel cost (TC) of the overall thermal plants which are involved in this process and it is modelled by the following equation.

$$\min TC = \sum_{t=1}^{T} \sum_{i=1}^{N} a_i P_{sit}^2 + b_i P_{sit} + c_i + \left|d_i \times \mathrm{Sin}\left[e_i \times \mathbf{Psitmin{-}Psit}\right.\right. \quad (3)$$

2.2 System and unit constraints

The primary system and unit constraints of STHTS problem is power balance, thermal generation limits, hydro generation limits, spinning reserve, water balance and water storage volume are mathematically expressed as.

a. Power balance constraints

$$\sum_{i=1}^{N} P_{sit} + \sum_{j=1}^{M} P_{hjt} - P_{D_t} - P_{Loss_t} = 0 \quad (4)$$

The output of hydro power plant mainly depends upon the water discharge and volume of the reservoir. Hence it can be expressed as a quadratic equation.

$$P_{ht} = C_{1j}V_{hj}^2 + C_{2j}Q_{hj}^2 + C_{3j}V_{hj}Q_{hj} + C_{4j}V_{hj} + C_{5j}Q_{hj} + C_{6j} \quad (5)$$

b. Thermal generation limits

$$P_{si}^{min} \le P_{sit} \le P_{si}^{max} \quad (6)$$

c. Hydro generation limits

$$P_{hj}^{min} \le P_{hjt} \le P_{hj}^{max} \quad (7)$$

d. Spinning reserve constraints

$$\sum_{i=1}^{N} P_{sit} X_{sit} \le SR_t \quad (8)$$

$$0 \le R_{sit} \le (P_{sit}^{max} - P_{sit}^{min})$$

$$R_{sit} + P_{sit} \le P_{sit}^{max}$$

e. Water discharge constraints

$$Q_{hj}^{min} \le Q_{hjt} \le Q_{hj}^{max} \quad (9)$$

f. Storage volume constraints

$$V_{hj}^{max} \le V_{hjt} \le V_{hj}^{max} \quad (10)$$

3. Solution methodology

3.1 TLBO algorithm

The TLBO algorithm is an optimization technique based on the teaching learning process, introduced by Rao et al. [20-23] Normally heuristic techniques performs well over the classical mathematical models, but the quality of solutions is mostly depends on the tunning of algorithmic parameters such as variation operators (mutations and recombination) and selection operators (parent selection and survivor selection). The algorithm has been organised on the basis of impact of guidance of a teacher on the learners in a class room. The productivity of individuals is weighed by the way of results or grades. The teacher is usually treated as a highly qualified and learned person who imparts his or her expertise to the learners in that class. Moreover, there is a chance for learners to educate themselves by means of iteration, which also helps in improving their results.

The algorithm prescribes two basic methods of learning, by the direction of teacher (recognised as teacher phase) and by exchanging the knowledge with other learners (recognised as learner phase). It is a population based optimization algorithm where a group of learners has been considered as a population and certain subjects imparted to the learners are equivalent to the design variables in the optimization problem. The outcome of the learner is assigned to the fitness value of the problem. The finest solution in the absolute population has been graded as the teacher.

a. Teacher Phase

This aspect is the basic component of the algorithm, wherein the students flourish their expertise from the guidance of the teacher who is the most intelligent person in the class room environment and whose responsibility is to activate the students to reach their objective. During this course, the teacher makes an attempt to enhance the subject mean performance of the learner based on their capacity.

At the instant of iteration G, let the quantity of subjects is D, the count of learners (population size, k = 1,2,...NP) is NP, then $mean_{j,g}$ indicates the mean outcome of learners in that subject "j" (j =1,2,...D)

It has been assumed that the teacher is an intelligent and experienced man on the subject, then the teacher is designated as the best learner in the total population. Let $\mathbf{X}_{\mathbf{total-kbest,G}}$ be the result of the finest learner of the entire subjects and who is identified as the teacher with regard to that sequence. The difference obtained from the result of the teacher and the mean result of the learners in every subject is furnished by the equation.

$$\text{Difference\_mean}_{j,G} = \text{rand}(X_{j,kbest,G} - T_F \text{Mean}_{j,G}) \quad (11)$$

Where X_{total} derives the best learner in the subject j, rand is a random in the magnitude (0, 1) and T_F will be the teaching factor which identifies the average to be qualified. The condition of T_F is randomly resolved by the equation.

$$T_F = \text{round}(1 + \text{rand}(0,1)) \quad (12)$$

The solution of the above equation can be modified by the following equation.

$$X_{j,k,G}^{new} = X_{j,k,G} + \text{Difference\_mean}_{j,G} \quad (13)$$

It is noticed that the values of random number (rand) and teaching factor (T_F) influence the performance of TLBO algorithm. However, the values of rand and T_F are generated arbitrally in the algorithm and these parameters are not used as input to the algorithm. Hence the tuning of rand and T_F is not mandatory in the TLBO algorithm.

b. Learner Phase

A student can also learn by interacting with other members in the domain. So the process of learning from the counterparts of their class is known as learner phase. It is another part of the algorithm, wherein the learners enrich their intelligence by exchanging ideas among them. Then every student arbitrarily selects another student for interaction and acquires new ideas from him if that student has better knowledge than him. The learning process has been expressed by the following equation (14) & (15).

Two learners $X_{j,p,G}$,$X_{j,Q,G}$ are randomly selected, such that

$$X_{j,P,G}^{new} = X_{j,p,G} + \text{rand}(X_{j,p,G} - X_{j,Q,G}) \text{ If}(X_{j,P,G}) < f(X_{j,Q,G}) \quad (14)$$

$$X_{j,P,G}^{new} = X_{j,p,G} + \text{rand}(X_{j,Q,G} - X_{j,P,G}) \text{iff}(X_{j,Q,G}) < f(X_{j,P,G}) \quad (15)$$

$X_{j,P,G}^{new}$ is considered if it explores the best result.

3.2 Improved TLBO algorithm

a. Feedback phase

In the fundamental TLBO algorithm, the teacher educates the learners and attempts to improve the mean result of the class. In practice of teaching learning, the activities of teacher are scattered and students admits lesser reciprocation which will scale down the capacity of learning. Besides, if the class has a larger group of inferior students, then the teacher has to pay more attention in increasing their output. Despite this exercise, there may not be any progress in the results. When this kind of exercise is applied on the optimization algorithm, it requires a numerous assessments to have optimum solution and yields imperfect converging point. In order to overcome this problem, the fundamental TLBO algorithm is enhanced by introducing the feedback phase. In this, a poorly performing student is randomly selected in the feedback phase and is made to discuss with the teacher directly. This phase thus decreases the search area, leads to a fine search and improves the speed and accuracy of the search [24-26].This phase is expressed by Eqs. (16) and (17).

Two learners $X_{j,R,G}, X_{j,S,G}$ are randomly selected, such that $X_{j,R,G} \neq X_{j,S,G}$

$$X_{j,R,G}^{new} = X_{j,R,G} + rand(X_{j,kbest,G} - X_{j,S,G}) \text{ iff}(X_{j,R,G}) < f(X_{j,S,G}) \quad (16)$$

$$X_{j,R,G}^{new} = X_{j,R,G} + rand(X_{j,kbest,G} - X_{j,R,G}) \text{ if } f(X_{j,S,G}) < f(X_{j,R,G}) \quad (17)$$

$X_{j,R,G}^{new}$ is accepted if it gives the superior result.

4. Solution of STHTS problem using ITLBO algorithm

The technical steps of the proposed algorithm are as follows

4.1 Evaluation and selection of STHTS variables

Step 1: Read the data of hydrothermal system.

Step 2: Initialize the proposed ITLBO algorithmic parameters such as population size NP, maximum number of generation G, number of design variables D, limits of design variables (L, U), scaling factor F, probability of the crossover rate CR.

Step 3: Randomly initialize the population of all dependent variables like water discharge rate and thermal plant generation outputs

$$Q(j,t) = rand(Qj^{min} - Qj^{max}) \quad (18)$$

$$P(i,t) = rand(Pi^{min} - Pi^{max}) \quad (19)$$

Step 4: Determine water discharge rate for the last interval of time while satisfying the initial and final reservoir constraints using the following equation

$$Q_{j,T} = V_j^{begin} - V_j^{end} - \sum_{j=1}^{T-1} Q_{j,t} + \sum_{j=1}^{T} I_{j,t} + \sum_{k=1}^{Ru_i} \sum_{j=1}^{T} \left(Q_{kj-Td_{k,i}}\right) \quad (20)$$

Step 5: Check the water discharge for its minimum and maximum limits. If it is less than the minimum limits it is made equal to its minimum value and if it is greater than maximum limit it is made equal to maximum limit.

Step 6: Compute the reservoir water storage volume of j^th hydro plant for t^th time interval using equation

$$V_{hj0} - V_{hjT} = \sum_{t=1}^{T} \sum_{l=1}^{R_{uj}} Q_{hl(t-t1j)} - \sum_{t=1}^{T} I_{hjt}, j \in N_h \quad (21)$$

Step 7: Check for the operating limits of water storage volume

$$V_{j,t} = V_j^{min} \quad \text{if } V_{j,t} < V_j^{min} \quad (22)$$

$$V_{j,t} = V_j^{max} \quad \text{if } V_{j,t} > V_j^{max} \quad (23)$$

Step 8: Estimate the hydro power generation of j^{th} hydro plant for t^{th} time interval using equation (5).

Step 9: Check it for its minimum and maximum limits.

$$Ph_{j,t} = Ph_j \min \quad \text{if } Ph_{j,t} < Ph_j^{min} \quad (24)$$

$$Ph_{j,t} = Ph_j^{max} \quad \text{if } Ph_{j,t} > Ph_j^{max} \quad (25)$$

Step 10: The thermal generation of plant can be estimated using equation (26) by subtracting hydro generation from the power demand by neglecting transmission losses.

$$\sum_{i=1}^{N} P_{sit} + \sum_{j=1}^{M} P_{hjt} - P_{D_t} - P_{Loss\,t} = 0 \quad (26)$$

Step 11: Check the inequality constraints of thermal power, if it is less than minimum limits it is made equal to its minimum value and if it is greater than maximum limit it is made equal to maximum limit.

4.2 Implementation of ITLBO algorithm

Step 12: Generates initial population of i^{th} Student

$$P = \left[P_{s1}, P_{s2}, \dots, P_{si}, \dots, P_{sN_s}, Q_{h1}, Q_{h2}, \dots, Q_{hj}, \dots, Q_{hN_h}\right]^T \quad (27)$$

Where

$$P_{si1} = [P_{si1}, P_{si2}, \dots, P_{sit}, \dots, P_{siT}] \quad (28)$$

$$Q_{hj1} = [Q_{hj1}, Q_{hj2}, \dots, Q_{hjt}, \dots, Q_{hjT}] \quad (29)$$

Step 13: Determine the mean of the population which will give the mean marks of all subjects of the students.

Step 14: Identify the best solution that acts as the best teacher for that cycle and the mean result of the learners has been obtained.

Step 15: The learners' knowledge is updated with the help of teacher using equation (13).

Step 16: The learners' knowledge is updated through the knowledge of some other learners using equation (14) and (15).

Step 17: The learners' knowledge is updated through the feedback phase using equation (16) and (17).

Step 18: Evaluate the objective function (minimum thermal fuel cost) with these updated values in feedback phase.

Step 19: Save the new solution if it gives the better value of objective function.

Step 20: Stop if maximum number of generation is reached, else go to step 12.

5. Simulation results

The performance and potentiality of the proposed ITLBO algorithm has been proved by applying on two test systems to solve short-term hydrothermal scheduling problem with valve-point loading effect. The suggested algorithm has been programmed in MATLAB 14.0 and numerical simulations are carried out in a computer with i3 processor, Intel (R), core (i3), is 2.40 GHz, 4GB RAM.

5.1 Test system 1: Four hydro with an equivalent thermal test system

In this assignment, a test system [17] has been considered to illustrate the proposed ITLBO algorithm. The data for valve-point loading effect is adopted from the reference [28] and it is given in appendix A. It includes the load demand, hydro power generation coefficient of hydro unit. Reservoir limits, river inflows are given in Table A1 - Table A5. Table A6 displays the generation limits and cost coefficients of thermal units. The lower and upper operational limits of this thermal plant are 500 MW and 2500 MW respectively. The proposed test system consists of a multi-chain cascaded four hydro plants and number of thermal units represented by an equivalent thermal plant. The model diagram of multi-chain cascaded hydro system network is shown in Fig. 2.

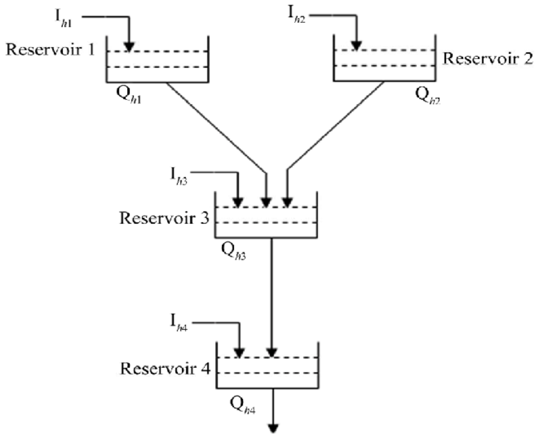

Fig. 2. Standard multi-chain hydro system network

The implementation of an ITLBO algorithm for an optimization problem starts with selection of control parameters and scheme which are crucial for the overall efficiency of the algorithm. The selection is made through trial and error process for the present test system where the population size is said to be not more than 30 in order to show the effect of small population and the maximum iteration is usually set to be not more than 200 to avoid large computational burden and to provide the best solution. The test system under consideration is divided in to two cases based on the types of their fuel cost function and standard prevailing constraints.

5.1.1 Case A: STHTS problem with quadratic cost functions

In hydrothermal systems, the fuel cost of thermal plant has been referred as a quadratic function by neglecting valve-point loading effect. The absolute fuel cost depends on the power output of thermal unit which is represented by the equation.

$$\min TC = \sum_{t=1}^{T}\sum_{i=1}^{N} a_i P_{sit}^2 + b_i P_{sit} + c_i \qquad (30)$$

Table 1 - Simulation results for four hydro and an equivalent thermal system without valve point loading effect (Case A)

Hour (h)	Hydro Gen. (MW)				Total Hydro Gen. (MW)	Thermal Gen. (MW)	Load (MW)	Fuel cost ($)
	Ph_1	Ph_2	Ph_3	Ph_4				
1	85.5115	49.8209	0.0000	218.0775	353.4099	1016.5901	1370	26585.4407
2	90.9745	64.7832	0.0000	191.4874	347.2451	1052.7549	1390	27429.4798
3	092.3558	73.6649	0.0000	207.9399	373.9606	986.0394	1360	25876.5038
4	89.9101	53.7400	0.0000	151.1682	294.8183	995.1817	1290	24246.6037
5	71.2868	69.0341	49.5267	178.3400	368.1876	921.8124	1290	24398.2742
6	90.7834	71.9312	29.4099	197.2868	389.4113	1020.5887	1410	26678.5056
7	96.8104	41.3463	17.2386	220.7834	376.1787	1273.8213	1650	32702.6103
8	97.6730	72.5986	52.6833	243.5141	466.4690	1533.5310	2000	39147.2298
9	79.8282	44.5552	47.5635	223.9454	395.8923	1844.1077	2240	47208.3342
10	86.0086	44.4421	53.8308	230.3313	414.6128	1905.3872	2320	48844.4350
11	75.1254	44.1282	54.4479	230.4211	404.1226	1825.8774	2230	46724.5026
12	97.6161	61.2104	57.8402	253.5381	470.2048	1839.7592	2310	47092.8045
13	67.8000	37.3048	57.1879	312.4216	474.7143	1755.2857	2230	44863.5412
14	90.0537	39.3635	58.7309	311.7554	499.9035	1700.0965	2200	43422.5090
15	85.9894	52.0439	59.6800	301.2126	498.9259	1811.0741	2310	46332.6015
16	92.0732	71.9992	41.4446	284.9762	490.4932	1579.5068	2070	40316.2140
17	73.7873	38.9118	56.7052	290.6911	460.0954	1669.9046	2130	42639.3310
18	75.8029	72.2318	56.5483	279.9264	484.5094	1635.4906	2140	41751.0785
19	90.8502	35.6000	28.2090	287.4567	442.1159	1797.8841	2240	45984.1491
20	93.4007	46.4474	59.9270	284.4578	484.2329	1815.7671	2280	45928.2872
21	97.2895	36.6465	0.0000	300.0000	433.9360	1806.0640	2240	46200.1631
22	85.3895	53.6606	59.5503	300.9878	499.5882	1620.4118	2120	41363.3753
23	80.3942	51.9851	29.5734	291.7824	453.7351	1396.2649	1850	35707.3974
24	67.8000	46.5119	0.0000	283.4712	397.7831	1192.2169	1590	30733.3267
Total fuel cost ($)								922176.7000

The simulation results of proposed case studies are presented in Table. 1. This table summarizes hydro generation, hydro discharge, total hydro generation, thermal generation and fuel cost of thermal units without valve-point loading effect.

The fuel cost obtained from the proposed method has been compared with that of other available methods and it is reported in Table 2. The ITLBO algorithm provides the minimized fuel cost of $ 922176.70. The water discharge and water storage volume of proposed four hydro systems are graphically represented in Fig. 3 and Fig. 4. Fig. 5 displays the load demand, hydro generation and thermal generation for the period of twenty four hour time intervals and the obtained fuel cost is graphically reported in Fig. 6.

Table 2 - Comparison of fuel cost of proposed method with existing methods (Case A)

Methods	**Minimum cost ($)**	**Maximum cost ($)**	**Average cost ($)**
GA[17]	942600.00	NA	NA
GWPSO [17]	930622.50	951 253.20	940 036.30
FEP [20]	930267.92	931 396.81	930 897.44
IFEP [20]	930129.82	930 881.92	930 290.13
GCPSO [17]	927288.40	972 658.30	936 717.10
QEA [28]	926538.29	930 484.13	928 426.95
RCGA [20]	925940.00	926 538.00	926 120.00
LCPSO [17]	925618.50	928 219.80	926 651.40
DE [20]	923234.56	928 395.84	925 157.28
MAPSO [20]	922421.66	923 508.00	922 544.00
TLBO [20]	922373.39	922 873.81	922 462.24
ITLBO (Proposed)	922176.70	922794.50	922386.20

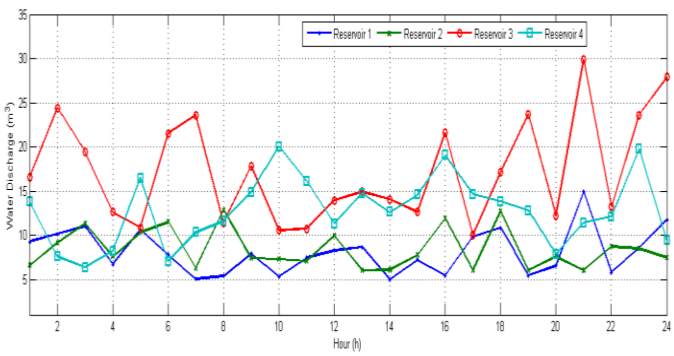

Fig. 3. Water discharge in (m^3) of four hydro and equivalent thermal system without valve point loading effect

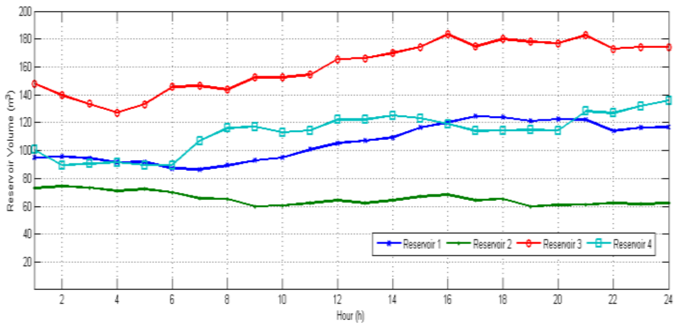

Fig. 4. Reservoir storage volume (m^3) of the four hydro and an equivalent thermal system without valve point loading effect

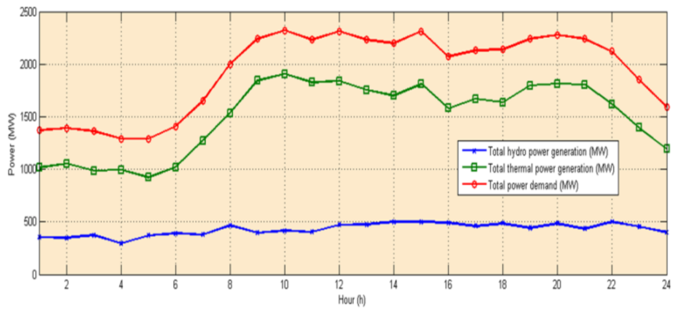

Fig. 5. Hydro generation, thermal generation, and total load demand for four hydro and an equivalent thermal system without valve-point loading effect

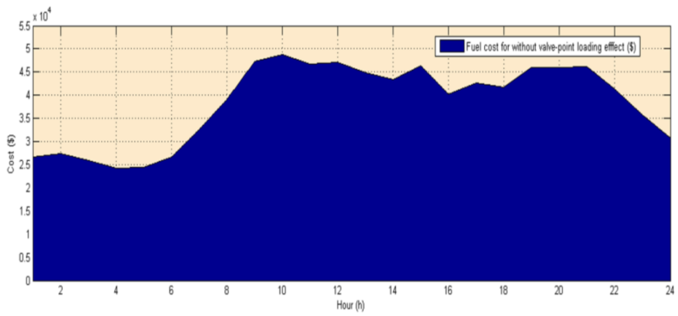

Fig. 6. Fuel cost for four hydro and an equivalent thermal system without valve-point loading effect

5.1.2 Case B: STHTS problem with valve-point loading effect

In order to express the viability of the proposed method, Valve-Point Loading effect of thermal generator is considered in this case. Th total fuel cost as a function of power output of the thermal system with valve-point loading effect is mathematically expressed in a quadratic form.

$$\min TC = \sum_{t=1}^{T}\sum_{i=1}^{N} a_i P_{sit}^2 + b_i P_{sit} + c_i + \left|d_i \times \mathrm{Sin}\{e_i \times \left(P_{sit}^{min} - P_{sit}\right)\right|\} \quad (31)$$

Table 3 - Simulation results for four hydro and an equivalent thermal system with valve point loading effect (Case B)

Hour (h)	Hydro Gen (MW)				Total Hydro Gen. (MW)	Total Thermal Gen. (MW)	Load Demand (MW)	Fuel cost ($)
	Ph_1	Ph_2	Ph_3	Ph_4				
1	82.2387	46.798	0.0000	225.5115	354.5482	1015.4518	1370	26558.9593
2	89.312	38.5192	0.0000	201.4874	329.3186	1060.6814	1390	27615.1729
3	83.1938	72.4855	0.0000	192.3558	348.0351	1011.9649	1360	26477.872
4	78.6960	39.5631	0.0000	170.4364	298.6955	991.3045	1290	25998.4156
5	52.6711	59.6035	42.9633	201.3850	356.6229	933.3771	1290	24663.2259
6	63.0135	69.3240	40.0151	182.8388	375.1914	1024.8086	1410	26776.7904
7	72.4921	49.7591	54.5084	211.2905	388.0501	1261.9499	1650	32414.4732
8	79.1413	32.7414	64.2851	193.9123	370.0801	1629.9199	2000	41607.7424
9	55.0610	34.0999	41.5184	270.9272	401.6065	1838.3935	2240	47056.5498
10	48.7224	65.5471	63.2552	251.4321	428.9568	1891.0432	2320	48460.1128
11	76.8641	63.6405	36.6400	274.2587	451.4033	1778.5967	2230	45475.8769
12	79.4629	55.2129	64.4590	233.5381	432.6729	1877.3271	2310	48093.3917
13	81.0087	57.5632	46.3567	258.9992	443.9278	1786.0722	2230	45672.6887
14	98.4336	57.7449	60.2647	213.0480	429.4912	1770.5088	2200	45263.1770
15	84.5337	69.2428	65.1567	318.6014	537.5346	1772.4654	2310	45314.5923
16	96.2355	84.2205	40.4318	254.5693	475.4571	1594.5429	2070	40700.3603
17	86.6026	59.3448	38.0758	269.2151	453.2383	1676.7617	2130	42816.8920
18	91.5925	74.9459	55.0595	252.7243	474.3222	1665.6778	2140	42529.984
19	87.4655	51.9033	64.0702	287.4587	490.8977	1749.1023	2240	44701.4740
20	85.7286	73.5987	36.6400	284.4578	480.4251	1799.5749	2280	46028.7803
21	82.0586	68.5000	36.6400	300.0000	487.1986	1752.8014	2240	44798.4019
22	76.0772	69.9540	46.6400	310.6878	493.3590	1626.6410	2120	41523.4291
23	85.5207	48.2801	60.6325	303.7175	498.1508	1351.8492	1850	34610.4927
24	87.7628	69.6254	36.6400	269.4212	463.4494	1126.5506	1590	29168.0135
Total fuel cost ($)								924326.9000

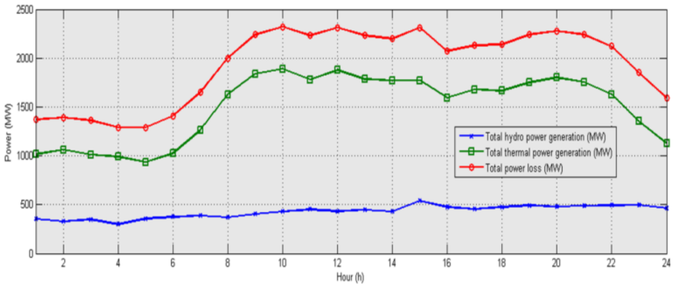

Fig. 7. Hydro generation, thermal generation, and total load demand for four hydro and an equivalent thermal systems with valve-point loading effect

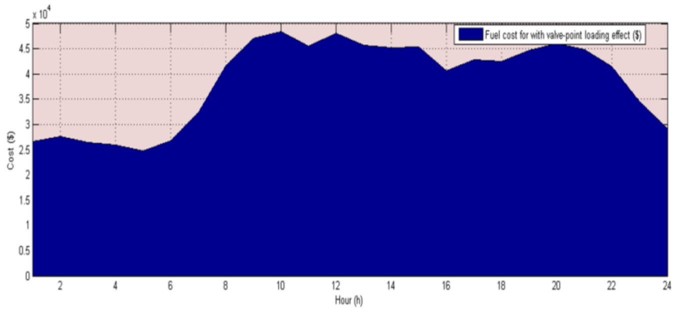

Fig. 8. Fuel cost per hour for four hydro and an equivalent thermal systems with valve-point loading effect

Table 4 - Comparison of fuel cost of proposed method with existing methods (Case B)

Methods	Best total fuel cost ($)
NLP [20]	936 709.52
DP [20]	935 617.76
IFEP [20]	933 949.00
QEA [28]	930 647.96
DE [20]	928 662.84
RQEA [28]	926 068.33
MDE [20]	925 960.56
IPSO [28]	925 948.84
MHDE [20]	925 547.31
DRQEA [28]	925 485.21
ITLBO (Proposed)	924326.90

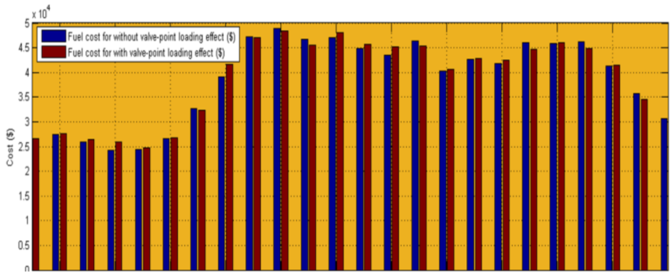

Fig. 9. Comparison of fuel cost with and without valve-point loading effect

After 200 independent iterations, the results given by the proposed ITLBO for twenty four hour time schedule in terms of optimal hydro and thermal power generations along with corresponding cost are listed in Table 3. Graphical presentation of Hydro generation, thermal generation to load demand over 24 hour is shown in Fig. 7.

Fig. 8 shows the fuel cost obtained by proposed method and a comparison of fuel cost of with/without valve-point loading effect has been done and displayed in Fig. 9. The optimal fuel cost achieved from the suggested method had been correlated with existing methods in the literature IFEP [20], IPSO [27], NLP [20], DP [20]. From Table 4, it is observed that the proposed ITLBO algorithm has superior searching capability in providing minimized fuel cost.

5.2 Test system 2: Four Hydro with ten thermal test systems

The second test system of the STHTS problem consists of four cascaded hydro and ten thermal plants. The valve-point loading effect of the thermal cost function is examined to illustrate the robustness of the proposed approach. The detailed data of four hydro plants, ten thermal plants with valve-point loading and load demands has been taken from [17]. The control parameters of proposed ITLBO algorithm has been choosen through trial and error process for this test system, where the population size is 50 and the maximum number of iteration is 300 in order to provide the best solution.

After 300 independent iterations, the simulation results of proposed test system are presented in Table 5 and Table 6. This table summarizes the thermal power generation, hydro power generation, total hydro generation, total thermal generation and fuel cost of thermal units with valve-point loading effect. The proposed ITLBO algorithm provides the minimum fuel cost of $ 170257.352. This experiment has been validated by comparing the results with the other available methods and reported in Table 7. Graphical presentation of Hydro generation, thermal generation corresponding to load demand over twenty four hour is shown in Fig. 10.

Table 5 - Thermal generation of the Second test system with valve point loading effect

Hour (h)	Thermal power generation (MW)									
	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{s5}	P_{s6}	P_{s7}	P_{s8}	P_{s9}	P_{s10}
1	84.7437	224.0207	88.0875	101.7420	97.2378	152.0397	266.7387	66.7722	147.9718	74.6459
2	226.4829	169.2458	79.2377	116.7643	235.5702	110.8121	212.7885	104.6026	97.5385	96.9770
3	321.0426	84.4551	94.7123	62.5884	70.0380	132.7249	158.8001	104.2933	120.8142	145.5312
4	222.8898	125.7253	91.9717	90.8052	156.6650	284.5522	59.0723	78.1605	92.6837	49.4772
5	244.2503	164.4969	65.5658	27.9052	191.0833	180.6611	159.0250	51.8582	68.7807	110.3735
6	269.5192	232.7908	78.9078	112.2335	109.2742	117.2047	212.1728	53.6723	97.4216	130.8032
7	355.7705	212.4114	99.8037	37.1962	250.4581	319.4882	107.3523	52.0170	70.9642	94.5351
8	144.3388	299.5638	83.9144	75.4900	272.2568	278.2565	107.3039	136.9434	128.0394	110.8930
9	253.6003	342.0628	73.2997	117.3384	180.7919	358.2287	76.7046	35.8171	105.2260	157.9306
10	284.0841	215.1688	78.8677	83.6384	378.4211	236.8079	156.0892	68.5022	89.4794	84.9414
11	112.7174	361.9113	89.3314	67.2471	318.8805	275.8845	167.8521	60.9584	113.4399	130.7771
12	86.1832	284.7432	99.0386	73.3814	335.0800	362.2702	267.2695	35.9846	90.1885	120.8398
13	112.7563	326.4290	97.3410	83.1582	279.1437	226.7585	207.4489	56.8087	142.8379	172.3177
14	289.1475	306.7023	114.3820	71.0897	364.1065	111.5989	55.2901	69.9631	135.6819	146.0263
15	372.4336	286.6478	49.7464	50.3885	121.4294	240.7900	275.8846	47.5814	49.6113	101.5115
16	230.3276	399.2560	105.7956	24.1219	146.0958	317.0638	175.4898	94.2131	79.2449	61.3910
17	230.6181	143.1288	123.5930	116.1448	331.8190	125.6125	336.4775	86.4065	58.5771	90.6228
18	230.7439	169.2622	64.3713	72.8120	308.0937	299.7540	244.0972	56.4528	107.9789	128.4340
19	152.0927	319.3810	62.1170	24.0462	87.5251	305.7227	289.0308	138.3459	142.8286	121.9123
20	195.9049	328.2614	46.0633	59.3611	166.7850	269.9129	234.2355	88.4381	84.2786	149.7593
21	276.4963	133.9812	40.6270	106.6686	120.3887	284.7758	156.7301	75.9945	113.3965	104.8130
22	179.3942	162.4543	102.9591	69.4341	127.4962	168.3678	347.7384	58.3710	139.9504	118.8347
23	289.3459	359.3401	62.9556	86.9817	135.8037	163.9149	53.4661	124.3186	47.9619	89.9114
24	240.2949	185.6124	65.0184	71.4551	75.7359	336.4617	156.0277	71.0499	74.7305	129.6135

Table 6 - Hourly hydro, and cumulative values of hydro, thermal power generation and fuel cost with valve point loading effect for the second test system

Hour (h)	Hydro power generation (MW)				Total hydro generation (MW)	Total thermal generation (MW)	Demand (MW)
	P_{h1}	P_{h2}	P_{h3}	P_{h4}			
1	95.5115	69.8209	0.0000	258.0775	445.069	1304.931	1750
2	90.9745	74.7832	0.0000	231.4874	329.993	1450.007	1780
3	92.3558	83.6649	0.0000	297.9399	404.451	1295.549	1700
4	89.9101	73.7400	0.0000	231.1682	397.095	1252.905	1650
5	71.2868	69.0341	49.5267	178.3400	405.221	1264.778	1670
6	90.7834	71.9312	49.4099	277.2868	385.639	1414.361	1800
7	96.8104	51.3463	47.2386	250.7834	349.155	1600.845	1950
8	97.6730	72.5986	52.6833	243.5141	372.332	1637.668	2010
9	79.8282	44.5552	47.5635	223.9454	388.337	1701.663	2090
10	86.0086	44.4421	53.8308	230.3313	403.713	1676.287	2080
11	75.1254	44.1282	54.4479	230.4211	400.717	1699.282	2100
12	97.6161	61.2104	57.8402	253.5381	394.321	1755.679	2150
13	67.8000	37.3048	57.1879	312.4216	404.785	1705.214	2110
14	90.0537	39.3635	58.7309	311.7554	365.242	1664.758	2030
15	85.9894	52.0439	59.6800	301.2126	413.882	1596.118	2010
16	92.0732	71.9992	41.4446	284.9762	426.974	1633.026	2060
17	73.7873	38.9118	56.7052	290.6911	406.004	1643.996	2050
18	75.8029	72.2318	56.5483	279.9264	437.987	1682.013	2120
19	90.8502	65.6000	68.2090	317.4567	426.574	1643.426	2070
20	93.4007	86.4474	79.9270	318.4578	426.030	1623.970	2050
21	97.2895	66.6465	60.0000	310.0000	448.695	1461.305	1910
22	85.3895	53.6606	59.5503	300.9878	384.730	1475.269	1860
23	80.3942	51.9851	29.5734	291.7824	435.893	1414.106	1850
24	87.8000	56.5119	30.0000	283.4712	393.800	1406.200	1800
Total fuel cost ($)					170257.3520		

Table 7 - Comparison of fuel costs of proposed with existing methods for the Second test system

Method	Min cost ($)	Avg. Cost ($)	Max cost ($)
SPSO [29]	189350.63	190560.31	191844.28
MDE [29]	177338.60	179676.35	182172.01
DE [17]	170964.15	NA	NA
ITLBO (Proposed)	**170257.352**	**171383.138**	**172482.908**

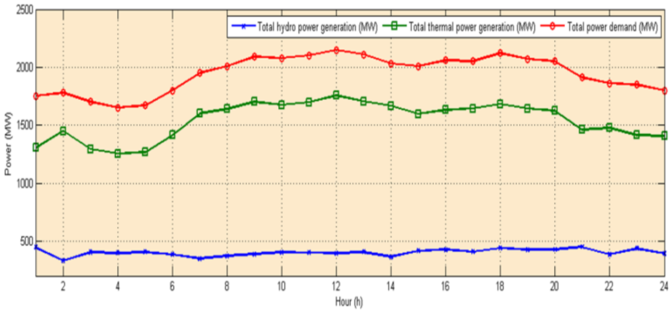

Fig. 10. Comparison of total hydro generation, total thermal generation, total load demand for the test system 2

6. Conclusion

The optimal generation scheduling of hydrothermal plants plays a dynamic role in an interconnected power system in order to curtail down the total fuel cost of thermal power plants. In this paper, an innovative approach based on improved TLBO algorithm has been projected and scrupulously employed in evolving the solution for hydrothermal plants. The effectiveness and applicability of this method has been proved by testing the algorithm on multi-chain cascaded four hydro plants and number of thermal units represented by an equivalent thermal plant for twenty four hour planning period. The results have been obtained for the water discharge, reservoir storage volume, and optimal MW values of hydro and thermal real power, hourly fuel cost and the total cost of hydrothermal system. The superior performance of the proposed method has been compiled by comparing with that of other examples used by other researchers such as GA, IPSO, EP, DE, modified DE and TLBO. The outcomes of the case studies clearly enumerate that the algorithmic features of proposed methodology in minimising the fuel cost of the hydrothermal plants.

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Appendix A

Table A1 - System Load Demand (MW)

Hour (h)	Load Demand (MW)	Hour (h)	Load Demand (MW)
1	1370	13	2230
2	1390	14	2200
3	1360	15	2310
4	1290	16	2070
5	1290	17	2130
6	1410	18	2140
7	1650	19	2240
8	2000	20	2280
9	2240	21	2240
10	2320	22	2120
11	2230	23	1850
12	2310	24	1590

Table A2 - Number of upstream plant and transportation Delay time

Plant	1	2	3	4
R_u	0	0	2	1
t_d (s)	2	3	4	0

Table A3 - Hydro power generation coefficients

Plant	c_{1j}	c_{2j}	c_{3j}	c_{4j}	c_{5j}	c_{6j}
1	-0.0042	-0.42	0.030	0.90	10.0	-50
2	-0.0040	-0.30	0.015	1.14	9.5	-70
3	-0.0016	-0.30	0.014	0.55	5.5	-40
4	-0.0030	-0.31	0.027	1.44	14.0	-90

Table A4 - Reservoir storage capacity limits, reservoir end conditions, plant discharge limits (*10^4 m^3) and plant generation limits (MW)

Plant	V_{hj}^{min}	V_{hj}^{max}	V_{hj0}	V_{hjT}	Q_{hj}^{min}	Q_{hj}^{max}	P_{hj}^{min}	P_{hj}^{max}	q_{pro}
1	80	150	100	120	5	15	0	500	8-9
2	60	120	80	70	6	15	0	500	7-8
3	100	240	170	170	10	30	0	500	22-27
4	70	160	120	140	6	20	0	500	16-18

Table A5 - Reservoir Inflows

Hour (h)	Plant				Hour (h)	Plant			
	Reservoir					Reservoir			
	1	2	3	4		1	2	3	4
1	10	8	8.1	2.8	13	11	8	4	0
2	9	8	8.2	2.4	14	12	9	3	0
3	8	9	4	1.6	15	11	9	3	0
4	7	9	2	0	16	10	8	2	0
5	6	8	3	0	17	9	7	2	0
6	7	7	4	0	18	8	6	2	0
7	8	6	3	0	19	7	7	1	0
8	9	7	2	0	20	6	8	1	0
9	10	8	1	0	21	7	9	2	0
10	11	9	1	0	22	8	9	2	0
11	12	9	1	0	23	9	8	1	0
12	10	8	2	0	24	10	8	0	0

Table A6 - Thermal unit characteristic coefficients

Unit	a_i	b_i	c_i	d_i	e_i	P_s^{min}	P_s^{max}
1	0.002	19.2	5000	700	0.085	500	2500