Optimal Scheduling of Multi-Chain Hydrothermal System using Teaching-Learning Based Optimization

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in

POWER SYSTEMS

by

Prerna Charak

(Reg. No. 801241018)

Under the supervision of

Dr. Sanjay K. Jain

ELECTRICAL & INSTRUMENTATION ENGINEERING DEPARTMENT

THAPAR UNIVERSITY

PATIALA–147004

PUNJAB–INDIA

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CERTIFICATE

I hereby certify that the work which is being presented in the dissertation entitled, **"Optimal Scheduling of Multi-Chain Hydrothermal System using Teaching-Learning Based Optimization"** in partial fulfillment of the requirement for the award of the Degree of ***Master of Engineering*** in **Power Systems** and submitted in the ***Electrical & Instrumentation Engineering Department*** of the **THAPAR UNIVERSITY** is an authentic record of my own work carried out under the supervision of **Dr. Sanjay K. Jain**, Associate Professor, EIED.

The matter presented in this dissertation has not been submitted for the award of any other degree of this or any other University.

Prerna Charak
801241018

This is to certify that the above statement made by the candidate is correct and true to best of my knowledge.

Dr. Sanjay K. Jain
Associate Professor

Date: 17/07/2014

Countersigned by :

(Dr. Ravinder Agarwal)
Professor & Head
Electrical & Instrumentation Engg. Deptt.
Thapar University, Patiala

(Dr. S.K. Mohapatra)
Senior Professor & Dean
Academic Affairs
Thapar University, Patiala

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Prerna Charak
(801241018)

Abstract

The optimal, short term scheduling of hydrothermal plants is important in planning the operation of the power system. In this scheduling, the hydroelectric and thermal power generation is optimized to minimize the total operating cost (fuel cost) of the thermal plant. This problem of short term hydrothermal scheduling (STHTS) is complex due to consideration of equality and inequality constraints and nonlinearties like valve point loading and prohibited discharge zone.

In this dissertation, teaching - learning based optimization (TLBO) algorithm is used to solve the problem of short-term hydrothermal scheduling (STHTS) considering nonlinearities like valve point loading effects of the thermal unit and prohibited discharge zone of water reservoir of the hydro units. The proposed algorithm has been tested on the multi-chain test system having four hydro units and one thermal. The results are compared with results reported in literature and the implementation is found effective.

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Nomenclature

FC	Total fuel cost of thermal units
$Ps_{i,j}$	Power generation of the ith thermal at jth interval
$Ph_{i,j}$	Power generation of ith hydro unit at jth interval
$Ps_i^{min}; Ps_i^{max}$	Operating limits of ith thermal unit
$Ph_i^{min}; Ph_i^{max}$	Operating limits of ith hydro plant
$Ploss_j$	Transmission loss at jth time interval
Pd_j	Load demand at jth time interval
$a_i - e_i$	Fuel cost coefficients of the ith thermal generating unit
$c_{i,1} - c_{i,6}$	Power generation coefficients of ith hydro unit
$Q_{i,j}$	Water discharge of ith hydro plant during jth time interval
$Q_i^{min}; Q_i^{max}$	Lower and upper limits of reservoir water discharge of ith hydro plant
q_{pro}	Prohibited discharge zone of thermal unit
$V_{i,j}$	Water storage level of ith hydro reservoir at jth time interval
V_i^{begin}	Initial storage volume
V_i^{end}	Final storage volume
$V_{i,j}\|_{j=0}$	Volume of reservoir at 1st hour
$V_{i,j}\|_{j=NH}$	Volume of reservoir at end of 24th hour
$V_i^{min}; V_i^{max}$	Water storage level limits ith hydro reservoir
$Td_{k,i}$	Water transport delay from kth to ith reservoir
Ru_i	Number of upstream hydro generating plants immediately above the ith reservoir
$Inf_{i,j}$	Natural inflow of the ith reservoir at jth time interval
$S_{i,j}$	Spillage discharge rate of the ith reservoir at jth time interval
nh, nt	Number of hydro and thermal unit s
NH	Time horizon

Chapter–1

INTRODUCTION

1.1 OVERVIEW

In present set-up, optimum scheduling of hydrothermal plants is important because of its economical aspect in interconnected power system operation. The hydrothermal scheduling problem is directed to minimize the operating cost of thermal plants as the operating cost of hydrothermal plants is negligible. Thus, the problem of minimizing the operational cost of a hydrothermal system is to minimize the fuel cost of thermal plants subjected to various equality and inequality constraints offered by the operation of hydrothermal plants and power system network. Limited energy storing capacity of water reservoirs and having the stochastic nature of availability of water makes the solution more difficult for hydrothermal systems compared to pure thermal systems [1]. Hydroelectric plants also meet purposes other than power generation including flood control and irrigation purpose [2].

Most of the hydro-systems are having different characteristics mainly due to differences in availability of water, control constraints, non-uniform water flow, number of hydro stations and their locations etc. The problem is different when the plant is located on the same stream or on a different stream. To minimize overall cost of system available hydro resources has to be utilized fully. The hydrothermal problem includes long range problem and short range problem.

The **Long-range hydro scheduling problem** involves the long range forecasting of water availability and the scheduling of water releases. Typical long-range scheduling goes anywhere from one week to one year or several years. Long range scheduling involves optimizing policy in the context of unknowns such as loads, hydraulic inflows and unit availabilities. These unknowns are treated statistically and long-range scheduling involves optimization of statistical variables. This problem is classified as: multi-storage hydroelectric systems, cascaded hydroelectric systems, multi-chain hydroelectric systems. The **Short-range hydro scheduling problem**

involves one day to one week or hour-by-hour scheduling of all generations on a system to achieve minimum production cost for the given time period. A set of starting conditions is given to get the optimized schedule with the minimum cost which is desired. The amount of water to be utilized for short-range scheduling problem is known from the solution of long-range scheduling problem. This problem is classified as: fixed head hydrothermal scheduling and variable head hydrothermal scheduling.

Several methods for solving the problem of short-term hydrothermal scheduling have been proposed. The classical methods of solving the scheduling problem are not suitable when the system size increases. Further the computational requirements also increases with he classical methods. Therefore, various evolutionary techniques such as particle swarm optimization(PSO)[3] [4] [5], constriction factor based particle swarm optimization technique (CFPSO) [6], evolutionary programming (EP) [7], genetic algorithm (GA) [8][9], differential evolution [10] [11] are used for hydrothermal scheduling.

In this dissertation, teaching-learning based optimization, developed by Rao et al., is used to solve the problem of short-term hydrothermal scheduling. This method is based on the process of learning in the class by teacher and their mutual interactions with each other. The algorithm uses the mean of decision variable of the population and uses this mean to update the solution. Also the students (population) interact with each other to update the solution.

The proposed algorithm is used to solve the problem with test system having four hydro units and one thermal unit considering valve point loading of thermal unit and neglecting transmission losses.

1.2 LITERATURE REVIEW

Gil et al. [1] proposed a genetic algorithms using specialized operators to deal with the short-term generation scheduling problem incorporating three types of scheduling: short-term HCP, UCP, and ELDP for scheduling horizon of a week, and hourly generation schedules are obtained for each hydro and thermal units.

Kothari and Dhillon [2] compiled the problems regarding planning and control of thermal as well as hydrothermal systems. Evolutionary algorithms were used to solve optimization and multi-objective optimization problems.

Mandal and Chakraborty [3] presented self-organizing hierarchical particle swarm optimization technique with time-varying acceleration coefficients algorithm for solving the problem of hydrothermal scheduling. The problem of premature convergence in PSO is avoided.

Sreenivasan et al. [4] presented optimized hourly scheduling of hydrothermal power system using PSO technique and compared the fuel cost and computation time.

Hota et al. [5] used PSO to solve the HTS problem and to find finding global solution. To show efficiency, the algorithm is applied to problem having prohibited operating zones.

Salama et al. [6] solved the problem of multi-chain hydrothermal scheduling for four hydro units and three thermal units with objective function having valve point loading effect using PSO. Less computational time is expected in this.

Sinha et al. [7] developed fast evolutionary programming algorithms which utilizes evolutionary programming algorithms with Gaussian and Cauchy mutation for the solution of short-term hydro thermal scheduling problems.

Orero and Irving [8] formulated optimal hourly scheduling of hydrothermal power system by genetic algorithm. The system having a non-linear relationship between water discharge rate, net head and power generation was analyzed. The hourly optimal loading of the system generators was offered by a multiple step genetic algorithm search sequence.

Kumar and Naresh [9] solved the scheduling problem of hydrothermal with real coded genetic algorithm which eliminates the need of penalty parameters. The algorithm use binary crossover and polynomial mutation.

Mandal and Chakraborty [10] presented differential evolution based optimization technique for solving optimal generation scheduling of hydrothermal systems and applied to multi-reservoir cascaded hydrothermal system by considering constraints of hydro and thermal units and the effect of valve point loading.

Lakshminarasimman and Subramanian [11] formulated the optimal scheduling problem of short term hydrothermal system with the modified differential evolution algorithm. The algorithm does not require the use of penalty functions to explores the optimum solution.

Hinojosa and Leyton [12] formulated the hydro generation scheduling problem taking into account water discharge as continuous variables and binary thermal states using mixed-binary evolutionary particle swarm optimization. The algorithm works to keep the decision variables in feasible space through the correction operators to improve the quality of the solutions and the convergence of the search process.

Wood and Wollenberg [13] provide the techniques used in modern power systems with the emphasis on the economic aspects of energy management and characteristics of thermal and hydroelectric power generation systems along.

Kim et al. [14] solved the problem of economic load dispatch for valve point discontinuities using genetic algorithm. Lee and Breipohl [15] suggested the method for reserve constrained economic dispatch problem of generating units having prohibited operating zone(s) and for a unit the zone(s) is divided into its minimum and maximum limits.

Rao et al. [16] presented TeachingLearning-Based Optimization (TLBO), optimization procedure for mechanical design. The working of this technique is similar to teaching-learning process in the class. The population in this technique is considered as the number of students in a class and the global solution is obtained by the effect of teacher on students and by the interaction of students in class.

Roy [17] used TLBO to solve short-term hydrothermal scheduling problem considering valve point effects of thermal units and prohibited discharge zone of water reservoir of hydro

plants and the results shows the effectiveness of the proposed algorithm over the other mentioned algorithms.

Rao and Patel [18] proposed elitism concept in the TLBO algorithm and explore the effect of elitism and controlling parameters, the population size and the number of generations, on the performance of the algorithm. The performance of the algorithm is compared with that of other well known optimization algorithms.

Rao et al. [19] suggested that proper selection of parameters is essential for other nature-inspired algorithms and otherwise the effectiveness of the algorithm is affected where as TLBO is parameter free algorithm.

1.3 OBJECTIVE OF WORK

The objective of this study is to determine the optimal scheduling of multi-chain hydrothermal system to meet the load demand over the scheduled horizon of 24 hours with one hour intervals while satisfying the various equality and inequality constraints of hydro and thermal power system network considering valve point loading effect of thermal unit and prohibited discharge zones of hydro units.

1.4 ORGANISATION OF DISSERTATION

The **Chapter 1** review the hydrothermal generation scheduling problem with introduction to the optimization algorithms, the literature review, objective of report and organisation of dissertation. **Chapter 2** describes the short-term hydrothermal scheduling, need for hydrothermal scheduling, classification of hydro plants and the problem formulation. **Chapter 3** explains the teaching-learning based optimization technique, algorithm and its implementation to the problem of short-term HTS. **Chapter 4** details the test system and the results obtained after the implementation of TLBO algorithm. **Chapter 5** summarises the conclusions and scope of future work.

Chapter–2

SHORT-TERM HYDROTHERMAL SCHEDULING

2.1 INTRODUCTION

The basic idea for the scheduling of hydrothermal plant is to meet the given load demand for the specified time horizon. The optimal scheduling of hydrothermal plant involves generation of power from hydro as well as thermal plants so as to minimise the total fuel cost of thermal plant. Thus the problem scheduling problem can be solved by minimizing the fuel cost of thermal plant while considering the various hydro plant constraints. The main constraints of problem include: cascaded nature of the hydraulic network, the time coupling effect of the hydro sub problem where the water inflow of an earlier time interval affects the discharge capability at a later period of time, the varying hourly reservoir inflows, the physical limitations on the reservoir storage and turbine flow rate, the varying system load demand and the loading limits of both thermal and hydro plants [8] [12].

In short-term hydrothermal scheduling, the scheduling period is taken as one day to one week and involves hour-by-hour generation of the scheduling horizon to achieve the minimum production cost for the generation of power. The amount of water utilized for the short-range scheduling problem is known from the solution of long-range scheduling problem. A set of reservoirs conditions for hydro plants is given and the optimal hourly schedule of the desired objective i.e. minimizing the fuel cost, while satisfying the hydro system constraints, is obtained [13].

Prohibited Discharge Zone of hydro units: A hydro generating unit may have prohibited zone(s) due to the physical limitations of power plant components (e.g. vibrations in a shaft bearing are amplified in a certain operating region). For a prohibited zone, the unit can only operate above or below the zone. For example, an 500 MW generator, with a minimum

generation limit (Pmin) of 100 MW and a maximum generation limit (Pmax) of 500 MW, may have a prohibited operating zone, say, between 250 MW and 350 MW. This prohibited zone results in two disjoint convex regions - the region between 100 MW and 250 MW and the region between 350 MW and 500 MW. These two disjoint regions form a non-convex set [15].

Valve point loading in thermal units: In general, the input-output characteristics of a thermal generator can be approximated by quadratic or piecewise quadratic function. However, real input-output characteristics contain higher order non-linearity and discontinuity owing to valve point effect, so classical methods for approximation by quadratic function is not suitable for obtaining real global optimal point.

$$FC = a_i * Ps_i^2 + b_i * Ps_i + c_i \tag{2.1}$$

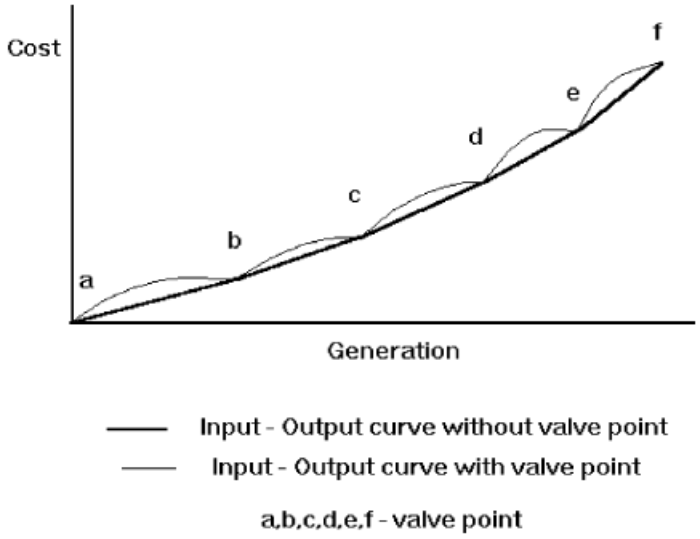

Fig. 2.1 Input-Output curve of thermal generator

The Fig. 2.1 shows the performance curve for a typical thermal unit. Bold line represents the curve approximated by the quadratic function shown in eq. 2.1. This curve, however, can not represent the real input-output characteristics of thermal generators. The ripples in the input-output curve in the thin line express the result of the sharp increase in losses due to the wire drawing effects which occur as each steam admission valve starts to open. This phenomenon is called as valve point effect. Cost function is obtained based on the ripple curve for more accurate modeling. As shown in Fig. 2.1, this curve contains higher order non-linearity and discontinuity

due to valve point effect, and should be refined by sine function. Therefore, above eq. 2.1 can be modified as:

$$FC = FC + |d_i * sine(e_i(Ps^{min} - Ps_i))| \tag{2.2}$$

A turbine loaded at a valve point just before next valve open is working at maximum efficiency at that loading. Therefore if all parallel turbine are loaded on selected valve point maximum efficiency can results. The concept of valve point loading is inherently unsuited for matching generation to a continuously varying load. Therefore a certain amount of capacity must be withheld from valve point operation in order to be operated in continuous manner and is explain in [14] [20].

2.2 NEED OF HYDROTHERMAL SCHEDULING

The idea of hydrothermal coordination is to utilize all energy resources in most economic and efficient manner. The scheduling of hydroelectric plant is more complex than the scheduling of thermal plants. The hydroelectric plants are associated with the water discharge (i.e. water outflow from one plant is the water inflow for one or more downstream plant) from one reservoir to other and plays very significant role for the optimal power generation. It is vital to use the amount of water available by water reservoirs of hydro systems to full extent in hydrothermal integration. In hydro system, there is no fuel cost associated with power generated i.e. the charges are fixed for hydropower regardless of the amount generated.

In hydrothermal systems the optimal cost is achieved by utilizing the available water resources for a given time horizon and run the hydro generation units according to the forecasted load demand so that the fuel cost for thermal generation is minimized.

Thus the hydrothermal scheduling is important as the operating cost of thermal plant is very high, though their capital cost is low. On the other hand, the operating cost of hydroelectric plant is low, though their capital cost is high. So, it has been economical as well as convenient to have both thermal as well as hydro plants in the same grid. The hydroelectric plant can be started quickly and it has higher reliability and greater speed of response. Hence hydro plants can take up the fluctuating loads. In contrast to hydro plants, starting of thermal plant is slow and their

speed of response is slow as well. This is the reason why thermal plants run as base load plants and hydro plants run as peak load plant [2].

2.3 CLASSIFICATION OF HYDRO PLANTS

Classification has been reported based on -

- type
- location
- water head
- nature of load

2.3.1 Based on type

Hydro power plants, on the basis of their type, are classified as:

- Pumped storage plants
- Conventional plants

Pumped Storage Plants : When power from the plant is needed, water stored in an upper reservoir is released into an underground tunnel. The water rushes down the intake tunnel form upper reservoir. The force of the water form reservoir drives huge turbines, which are at the base of a dam. These turbines are connected to large generators, which produce the electricity. The water then flows through a discharge tunnel into a lower reservoir. When demand for electricity is low, the turbines spin backward and pump the water back up into the upper reservoir to make it available to generate electricity when it is needed.

Conventional Plants : These plants utilize the hydraulic energy of the flowing water of the rivers. Dams are constructed to collect the water in the reservoir and is used to run the turbines. Conventional plants are further classified as

Run-of-river plants without pondage :- These plants does not have storage or pondage to store water. Run-off river plants without pondage uses water as it comes. The plant can use water

as and when available. Since, generation capacity of these type of plants these plants depend on the rate of flow of water, during rainy season high flow rate may mean some quantity of water to go as waste while during low run-off periods, due to low flow rates, the generating capacity will be low.

Run-off river plants with pondage :- In these plants, pondage allows storage of water during lean periods and use of this water during peak periods. Based on the size of the storage structure provided it may be possible to cope with hour-to-hour fluctuations. This type of plant can be used on parts of the load curve as required, and is more useful than a plant without pondage. If pondage is provided, tail race conditions should be such that floods do not raise tail-race water level, thus reducing the head on the plant and impairing its effectiveness.

Reservoir plants :- A reservoir plant is that which has a reservoir of such size as to accede carrying over storage from wet season to the next dry season. Water is stored behind the dam and is available to the plant with control as required. This type of plant has better extent and can be used efficiently throughout the year. Its firm capacity can be expanded and can be utilized either as a base load plant or as a peak load plant as required. It can also be used on any portion of the load curve as required. Maximum hydro-electric plants are of this type.

2.3.2 Based on location

On the basis of their location, hydro plants are classified into three different categories:

- Hydro plants on different streams
- Hydro plants on same stream
- Multi-chain hydro plants

Hydro plants on different streams: These are those hydro plants which are located on different streams and does not depend on each other as shown in Fig. 2.2.

Hydro plants on same stream: These plants are in series with each other. The downstream plant depends on the immediate upstream plant and is shown in Fig. 2.3.

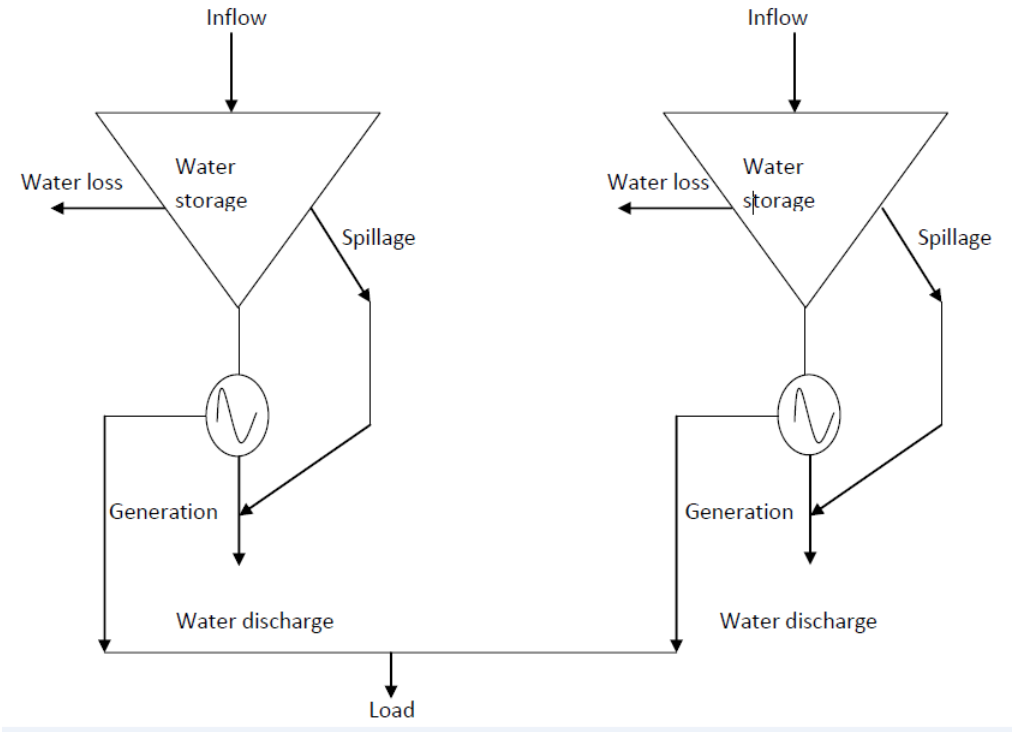

Fig. 2.2 Hydro plants on different streams

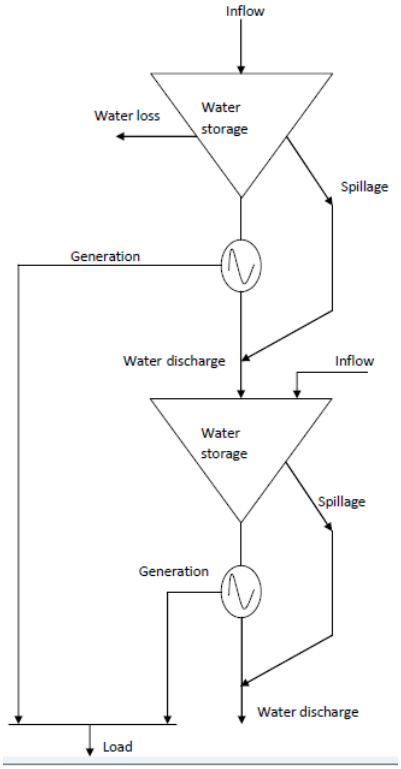

Fig. 2.3 Hydro plants on same stream

Multi-chain hydro plants: These hydro plants are located on different as well as on the same stream, i.e. they are in series with plants located on the different streams and is shown in Fig. 2.4.

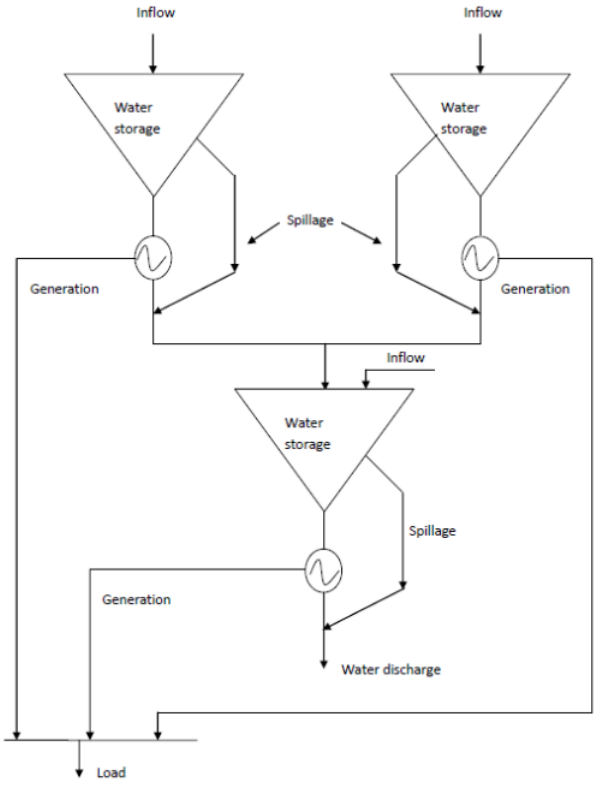

Fig. 2.4 Multi-chain hydro plants

2.3.3 Based on availability of water head

There are three types of hydroelectric power plants based on the height of water head available in the reservoir, these are:

- Low-head hydro-electric plants (less than 30 m)
- Medium-head hydro-electric plants (30 - 300 m)
- High-head hydro-electric plants (greater than 1,000 m)

Low-head hydro-electric plants : Low head hydro-electric plants are power plants which generally utilize heads of only a few meters or less. Power plants of this type may utilize a low dam or weir to channel water, or no dam and simply use the run of the river. Run of the river

generating stations cannot store water, thus their electric output varies with seasonal flows of water in a river. A large volume of water must pass through a low head hydro plants turbines in order to produce a useful amount of power. Hydro-electric facilities with a capacity of less than about 25 MW are generally referred to as small hydro, although hydro-electric technology is basically the same regardless of generating capacity.

Medium-head hydro-electric plants : These plants consist of a large dam in a mountainous area which creates a huge reservoir. Dams are also used for flood control, irrigation, recreation, and often are the main source of potable water for many communities. Hydro-electric development is also possible in areas such where natural elevation changes can be used.

High-head hydro-electric plants : High head power plants are the most common and generally utilize a dam to store water at an increased elevation. The use of a dam to impound water also provides the capability of storing water during rainy periods and releasing it during dry periods. This results in the consistent and reliable production of electricity, able to meet demand. Heads for this type of power plant may be greater than 1,000 m. Most large hydro-electric facilities are of the high-head variety. High-head plants with storage are very valuable to electric utilities, because they can be quickly adjusted to meet the electrical demand on a distribution system.

2.3.4 Based on nature of load

Depending on the nature of load on the hydroelectric power plant, two types of hydroelectric power plants are:

- Peak Load
- Base Load

Peak Load: The peak load plants are used to supply power at the peak demand phase. The pumped storage plants and Gas Turbine plants are this type of plants. Their efficiency varies between 60 - 70 percent.

Base Load: A base load power plant is one that provides a steady flow of power regardless of total power demand by the grid. These plants run at all times through the year except in the case of repairs or scheduled maintenance.

2.4 MATHEMATICALLY FORMULATION OF STHTS PROBLEM

In this study, the hydrothermal problem has been formulated for one day ahead taking into account in the optimization problem. The cost of generation of power from hydro units are almost negligible as the power is generated from water. So the main objective of the problem is to minimize the fuel cost for generation of power from thermal plants using hydropower as much as possible to supply the load demand for the scheduled period, satisfying the various operational constraints.

2.4.1 Objective function

The total fuel cost for the equivalent thermal over the scheduled horizon is given by FC. The objective function with quadratic cost function for thermal units is expressed as:

$$MinimizeFC = \sum_{i=1}^{nt} \sum_{j=1}^{NH} a_i \times Ps_{i,j}^2 + b_i \times Ps_{i,j} + c_i \tag{2.3}$$

For more accurate results the fuel cost function, considering valve point effect, is the sum of quadratic function and sinusoidal function and is expressed as:

$$MinimizeFC = \sum_{i=1}^{nt} \sum_{j=1}^{NH} a_i \times Ps_{i,j}^2 + b_i \times Ps_{i,j} + c_i + |d_i * \sin(e_i * (Ps_i^{min} - Ps_{i,j}))| \tag{2.4}$$

2.4.2 Constraints

- **Equality constraints :** Various equality constraints for solving the problem of STHTS are discussed as :

  i. Power balance constraints : The total active power generation at each hour must be equal to predicted demand and the transmission loss.

$$\sum_{i=1}^{nh} Ph_{i,j} + \sum_{i=1}^{nt} Ps_{i,j} = Pd_j + Ploss_j \tag{2.5}$$

ii. Power generation constraints : The hydro power generation is a function of water discharge rate of reservoir and storage volume.

$$Ph_{i,j} = c_{i,1} \times V_{i,j}^2 + c_{i,2} \times Q_{i,j}^2 + c_{i,3} \times V_{i,j} \times Q_{i,j} + c_{i,4} \times V_{i,j} + c_{i,5} \times Q_{i,j} + c_{i,6} \quad (2.6)$$

iii. Hydraulic continuity equation constraint : Water transportation delay between reservoirs is considered to determine the water storage volume.

$$V_{i,j+1} = V_{i,j} + Inf_{i,j} - Q_{i,j} - S_{i,j} + Z_{i,j} \quad (2.7)$$

where

$V_{i,j}$ = $V_{i,j-1} + Inf_{i,j} - Q_{i,j}$

$Z_{i,j}$ = $\sum_{k=1}^{Ru_i}(Q_{k,j-Td_{K,J}} + S_{k,j-Td_{K,J}})$

and $Z_{i,j}$ is the water discharge matrix from the upstream reservoir which will reach the next reservoir after the time delay, Td, in multi-chain cascaded reservoirs.

iv. Reservoir end conditions : The desired volume of water to be discharged by each reservoir over the scheduling period,

$$V_{i,j}|_{j=0} = V_i^{begin}; V_{i,j}|_{j=NH} = V_i^{end} \quad (2.8)$$

- **Inequality constraints :** These constraints are the limits pre specified in the problems and values must satisfies these constraints. The following are the constraints :

i. Thermal generation constraints : Power generation by equivalent thermal plant must lie within its limits:

$$Ps_i^{min} \leq Ps_{i,j} \leq Ps_i^{max} \quad ; i = 1, 2, ..., nt; j = 1, 2, ..., NH \quad (2.9)$$

ii. Hydro generation constraints : Power generation by the ith hydro plant must lie between its limits:

$$Ph_i^{min} \leq Ph_{i,j} \leq Ph_i^{max} \quad ; i = 1, 2, ..., nh; j = 1, 2, ..., NH \quad (2.10)$$

iii. Water discharge constraints : Water discharge of the ith hydro plant must lie within its maximum and minimum limits to satisfy the other constraints:

$$Q_i^{min} \leq Q_{i,j} \leq Q_i^{max} \quad ; i = 1, 2, ..., nh; j = 1, 2, ..., NH \tag{2.11}$$

In practice, hydro units may have prohibited discharge zones (PDZ). The water discharge rate of the hydro plant reservoirs having PDZ may be modelled as follows:

$$Q_i^{min} \leq Q_{i,j} \leq Q_i^{LB,1} \tag{2.12}$$

$$Q_i^{UB,n-1} \leq Q_{i,j} \leq Q_i^{LB,1} \quad ; n = 2, 3, , NDi \tag{2.13}$$

$$Q_i^{UB,n} \leq Q_{i,j} \leq Q_i^{max} \qquad ; n = NDi \tag{2.14}$$

where i= 1,2,.....,nh ; j=1,2,....,NH;

NDi is the number of prohibited discharge zones of the ith unit.

iv. Reservoir capacity constraints : The operating volume of reservoir storage limit must lie in between the minimum and maximum capacity limits:

$$V_i^{min} \leq V_{i,j} \leq V_i^{max} \quad ; i = 1, 2, ..., nh; j = 1, 2, ..., NH \tag{2.15}$$

Chapter–3

IMPLEMENTATION OF TLBO TO SHORT TERM HTS

3.1 TEACHING-LEARNING BASED OPTIMIZATION

Teaching-Learning based optimization algorithm is a new optimization technique developed by Rao et al. [16][21]. It is also a population based optimization method like other optimization algorithms and is inspired by the teaching-learning process in a class between teacher and learners. Teachers are considered as the most knowledgeable person and always try to influence the learners to achieve their goal. The quality of a teacher affects the outcome of the learners [16]. Also, the students in the class also improve their knowledge by discussing it with other students in class. The final result of the class is evaluated on the basis of the knowledge that the students have. Teaching-Learning Based Optimization (TLBO) obtain global solutions for continuous non-linear functions with less computational effort and high consistency [16].

The TLBO algorithm is also a population-based algorithm inspired by nature like other algorithms with a pre-defined population size. In all nature-based algorithms, initially the population is generated randomly and an individual in that population represents an optimal solution of the problem [17]. In this algorithm the population refers to the students in a particular class and subjects offered to those students are the design variables of the optimization problem. Thus the objective function value and the design variables constitute the solution representing knowledge of particular students. The teacher for the entire population is the best solution of that population. The design variables are actually the parameters involved in the objective function of the given optimization problem and the best solution is the best value of the objective function [18].

Like genetic algorithm, particle swarm optimization, artificial bee colony and harmony search, teaching-learning based optimization is also a population-based technique which

Table 3.1 Controlling parameters of various algorithms

Genetic Algorithm (GA)	Crossover probability, mutation rate and selection method.
Particle Swarm Optimization (PSO)	Learning factor, the variation of weight and the maximum value of velocity.
Artificial Bee Colony (ABC)	Limit value.
Harmony Search(HS)	Harmony memory consideration rate, pitch adjusting rate and number of improvisation.
Teaching-Learning Based Optimization (TLBO)	Mean values of population to update solution.

implements a group of solutions to proceed to the optimum solution. The controlling parameters of these algorithms as discussed in [16] are shown in Table 3.1. The working of TLBO comprises of : (i) Teacher phase and (ii) Learner phase.

3.1.1 Teacher Phase

The first part of the algorithm, where learners increase their knowledge through teacher is known as Teacher Phase. In this phase, the teacher tries to increase the mean result of the class in the subject taught by him or her, depending on his or her capability [19]. The best solution which is defined by the value of its objective function, from the population, is considered as the teacher. The increase in the knowledge of students in a class depends upon the teacher. But practically, for a teacher, it is impossible to increase the knowledge in the students equally because every student possesses different learning levels. So the teacher, after teaching, can only improve the mean level of learners in class to some extent. If the new average grade of the jth subject at kth iteration is μ^k_{newj} , the difference between the existing mean and new mean of the jth subject at the kth iteration may be formulated as, [17];

$$\mu^k_{diffj} = rand * (\mu^k_{newj} - t_f \mu^k_j) \tag{3.1}$$

where t_f is teaching factor which is evaluated randomly by the following equation:

$$t_f = round(1 + rand(0, 1)) \tag{3.2}$$

The grade of the jth subject of the ith student at (k+i)th iteration is updated by

$$x^{k+1}_{i,j} = x^k_{i,j} + \mu^k_{diffj} \tag{3.3}$$

It may be noted that the random value, in the range[0,1], and teaching factor, Tf, affect the performance of the TLBO algorithm. However, the value of TF are generated randomly in the algorithm and are not supplied as input to the algorithm [22]. So the tuning of these parameters are not required by the proposed algorithm unlike the tuning of controlling parameters of other algorithms. Tuning of population size and generation number is required by TLBO algorithm.

3.1.2 Learner Phase

A student also learn by interacting with other students in the class. So the phase of learning from the other students of the class is known as the Learner Phase. Learner phase is second part of the algorithm, where learners increase their knowledge by interaction among themselves [19]. A learner further improve the quality of their knowledge by comparing their knowledge with other students if the other learners have more knowledge. Thus Each student randomly choose another student for interaction and learn new things from him if that student has better knowledge than him. Mathematically this learning phenomenon may be expressed as follows [17]:

$$x^{k+1}_{i,j} = x^k_{i,j} + rand * (x^k_{i,j} - x^k_{l,j}); if F(X_i) < F(X_l) \tag{3.4}$$

$$x^{k+1}_{i,j} = x^k_{i,j} + rand * (x^k_{l,j} - x^k_{i,j}); if F(X_i) > F(X_l) \tag{3.5}$$

where $x^{k+1}_{i,j}$;$x^k_{i,j}$ are the grade point of the jth subject of the ith student at the kth and (k + 1) th iterations; $x^k_{l,j}$ is the grade point of the jth subject of the lth student (randomly selected) at kth iteration; $f(X_l)$ is the overall grade point of the lth student;

$$X_l = [x_{l,1}, x_{l,2}, ...x_{l,j}, ...x_{l,d}]$$

3.2 TLBO ALGORITHM

The TLBO algorithm can be implemented in the following steps as in [16]:

Step 1: Define the optimization problem and generate random population according to population size (P_n) (students), number of generations (G_n) and number of design variables (D_n) (subjects) within the limits.

This population is expressed as:-

$$population = \begin{bmatrix} X_{1,1} & X_{1,2} & \cdots & X_{1,D} \\ X_{2,1} & X_{2,2} & \cdots & X_{2,D} \\ \vdots & \vdots & \ddots & \vdots \\ X_{p_n,1} & X_{p_n,2} & \cdots & X_{p_n,D} \end{bmatrix}.$$

Step 2: Teacher phase :

Calculate the mean of the population column-wise, i.e. the mean of the subjects of students as:-

$$Mean_{,D} = [m_1, m_2, ..., m_D]$$

The best solution for that iteration will act as a teacher

$$X_{teacher} = X_{f(X)=min}$$

The solution obtained, teacher, will always try to change the mean from $Mean_{,D}$ to $X_{,teacher}$. So, the best solution obtained, $X_{teacher}$, will act as a new mean for the iteration.

$$M_{new,D} = X_{teacher,D}$$

The difference between two means is expressed as

$$Diff_{,D} = r(Mean_{new,D} - T_F * M_{,D})$$

The obtained difference is added to the current solution to update its values using

$$X_{new,D} = X_{old,D} + Diff_{,D}$$

Accept X_{new} if it gives better function value.

Step 3: Learner phase :

In Learner phase as mentioned above, increase their knowledge by mutual interaction with each other and mathematically explained as:

for i=1:popsize

Select two learners randomly X_i and X_l, where $i \neq l$

If $f(X_i) < f(X_l)$

$$X_{new,i} = X_{old,i} + r_i(X_i - X_l)$$

else

$$X_{new,i} = X_{old,i} + r_i(X_l - X_i)$$

end if

end for

Accept X_{new} if it gives better function value.

Step 4: Stop if the maximum generation number is achieved; otherwise repeat from Step 2.

Two feasible solutions are obtained, i.e. at the end of teacher phase and learner phase, and solution giving better function value (or optimized value) is preferred [16][19].

3.3 TLBO APPLICATION TO STHTS

For realizing the teaching-learning based optimization algorithm to short-term hydrothermal scheduling problem for time horizon of 24 hour with one hour interval, following assumptions are made [4]:

- Spillage is assumed to be zero for simplicity.
- Transmission losses are also assumed to be zero.

The stepwise procedure for solving the problem of short-term hydro thermal scheduling problem by TLBO algorithm [17] is listed below:

Step-1 Read the given data, namely power generation coefficients, load demand for the given time horizon, thermal cost curve characteristics, time delays for the transport of water, inflow rate of water , operating limits of the system, i.e. hydro generation limits, thermal generation limits, water discharge rate limits and reservoir storage limits, number of hydro (nh) and thermal units (nt) and time horizon for scheduling.

Step-2 Generate the initial population of all dependent variables like water discharge rate for (NH-1) number of hours randomly within its limits as:

Q(i,j) = rand($Qi^{min} - Qi^{max}$)

and the water discharge rate for the last interval of time while satisfying the initial and final reservoir constraints is evaluated as:

$$Q_{i,24} = V_i^{begin} - V_i^{end} - \sum_{j=1}^{23} Qi, j + \sum_{j=1}^{24} I_{i,j} + \sum_{k=1}^{Ru_i} \sum_{j=1}^{24} (Q_{k,j-Td_{k,i}}) \tag{3.6}$$

where i=1, 2,....nh and j=1, 2,....NH Check the water discharge for its minimum and maximum limits. 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.

Step-3 Calculate the reservoir water storage volume of ith hydro plant for jth time interval using eq. 2.7 using water discharge rate and check for the operating limits.

$V_{i,j} = V_i^{min}$ if $V_{i,j} < V_i^{min}$

$V_{i,j} = V_i^{max}$ if $V_{i,j} > V_i^{max}$

Step-4 Calculate the hydro power generation according to eq. 2.6 and check it for its minimum and maximum limits.

$Ph_{i,j} = Ph_imin$ if $Ph_{i,j} < Ph_i^{min}$

$Ph_{i,j} = Ph_i^{max}$ if $Ph_{i,j} > Ph_i^{max}$

Step-5 The thermal generation of the equivalent plant can be calculated using eq. 2.5 by subtracting hydro generation from the power demanded and neglecting transmission losses. Check the inequality constraint 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.

Step-6 Initial population of ith student may be formulated as:

$$P = [P^1, ...P^i, ...P^{n_p}] \tag{3.7}$$

where $P^i = [Q(i,j)^T, Ps(nt, NH)^T]$

Step-7 Evaluate the objective function using eqs. 2.3 and 2.4.

Teacher Phase

Step-8 Calculate the mean($4 * 24$) of the population which will give the mean marks of all subjects of the students.

Step-9 Identify the solution which will give the best value of objective function, i.e. minimum thermal cost and this solution will act as the Teacher for the next iteration.
$X_{teacher} = min(FC)$

Step-10 Modify all the dependent variables, water discharge rates except for last interval (Qnew), according to the teacher's knowledge using eq. 3.3

Step-11 Evaluate the objective function using the modified values in teacher phase and accept the new solution (Qnew) if it gives better results.

Learner Phase

Step-12 Select two solutions Qi and Qj, $i \neq j$, randomly and update the dependent variable, water discharge except for last interval, using eq. 3.4.

Step-13 Evaluate the objective function with these updated values in learner phase.

Step-14 Accept the new solution if it give the better value of objective function.

Step-15 Stop if the maximum number of generation reached otherwise go to step-6.

RESULTS AND DISCUSSIONS

4.1 TEST SYSTEM

The TLBO algorithm, as discussed in Chapter-3, has been applied to the test system that has been adopted from [8]. The multi-chain hydraulic test system has shown as Fig. 4.1. The hydro system comprises of four hydro units connected in multi chain arrangement.

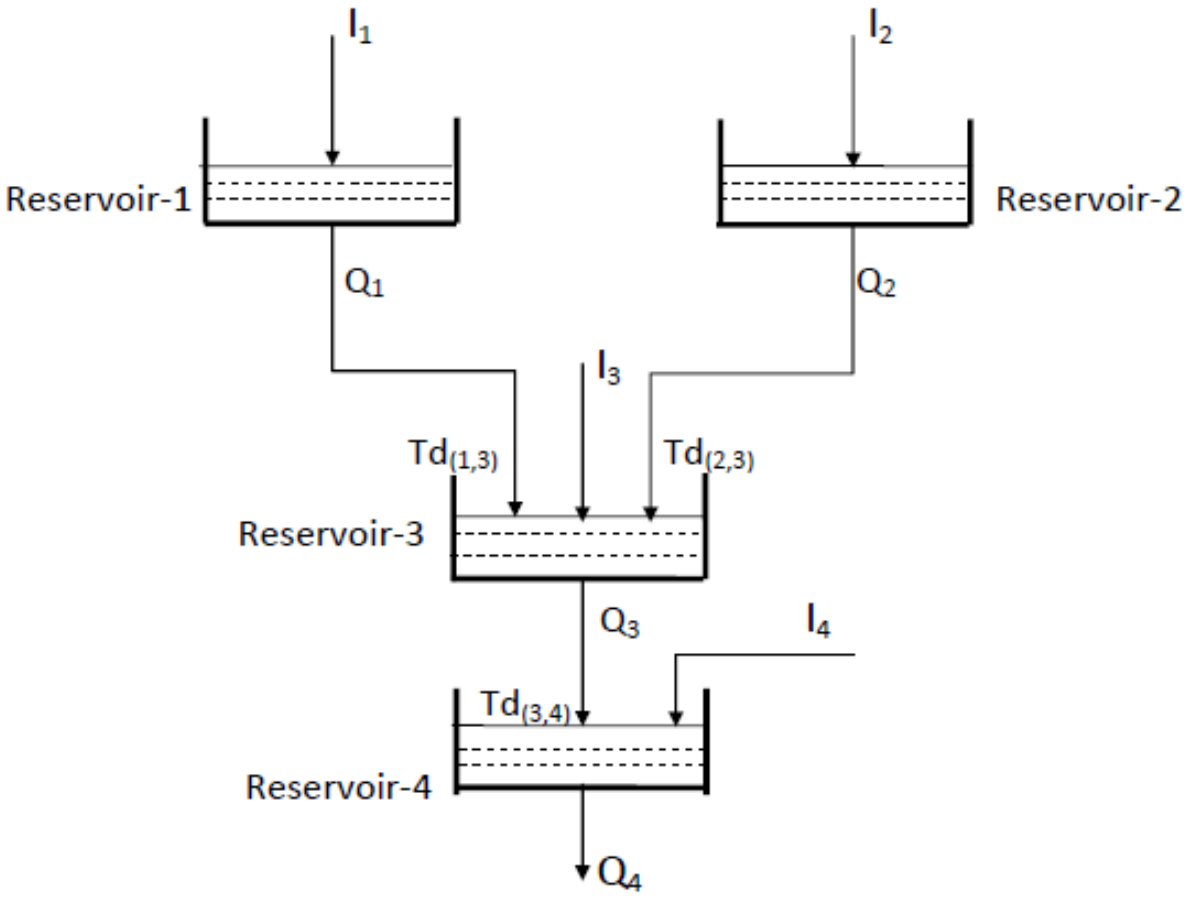

Fig. 4.1 Studied multi-chain hydro System

The hydraulic system is characterised by:

1. A multi-chain cascaded flow network
2. Reservoir transport delay between successive reservoirs
3. Variable head hydro plants
4. Variable natural inflow rates to each reservoir
5. Variable load demands over scheduling period

The time delay for the transport of water between the reservoirs is given in Table 4.1 whereas the hydro generation coefficients in Table 4.2. The reservoir inflows and load demand for 24-hours are summarized in Table 4.3. The operating limits of hydro plant in presented in Table 4.4 while the thermal unit characteristics is summarized in Table 4.5.

Table 4.1 No. of upstream plant and transportation delay time

Plant	1	2	3	4
Ru	0	0	2	1
Td(Hr)	2	3	4	0

Table 4.2 Hydro power generation coefficients

Plant	c_1	c_2	c_3	c_4	c_5	c_6
1	-0.0042	-0.42	0.30	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 4.3 Load demand and reservoir Inflows

Hour	Load Demand (MW)	Reservoir Inflows ($*10^4 m^3$)			
		Reservoirs			
		1	2	3	4
1	1370	10	8	8.1	2.8
2	1390	9	8	8.2	2.4
3	1360	8	9	4	1.6
4	1290	7	9	2	0
5	1290	6	8	3	0
6	1410	7	7	4	0
7	1650	8	6	3	0
8	2000	9	7	2	0
9	2240	10	8	1	0
10	2320	11	9	1	0
11	2230	12	9	1	0
12	2310	10	8	2	0
13	2230	11	8	4	0
14	2200	12	9	3	0
15	2130	11	9	3	0
16	2070	10	8	2	0
17	2130	9	7	2	0
18	2140	8	6	2	0
19	2240	7	7	1	0
20	2280	6	8	1	0
21	2240	7	7	2	0
22	2120	8	8	2	0
23	1850	9	9	1	0
24	1590	10	10	0	0

Table 4.4 Reservoir storage capacity limits, reservoir end conditions, plant discharge limits ($*10^4 m^3$) and plant generation limits (MW)

Plant	V^{min}	V^{max}	V^{begin}	V^{end}	Q^{min}	Q^{max}	Ph^{min}	Ph^{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	13	25	0	50	16-18

Table 4.5 Thermal unit characteristic coefficients

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

4.2 RESULTS

The short-term hydrothermal scheduling (STHTS) is studied on the multi-chain system detailed in section 5.1 for three cases namely -

- STHTS with quadratic cost function
- STHTS including the effect of valve point loading
- STHTS including the effect of prohibited discharge zone

4.2.1 Case-I STHTS with quadratic cost function

The cost function for the equivalent thermal unit of hydrothermal system is considered to be quadratic without prohibited discharge zones of hydro units. The best scheduled results with optimal hydro discharge rate and storage volume are shown in Table 4.6. The detailed schedules of hydro and thermal generations are given in Table 4.7. Fig. 4.2 and Fig. 4.3 shows the hourly water discharge rate and storage volume of reservoir. The total hydro and thermal power generation using TLBO and the load demanded are illustrated in Fig. 4.4 and the cost for each hour in Fig. 4.5.The total thermal generation cost for the system without valve point loading i.e. Quadratic function is **$ 896840.323**.

Table 4.6 Hourly water discharge and reservoir storage volume with quadratic cost function

Hour	Water Discharge ($*10^4 m^3$)				Volume ($*10^4 m^3$)			
	Plant1	Plant2	Plant3	Plant4	Plant1	Plant2	Plant3	Plant4
1	15	14.876	29.997	22.154	95	73.124	148.103	100.646
2	14.979	14.995	29.998	23.553	89.021	66.129	126.306	79.493
3	15	14.95	29.999	25	82.021	60.18	115.307	70
4	14.958	14.971	29.996	24.997	80	60	117.165	70
5	11.475	14.939	30	13.029	80	60	120.161	86.967
6	12.831	14.978	21.538	13.029	80	60	132.53	103.936
7	14.997	15	19.229	13.004	80	60	142.747	120.931
8	14.988	14.965	22.027	14.113	80	60	150.49	136.815
9	7.678	14.999	18.962	15.477	82.322	60	162.503	151.338
10	14.438	14.975	18.732	16.657	80	60	174.759	156.219
11	14.902	14.713	19.974	18.269	80	60	178.429	157.152
12	14.973	15	21.4	19.238	80	60	188.465	159.941
13	12.304	14.931	20.575	19.09	80	60	201.766	159.813
14	14.5	14.906	19.771	19.465	80	60	214.682	159.08
15	14.617	14.987	23.397	19.076	80	60	221.589	159.978
16	14.894	14.956	19.486	22.485	80	60	233.533	158.893
17	14.999	14.754	20.101	19.494	80	60	240	159.974
18	14.308	14.775	19.423	19.976	80	60	240	159.769
19	13.953	14.985	18.066	23.409	80	60	240	159.756
20	14.673	13.346	16.425	20.732	80	60	240	158.511
21	14.563	15	15.861	18.602	80	60	240	141.516
22	15	14.992	30	23.853	80	60	240	155.571
23	14.991	11.404	14.816	23.545	80	60	240	150.092
24	5	6	15.301	25	85	64	240	160

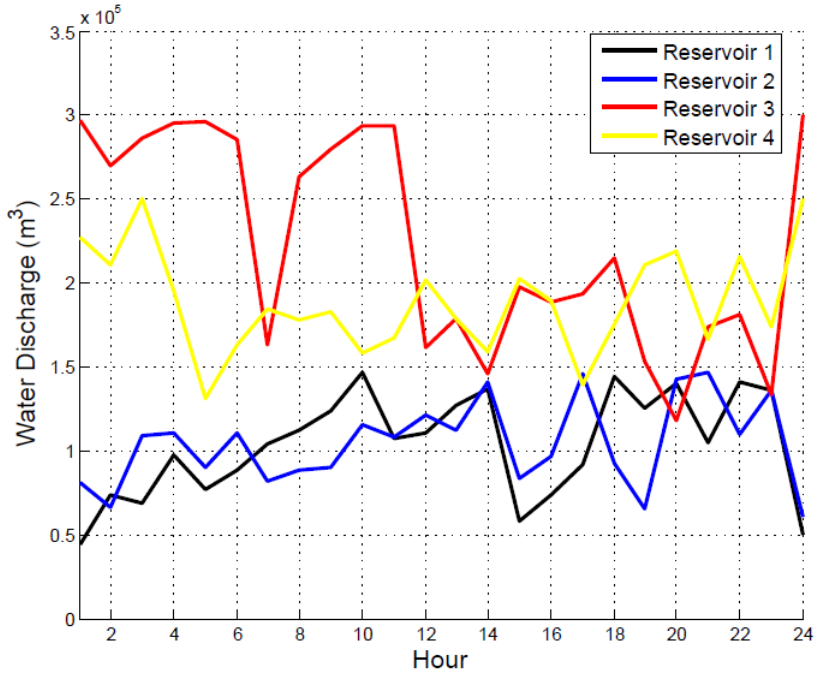

Fig. 4.2 Water discharge (m^3) of the hydro plants for STHTS with QCF

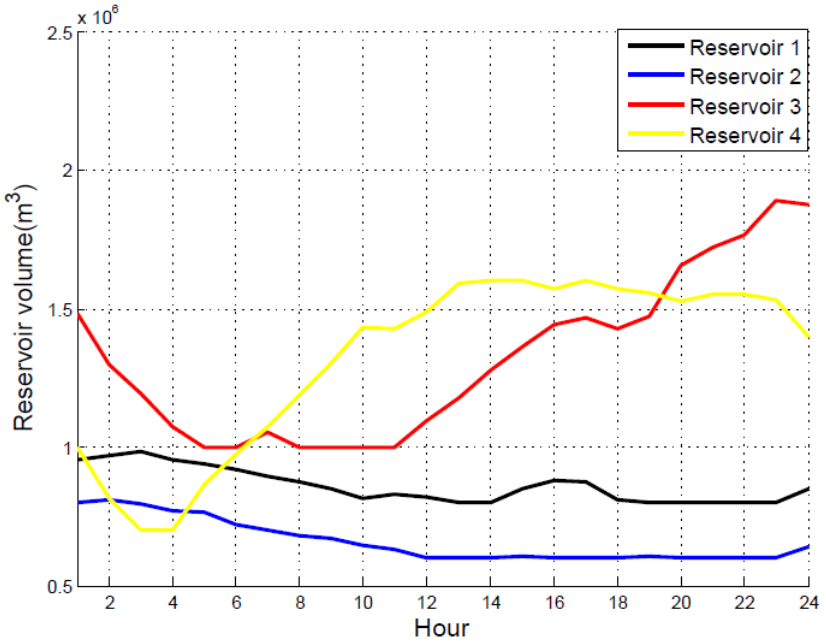

Fig. 4.3 Reservoir Storage volume (m^3) of the hydro plants for STHTS with QCF

Table 4.7 Generation and cost with quadratic cost function

Hour	Hydro Gen.(MW)				Thermal Gen.(MW)	Thermal Gen. Cost($)
	Ph_1	Ph_2	Ph_3	Ph_4	Ps	
1	95.845	83.223	0	242.751	948.181	25003.163
2	92.393	77.767	0	213.836	1006.004	26339.37
3	87.973	72.587	0	199.6	999.839	26196.275
4	86.628	72.46	0	199.599	931.314	24615.918
5	82.106	72.414	0	172.9217	962.5597	25334.174
6	85.079	72.469	24.042	193.604	1034.806	27009.913
7	86.621	72.5	39.168	212.359	1239.352	31867.535
8	86.622	72.451	28.533	238.826	1573.568	40164.728
9	66.609	72.498	46.688	264.877	1789.328	45758.485
10	86.6	72.464	50.841	279.187	1830.907	46857.866
11	86.636	72.074	47.262	292.213	1731.815	44249.204
12	86.625	72.5	43.6	301.253	1806.023	46199.071
13	84.107	72.401	50.118	300.171	1723.202	44024.321
14	86.615	72.366	55.23	301.814	1683.975	43003.861
15	86.635	72.482	40.353	300.243	1630.288	41617.196
16	86.637	72.438	58.152	317.592	1535.182	39189.055
17	86.62	72.137	56.721	302.899	1611.622	41137.794
18	86.557	72.17	58.751	305.621	1616.9	41273.212
19	86.369	72.478	61.992	322.309	1696.852	43338.165
20	86.64	69.363	64.432	308.613	1750.952	44749.952
21	86.627	72.5	64.897	297.121	1718.855	43910.943
22	86.62	63.585	65.171	316.168	1576.552	40240.831
23	86.622	72.489	65.256	311.74	1322.798	33897.3
24	48.405	38.536	0	305.477	1197.582	30861.991

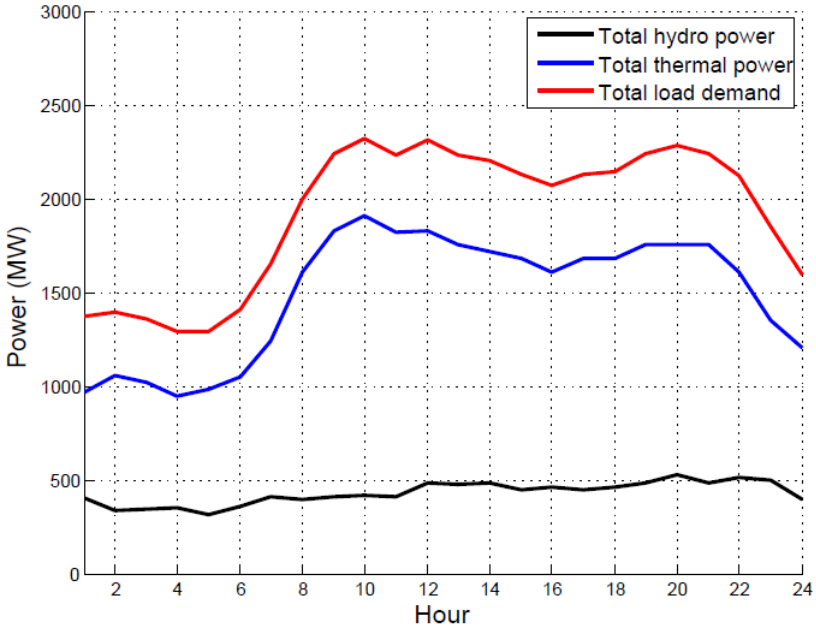

Fig. 4.4 Hydro generation, thermal generation and total load demand for STHTS with QCF

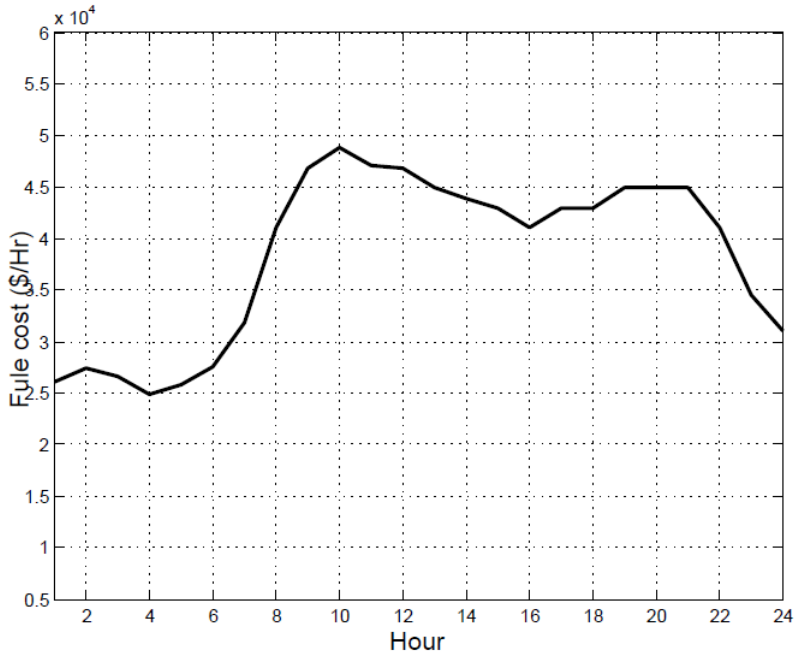

Fig. 4.5 Fuel cost per hour for STHTS with QCF

4.2.2 Case-II STHTS with effect of valve point loading

The optimized scheduled results for the problem considering the valve point loading of the thermal unit are given in Table 4.8 and Table 4.9. The hourly water discharge rate and reservoir storage volume are illustrated in Fig. 4.6 and Fig. 4.7. The total hydro and thermal power generation using TLBO and the load dmanded are shown in Fig. 4.8 and cost for case-II in Fig. 4.9. The total thermal generation cost for the system with valve point loading **$ 921168.06**

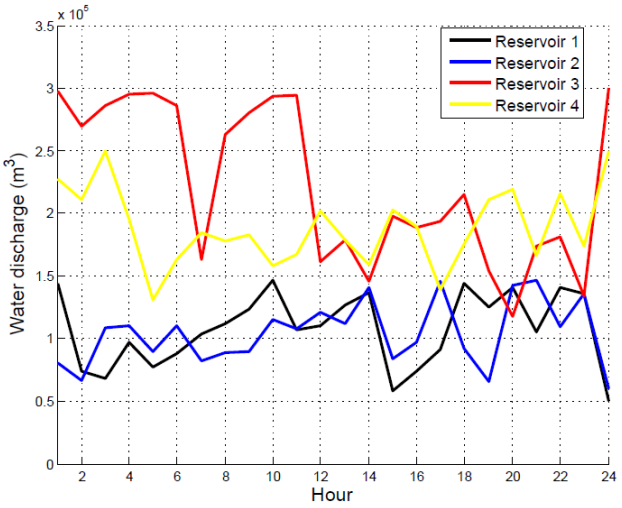

Fig. 4.6 Water discharge (m^3) ***of the hydro plants for STHTS with VPL***

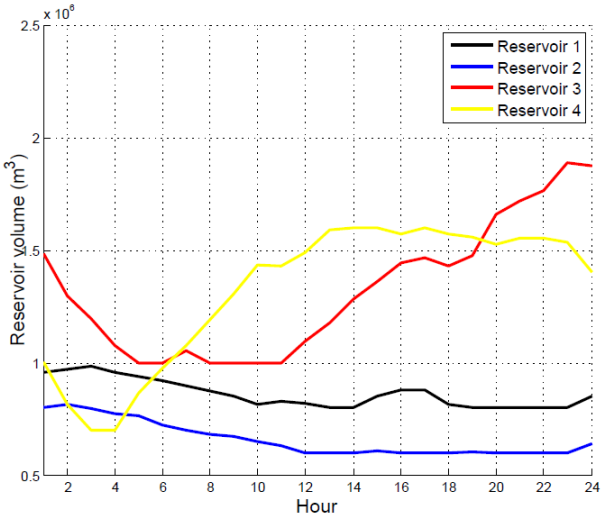

Fig. 4.7 Storage volume of reservoirs (m^3) ***of the hydro plants for STHTS with VPL***

Table 4.8 Hourly water discharge and reservoir volume with effect of Valve point loading

Hour	Water Discharge ($*10^4 m^3$)				Volume ($*10^4 m^3$)			
	Plant1	Plant2	Plant3	Plant4	Plant1	Plant2	Plant3	Plant4
1	14.39	8.082	29.725	22.738	95.61	79.918	148.375	100.062
2	7.39	6.652	26.973	21.094	97.22	81.265	129.602	81.368
3	6.846	10.88	28.602	24.999	98.375	79.385	119.39	70
4	9.701	11.059	29.5	19.495	95.674	77.326	107.362	70
5	7.698	8.957	29.59	13.123	93.976	76.369	100	86.602
6	8.805	11.018	28.585	16.287	92.17	72.351	100	97.288
7	10.376	8.196	16.294	18.478	89.795	70.155	105.464	107.412
8	11.21	8.855	26.325	17.787	87.585	68.3	100	119.125
9	12.324	8.98	28.002	18.274	85.261	67.32	100	130.441
10	14.67	11.548	29.338	15.834	81.591	64.772	100	143.193
11	10.691	10.766	29.387	16.692	82.9	63.006	100	142.794
12	11.059	12.102	16.145	20.152	81.841	60	109.505	148.968
13	12.711	11.212	17.892	17.857	80.129	60	117.851	159.113
14	13.702	14.102	14.576	15.892	80	60	128.1	160
15	5.796	8.339	19.765	20.28	85.204	60.661	136.148	160
16	7.355	9.674	18.837	18.939	87.849	60	144.226	157.207
17	9.123	14.55	19.356	13.912	87.726	60	146.768	160
18	14.416	9.229	21.47	17.538	81.309	60	142.992	157.039
19	12.526	6.537	15.357	21.103	80	60.463	147.433	155.701
20	14.049	14.219	11.797	21.883	80	60	165.602	152.655
21	10.495	14.631	17.343	16.639	80	60	172.014	155.371
22	14.095	10.962	18.083	21.591	80	60	176.517	155.25
23	13.599	13.604	13.387	17.384	80	60	188.845	153.223
24	5	6	30	25	85	64	187.571	140.02

Table 4.9 Generation and cost with effect of valve point loading

Hour	Hydro Gen.(MW)				Thermal Gen.(MW)	Thermal Gen. Cost($)
	Ph_1	Ph_2	Ph_3	Ph_4	Ps	
1	95.86	62.433	0	243.539	968.168	26069.472
2	70.314	54.257	0	211.03	1054.398	27467.987
3	66.868	76.095	0	199.599	1017.437	26605.242
0 4	82.99	75.432	0	188.059	943.519	24896.029
5	71.28	65.017	0	173.225	980.479	25747.886
6	77.109	71.75	0	210.266	1050.874	27592.038
7	83.442	56.624	34.237	236.498	1239.198	31863.835
8	85.383	58.873	0	247.121	1608.623	41071.268
9	87.176	58.804	0	263.463	1830.557	46848.573
10	87.693	67.976	0	259.854	1904.477	48820.019
11	81.239	63.627	0	266.126	1819.009	47124.523
12	81.903	65.922	36.391	295.228	1830.556	46848.586
13	84.956	62.894	34.485	291.035	1756.63	44899.216
14	86.172	71.002	46.77	276.453	1719.603	43934.846
15	54.86	50.382	34.407	307.634	1682.717	42971.247
16	66.864	56.535	41.231	296.575	1608.795	41065.443
17	76.914	71.809	40.091	258.469	1682.717	42971.256
18	87.451	54.427	28.71	286.695	1682.717	42971.248
19	84.545	39.516	51.719	307.583	1756.637	44898.985
20	86.43	71.224	57.686	308.022	1756.638	44899.035
21	78.999	71.943	54.184	278.238	1756.637	44898.995
22	86.457	61.953	53.276	309.517	1608.797	41065.38
23	86.076	69.962	62.063	281.822	1350.078	34566.931
24	48.405	38.536	0	303.575	1199.484	31070.02

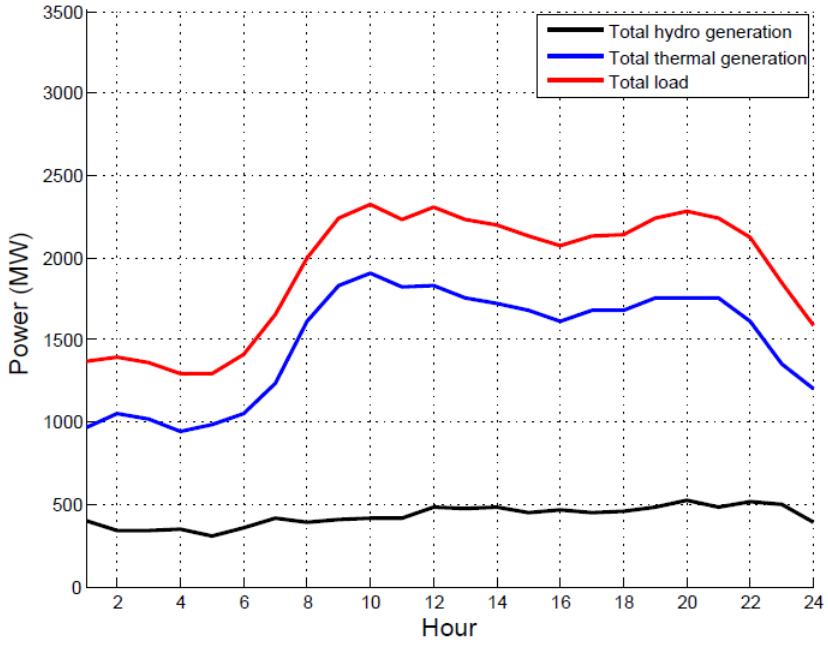

Fig. 4.8 Hydro generation, thermal generation and total load demand for STHTS with VPL

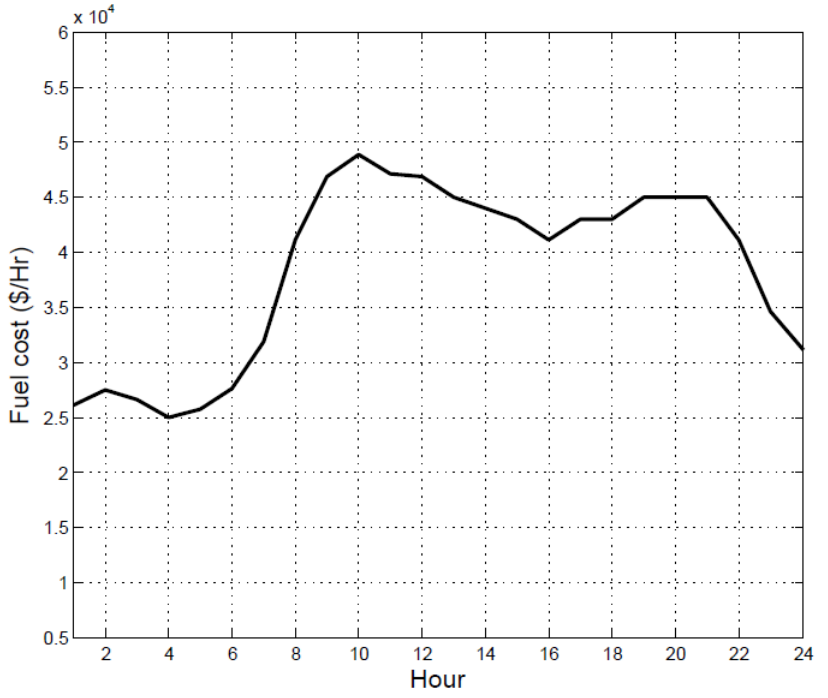

Fig. 4.9 Fuel cost per hour for STHTS with VPL

4.2.3 Case-III STHTS with effect of prohibited discharge zone

The cost function is considered to be quadratic with prohibited descharge zone of hydro units. The optimal hourly water discharge rate and reservoir storage volume are provided in Table 4.10 and the optimal hydro generation, thermal generation and fuel cost in Table 4.11. The graphical representation for the detailed schedules are given as: hourly water discharge rate in Fig. 4.10, volume of reservoir in Fig. 4.11 and total hydro generation, thermal generation, load demand in Fig. 4.12. The optimized fuel cost for the thermal power generation using TLBO is illustrated in Fig. 4.13.The total thermal generation cost for the system with valve point loading **$ 916970.663**

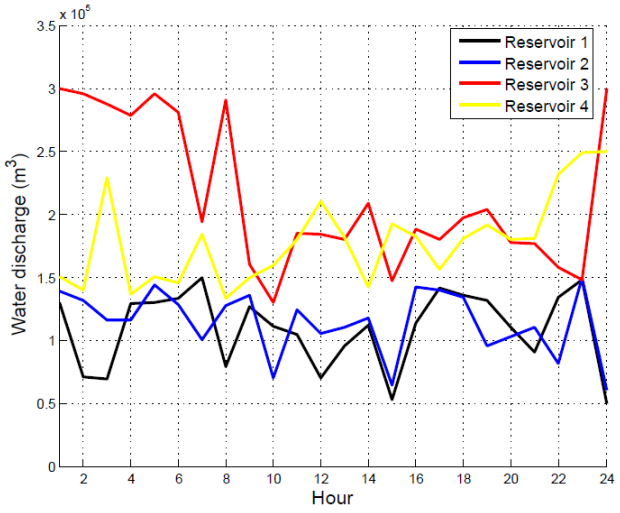

Fig. 4.10 Water discharge (m^3) ***of the hydro plants for STHTS with PDZ***

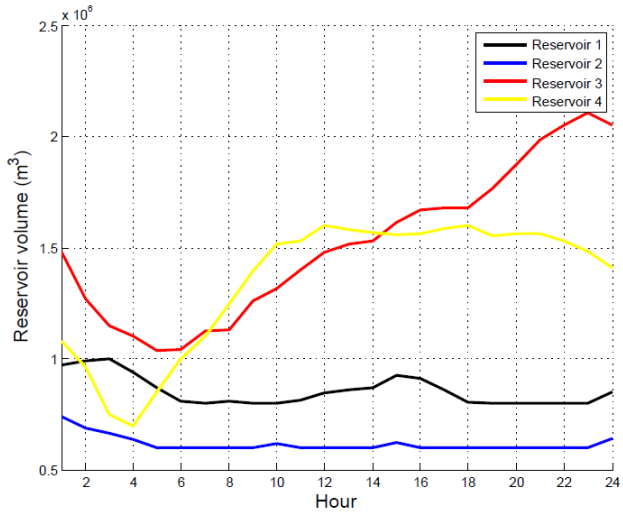

Fig. 4.11 Reservoir Storage volume (m^3) ***of the hydro plants for STHTS with PDZ***

Table 4.10 Hourly water discharge and reservoir storage volume with effect of prohibited discharge zone

Hour	Water Discharge ($*10^4 m^3$)				Volume ($*10^4 m^3$)			
	Plant1	Plant2	Plant3	Plant4	Plant1	Plant2	Plant3	Plant4
1	13.017	13.899	29.995	15.003	96.983	74.101	148.105	107.797
2	7.057	13.14	29.556	13.98	98.926	68.961	126.748	96.217
3	6.947	11.613	28.7	22.88	99.979	66.349	115.065	74.937
4	12.926	11.605	27.848	13.644	94.053	63.743	110.174	70
5	13.026	14.352	29.51	15.018	87.027	60	103.751	84.978
6	13.315	12.864	28.114	14.534	80.712	60	104.176	100
7	15	10.037	19.35	18.417	80	60	112.457	110.282
8	7.907	12.727	29.055	13.291	81.093	60	113.068	124.84
9	12.698	13.548	16.04	14.928	80	60	125.891	139.422
10	11.11	7	12.989	15.973	80	62	131.846	151.563
11	10.422	12.402	18.465	18.001	81.578	60	139.806	152.912
12	7.037	10.532	18.439	21.025	84.541	60	148.025	160
13	9.554	11.008	17.98	18.128	85.987	60	151.467	157.912
14	11.151	11.737	20.855	14.206	86.836	60	153.051	156.695
15	5.317	6.454	14.721	19.214	92.518	62.546	161.416	155.947
16	11.338	14.234	18.812	18.261	91.18	60	166.763	156.124
17	14.171	13.937	18.027	15.579	86.01	60	167.79	158.525
18	13.545	13.371	19.747	18.046	80.465	60	167.835	160
19	13.165	9.576	20.342	19.16	80	60	176.898	155.561
20	10.986	10.327	17.718	18.015	80	60	187.661	156.358
21	9.017	10.985	17.698	18.067	80	60	198.499	156.318
22	13.405	8.136	15.803	23.174	80	60	205.258	152.891
23	14.827	14.942	14.76	24.842	80	60	210.842	148.391
24	5	6	30	25	85	64	205.232	141.109

Table 4.11 Generation and cost with effect of prohibited discharge zone

Hour	Hydro Gen.(MW)				Thermal Gen.(MW)	Thermal Gen. Cost($)
	Ph_1	Ph_2	Ph_3	Ph_4	Ps	
1	94.658	82.047	0	214.299	978.996	25801.593
2	68.529	76.216	0	192.232	1053.023	27517.434
3	68.036	69.45	0	205.392	1017.122	26616.654
4	93.052	67.356	0	155.195	974.397	25953.295
5	89.519	71.466	0	185.495	943.52	24896.136
6	86.209	68.14	0	201.235	1054.416	27469.418
7	86.62	58.162	26.181	239.852	1239.185	31864.298
8	67.413	67.767	0	219.125	1645.695	42017.668
9	84.855	69.835	43.187	248.555	1793.568	45872.007
10	81.043	43.614	49.503	269.227	1876.613	48563.22
11	79.575	66.837	41.032	285.926	1756.629	44899.231
12	63.489	60.256	43.983	311.74	1830.533	46849.367
13	78.184	62.129	46.633	291.796	1751.258	45066.969
14	84.818	64.737	35.608	258.41	1756.426	44905.995
15	53.374	40.529	56.31	297.056	1682.731	42972.443
16	87.546	71.251	48.444	290.954	1571.805	40121.718
17	90.27	70.673	51.241	272.432	1645.384	42028.153
18	86.316	69.424	45.265	293.249	1645.747	42015.929
19	85.572	56.079	45.344	296.322	1756.683	44902.927
20	80.657	59.406	56.688	289.471	1793.778	45886.578
21	72.78	62.043	58.688	289.792	1756.697	44904.131
22	85.871	48.754	62.89	313.656	1608.829	41068.078
23	86.642	72.418	64.227	313.633	1313.079	33661.78
24	48.405	38.536	0	304.961	1198.098	31115.641

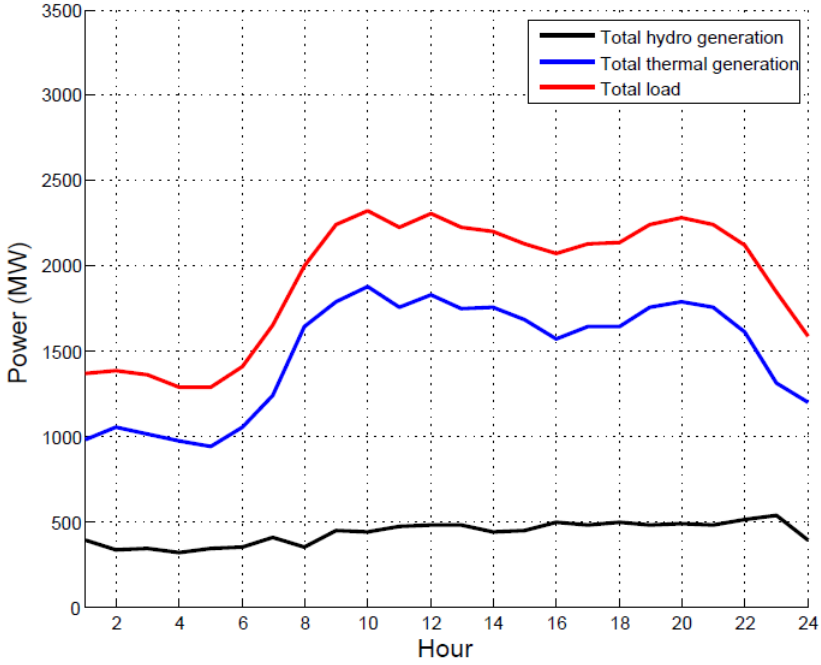

Fig. 4.12 Hydro generation, thermal generation and total load demand for STHTS with PDZ

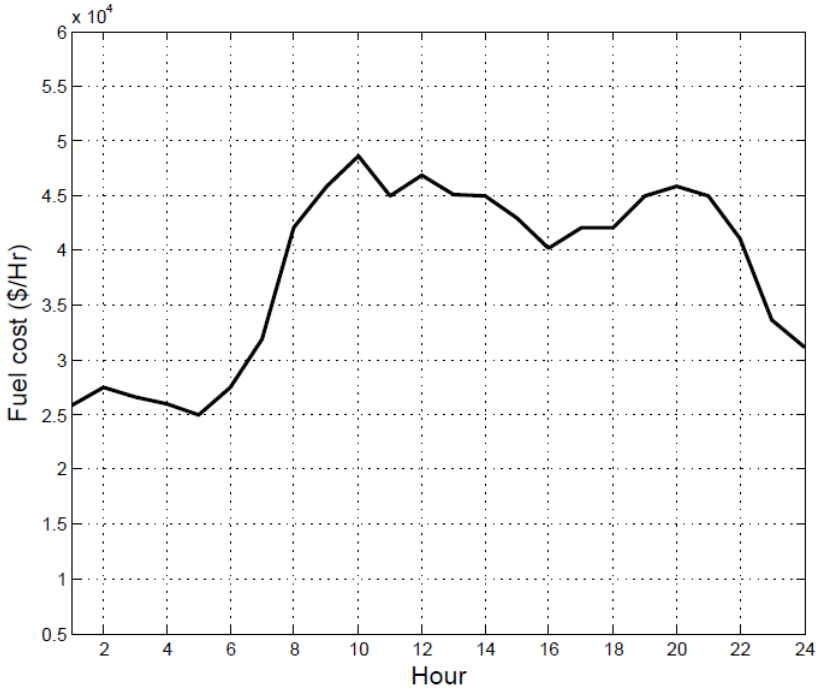

Fig. 4.13 Fuel cost per hour for STHTS with PDZ

4.3 COMPARATIVE STUDY

The proposed algorithm, TLBO, is applied on test system having four hydro units and one thermal unit given in section 5.1 and the detailed scheduled results obtained after applying the algorithm to the STHTS problem are discussed in section 5.2.

In graph shown in Fig. 4.14 gives the scheduled result of hydro power generation for plant1 in three cases. For plant1, the maximum hydro power is generated in case-I at Ist hour interval and minimum power generation is in case-III for the last interval. In Fig. 4.15, the hydro power generation for plant2 is represented showing that the plant generate maximum power at Ist interval in case-I and the minimum power is generated at last interval in case-III. Fig. 4.16 represent the generation for plant3 and maximum power is generated at 23rd time interval in case-I. Hydro power generation for plant4 is displayed in Fig. 4.17, power generated is almost similar in all cases. The thermal power generation and the fuel cost for thermal generation are shown in Fig. 4.18 and Fig. 4.19. The shapes of both the graphs are similar as fuel cost depends on the thermal power generation, if thermal generation increases the cost for fuel also increases. The comparative results for the fuel cost obtained in three cases are given in Table 4.12 and is clear from the table that the cost for fuel in minimum when the function in quadratic and this cost increases when effect of valve point loading in incorporated.

Table 4.12 Comparative total fuel cost

Case-I with QCF	Case-II with VPLE	Case-III with PDZE
$ 896840.323	$ 921168.06	$ 916970.663

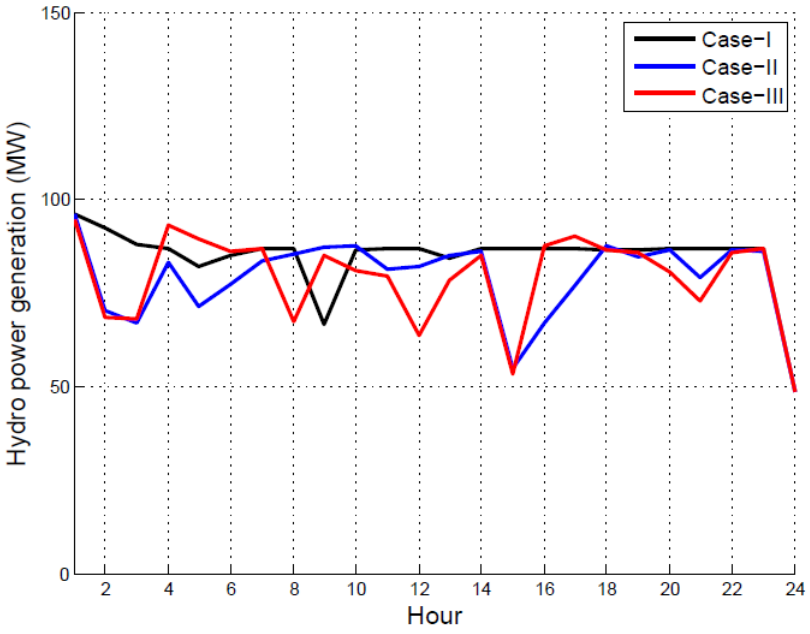

Fig. 4.14 Comparative hydro power generation for plant 1

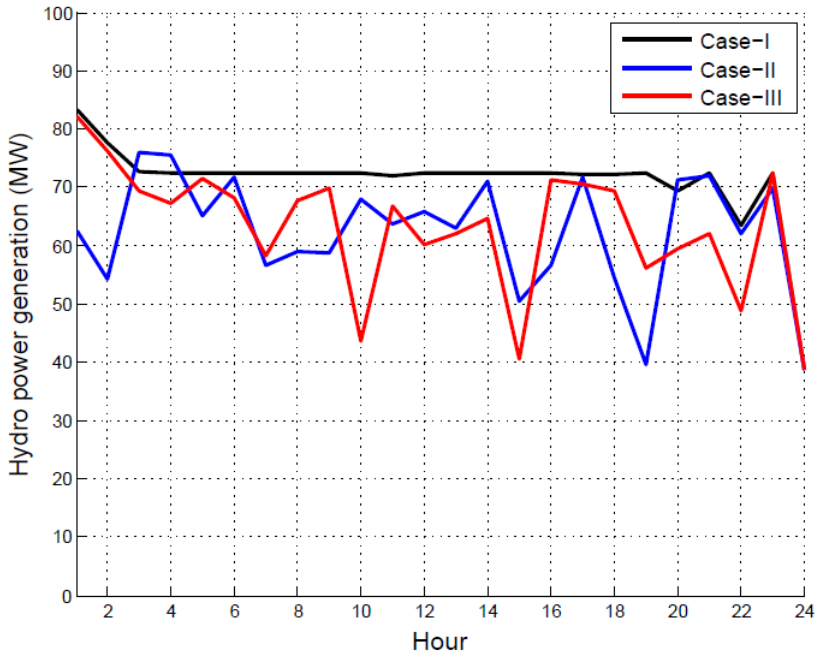

Fig. 4.15 Comparative hydro power generation for plant 2

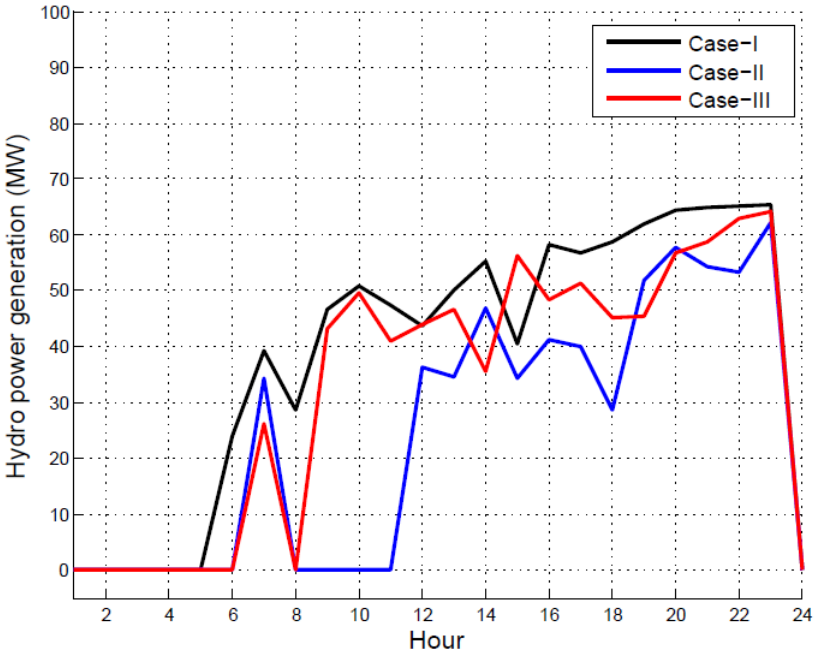

Fig. 4.16 Comparative hydro power generation for plant 3

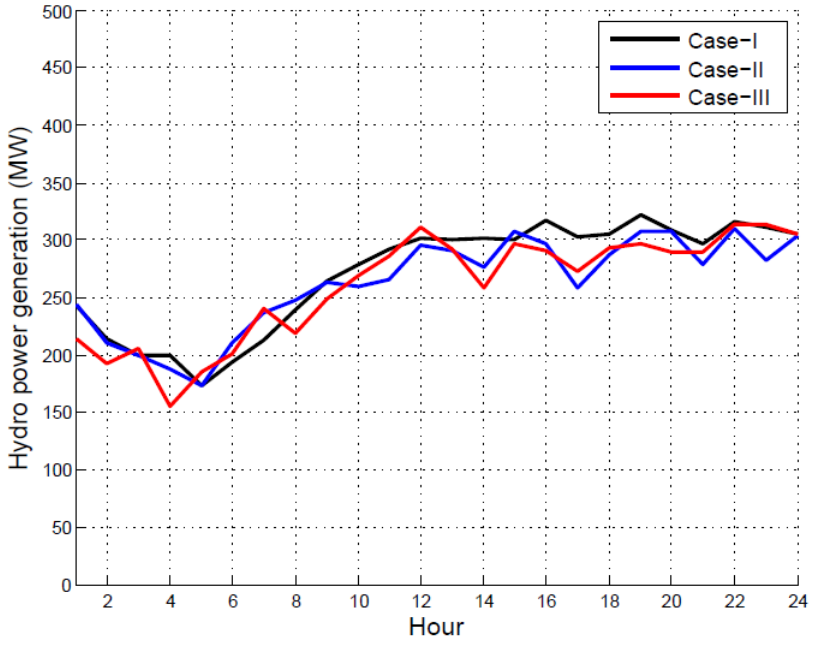

Fig. 4.17 Comparative hydro power generation for plant 4

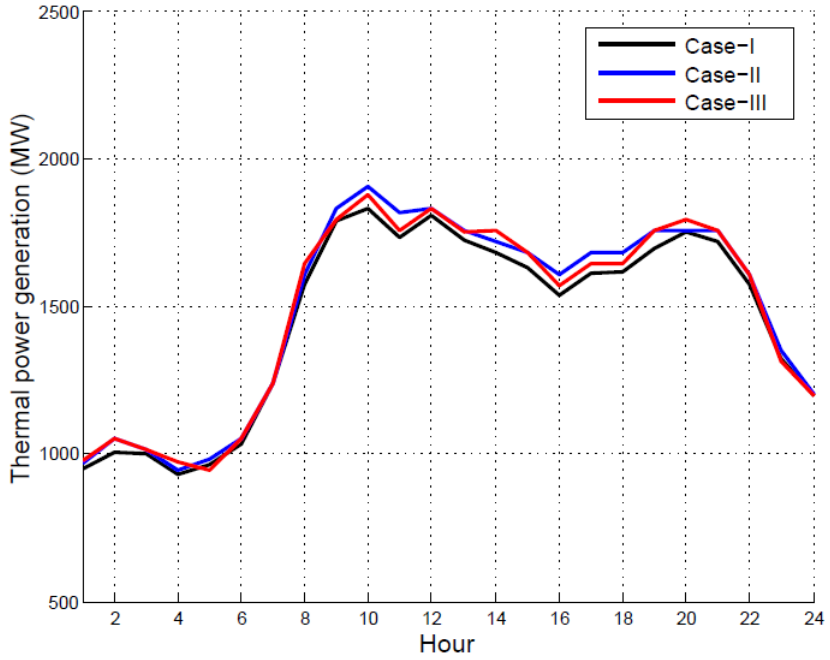

Fig. 4.18 Comparative thermal power generation

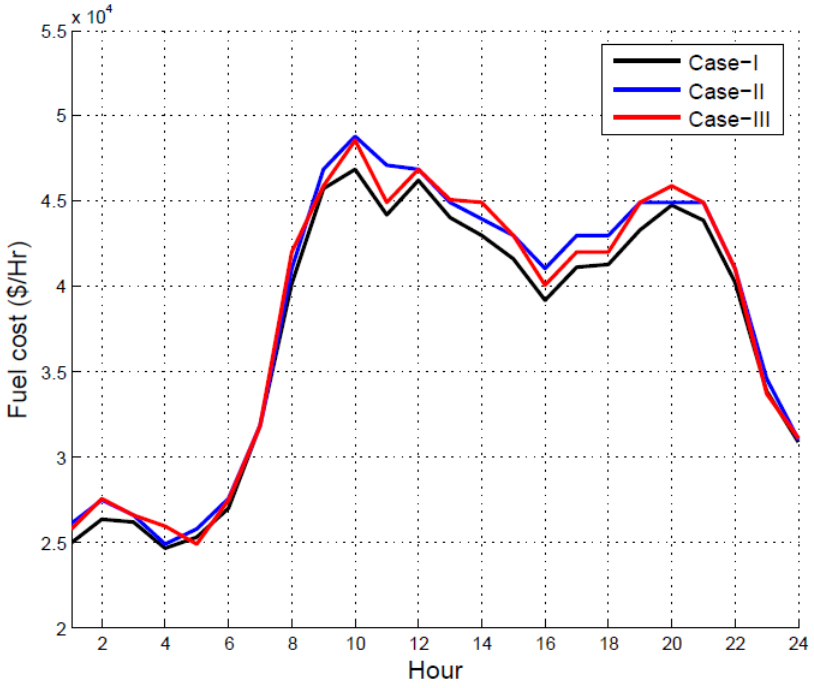

Fig. 4.19 Comparative fuel cost per hour

CONCLUSIONS AND FUTURE SCOPE

5.1 CONCLUSIONS

The TLBO algorithm has been applied to the short-term hydrothermal scheduling problem over the time horizon of 24 hours with one hour time interval. The presented algorithm determines the fuel cost of thermal generation for each time interval and gives the optimum solution. The proposed method has been applied to test system having four hydro units and one thermal unit. The hydro units are arranged in multi-chain arrangement. The analysis has been extended to include the effect of prohibited discharge zone for hydro units. The thermal unit is considered to have quadratic cost function and cost function with valve point loading. The following conclusions are drawn:

- It is observed that the thermal generation cost with quadratic cost function gives the minimum operating cost over other cases.
- The cost increases if valve point loading or prohibited discharge arrangement is considered.

5.2 FUTURE SCOPE

- In this work the problem of Short-term hydrothermal scheduling is solved for one thermal unit. It can applied to the problem having more than one thermal unit.
- The transmission losses shall be accounted for the optimal scheduling.

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