Applying Heuristic Optimization Techniques for Optimal Scheduling of Pumped Storage Hydrothermal System

A Dissertation submitted in fulfilment of the requirements for the Degree
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in
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Submitted by
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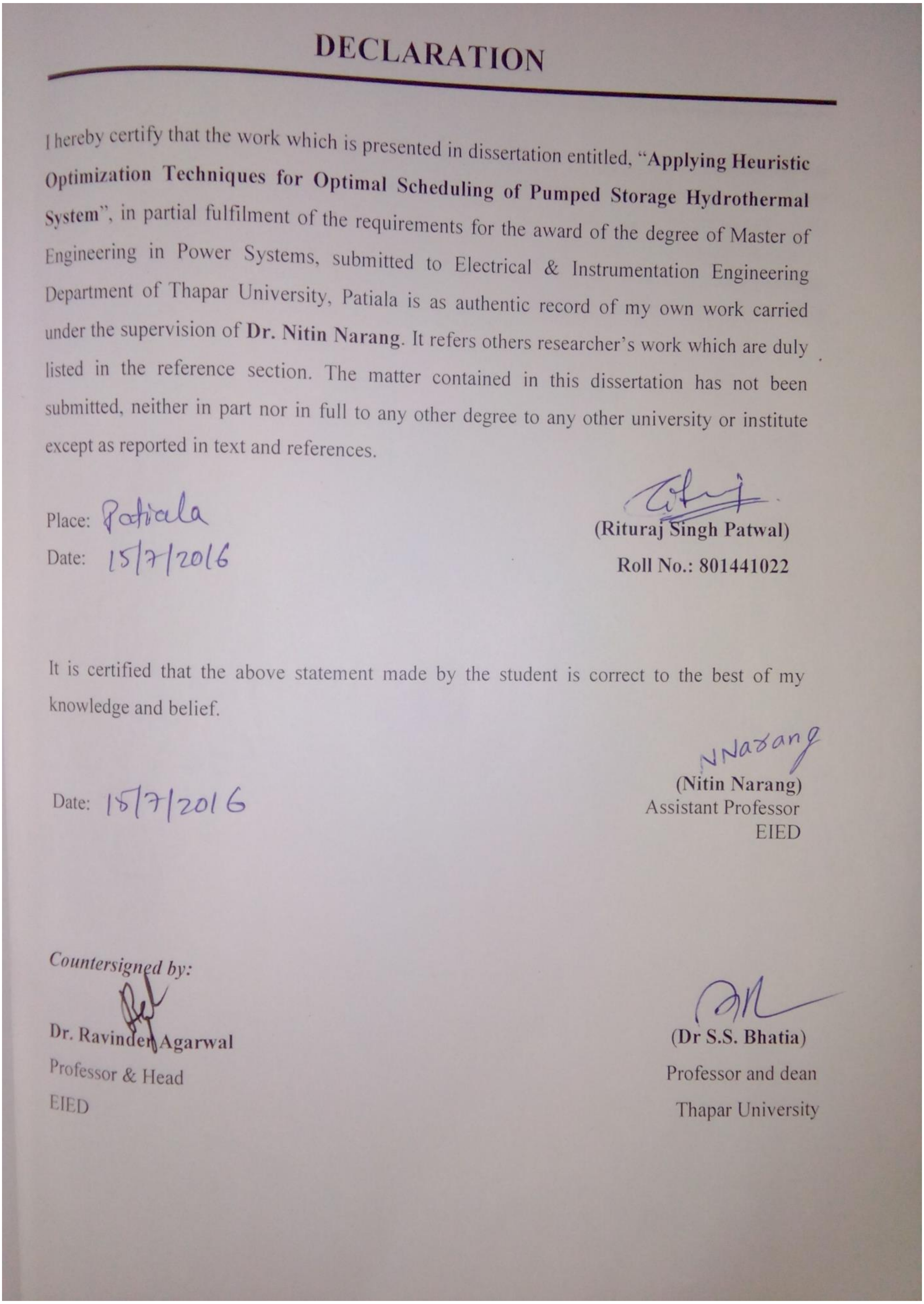

DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "**Applying Heuristic Optimization Techniques for Optimal Scheduling of Pumped Storage Hydrothermal System**", in partial fulfilment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is as authentic record of my own work carried under the supervision of **Dr. Nitin Narang**. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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CERTIFICATE

Certified that the dissertation entitled, **"Applying Heuristic Optimization Techniques for Optimal Scheduling of Pumped Storage Hydrothermal System"**, which is being submitted by **Rituraj Singh Patwal** in fulfilment of the requirements for the award of the Master of Engineering in Power Systems, to Thapar University, Patiala, is a bona-fide record of the candidate's own work carried out by him/her under our/my supervision and guidance. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other university or institute for award of any degree.

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ABSTRACT

In present scenario pumped storage hydrothermal system is becoming an important part of power systems for energy and water resource management. In this dissertation the economic scheduling of hydrothermal system is analysed in the presence of pumped-storage unit. To maximize the water as fuel input in hydroelectric system pumped storage units are added with an advantage of operating in generating as well as pumping mode. Apart from minimizing the cost of power generation pumped storage unit resolves other practical problems like scarcity of water for drinking and irrigation. In the past different optimization techniques have been used by various researchers to solve economic scheduling problem in hydrothermal plants for achieving better solutions. The purpose of this research is to implement a heuristic optimization technique for optimal economic scheduling of hydrothermal units considering a pumped storage unit. This dissertation has adopted two heuristic optimization techniques. The first technique involves leader enhancement strategies and variation in inertia weight, whereas in second technique time varying acceleration coefficient particle swarm optimization (TVAC-PSO) is integrated with leader enhancement strategies to solve hydrothermal scheduling (HTS) problem considering pumped-storage unit. The feasibility and effectiveness of optimization technique is validated by a test system containing four hydro plants, three thermal plants and one pumped storage unit. The global best solution obtained from PSO technique is further improved by applying TVAC-PSO and different mutation strategies. The global best solution is compared with result obtained from global search techniques mentioned in this dissertation.

TABLE OF CONTENTS

Page

NOMENCLATURE

t	Index for sub- interval (Hr).
i	Index for thermal generating units
j	Index for hydro generating units.
l	Index for pumped-storage units.
f_1	Total fuel cost ($).
a_i, b_i, c_i, d_i, e_i	Fuel cost coefficients of i^{th} thermal unit.
P_{git}	Output power of i^{th} thermal unit in t^{th} subinterval.
$P_{gi}^{\max}$ *and* $P_{gi}^{\min}$	Lower and upper limits of the i^{th} unit thermal power generated.
n_g *and* n_h	Number of thermal and hydro units.
P_{hjt}	Hydro power generated of the j^{th} hydro unit in t^{th} sub-interval.
P_d	Power demand in t^{th} sub-interval.
$P_{hj}^{\max}$ *and* $P_{hj}^{\min}$	Lower and upper limits of the j^{th} hydro power generated.
$V_{hj}^{\max}$ *and* $V_{hj}^{\min}$	Minimum and maximum storage limit of the reservoir j.
$q_{hj}^{\max}$ *and* $q_{hj}^{\min}$	Minimum and maximum limit of the water discharge rate of reservoir j.
V_{hj}^{init} *and* V_{hj}^{end}	Initial and final storage volume of the reservoir j.
F_{hjt} *and* S_{hjt}	Inflow and spillage of the reservoir j in t^{th} sub-interval.
d_{kj}	Water transport delay from k^{th} to the j^{th} reservoir.
R_{uj}	Number of upstream reservoir above the j^{th} reservoir.
$C_{1j}, C_{2j}, C_{3j}, C_{4j}, C_{5j}, C_{6j}$	Power generation coefficients of the hydro plant.
q_{hjt}	Water discharge of hydro plant j in t^{th} sub-interval.
V_{hjt}	Volume storage of the hydro plant j in t^{th} sub interval.
T	Scheduling Time Interval.
$P_{pslg}^{\max}$	Generating mode maximum output power of the l^{th} pump storage unit.
$P_{pslp}^{\max}$	Pumping mode maximum output power of the l^{th} pump storage unit.

LIST OF FIGURES

ABBREVIATIONS

PSP	Pumped Storage Plant
PSO	Particle Swarm Optimization
TVAC	Time Varying Acceleration Coefficient
STHTS	Short Term Hydrothermal Scheduling
MTHTS	Medium Term Hydrothermal Scheduling
LTHTS	Long Term Hydrothermal Scheduling
CSA	Colonial Search Algorithm
GSA	Gravitational Search Algorithm
DE	Differential Evolution
HTS	Hydrothermal System

LIST OF TABLES

Chapter-1

Introduction

1.1 Overview

Increase in energy demand and reduction in conventional energy reserves such as oil, petroleum, fossil fuels and so on with span of time has made us think for other options of efficient energy generation. It is predicted that if current condition on oil detection and consumption progresses, oil mineral deposits will be meet the end by 2038 [1]. Further the condition become worsens by global warming and for it electricity generation would be a reason. Therefore proper scheduling of power plant is required for trimming down the total energy generating cost during the operating process, hence improving the efficiency. One of the options from conventional power plants was the integration of hydro and thermal units for achieving low emission and operation cost of energy generation. At present interconnected power systems is being analysed economically by optimally scheduling hydrothermal units. Hydroelectric plant also meets purposes other than energy generation which includes flood control, irrigation and drinking purpose [2].

In hydroelectric plants water storage becomes an issue due to limited capacity and stochastic availability of water. Since the use of water in energy generation is more compare to fossil fuel in hydroelectric energy the cost of energy generation will reduce effectively using hydrothermal plants and it is also termed as zero emission energy. On the other hand sharing of load demand is another advantage of integrating hydroelectric and thermal plants. The other energy source which uses water as energy generation fuel is run off river turbine and pumped storage hydro units. Among these sources run off river produces less power and therefore minimally utilised.

Several researches have been done previously on scheduling hydrothermal units and economic dispatch problems. Direct search and gradient based methods were algorithms applied to optimize the problems. First method locates the minimum point based on objective function, and second method locates the minimum point while utilising objective functions derivatives. Factually gradient based method is more efficient if information’s are available. Other method is Lagrangian relaxation [3]–[5], this technique is suppler in controlling various constraints than erstwhile decomposition techniques [6]. The problem occurring in dealing with constraints on operation of generator and reservoir storage limits are overcome by using the dynamic programming (DP) approach.

However the drawback is, for non convex and non linear problems the conventional method cannot find the optimal solution for large size systems. Increase in computational time is also another disadvantage for classical approach. Hence global search techniques came into existence such as, genetic algorithm (GA) [7-9], ant colony optimization (ACO) [10], differential evolution (DE) [11-12], ant swarm optimization [13], particle swarm optimization (PSO) [14-15], bacterial foraging [16], and artificial bee colony (ABC) algorithm [17–19], gravitational search technique (GSA) [20]. The behaviour depicting the non-smooth characteristics for the global search technique in the search space allows improving the convergence rate and reduces the dependency of technique or the solution over the initial points of solution [21]. The drawback associated with this technique is of local trapping into the later on stages of the iteration [22].

1.2 Literature Review

The optimal scheduling of hydrothermal systems (HTS) is to find thermal and hydro power generation so that cost of operation is least while satisfying all the constraints. This field of research for many researchers in past years has become an area of interest. Initially, researchers have solved HTS problem by dividing it into two stages. During the first stage problem related to hydroelectric plant was solved. In the latter stage problem related to thermal plants was solve depending on the outcome of the first stage [23]. The negative feedback that arouse in this approach was no coherency between two different stages that led to the non-feasible solution. In order to make sure that the final solution arrived is the most feasible and optimal one, sub problems have been designed for both type of power generating methods hydro power and thermal power generation. These hydro sub problem and thermal sub problem [24-25] are solved iteratively to obtain the feasible output and more optimal solution.

In multi cascaded water reservoir system the maximum utilisation of water available can be done only by pumping back the water flowing from turbine to the reservoir located at a height on the stream. The types of plant with the ability of pumping water back to upper reservoir are called pump storage plant. These plants are planned to be built since they provide fast response for the changes in the power demand and efficient storage of fuel input. Pumped storage hydro plant besides serving the peak load also helps in pumping the water back to the reservoir during light load conditions. A pumped storage plant can be operated in any Mode from the three states as generated, pumped and zero modes. It also smoothen peak loads and hence reduces the total cost of generation in mixed systems. These are the clean sources of energy with low cost of power generation.

The pump storage plants are used from 20th century but have been progressed during recent years due to power system restructuring. Pumped storage plants has their operating mode restricted to power generation during peak load demand and during off peak load hours plant has their operation in pumping mode. For reducing the cost of energy vertically integrated markets are major field utilising the pumped storage plants. In the electricity market during energy trading pump storage improves the social welfare and has become the important consideration while energy trading. Due to fast response and operational flexibility of pumped storage plant with variation in load demand and ability to produce energy at low cost it has been beneficial in vertically integrated markets.

During past decades, a variety of classical methods had been implemented to solve short term hydrothermal system (STHTS) problem. The dynamic programming method used by Tang *et al.* [26] and Yang *et al*. [27] to solve the STHTS problem. The negative aspect of this method was the dimension which happens to be leading to the larger computational time and storage in the memory [28]. The linear programming method used by Piekutowski *et al.* [29] to obtain the economic solution for the STHTS problem over a large scale cascaded hydro system. Due to application of linear programming with the linear system the problem error occurring in the result happens because of linear approximation of hydrothermal constraints and the objective function [30]. Non –linear programming was applied by Kumar *et al.* [31] to the operation planning. The deficiency of this technique was continuous presence of a differentiable function [32] and a slow convergence of the objective function with increase in computational time.

The Lagrange relaxation method was applied by Salam *et al.* [33] to the hydrothermal system coordination. Lagrange Relaxation is well thought to be more flexible for managing the diverse constraints. The negative aspect of this technique was the alternation and correctness of the solution and slow convergence [34]. The major disadvantages of the classical approach are convergence rate, dimensionality and supposition made through the implementation of these techniques on the hydrothermal coordination problem. In the case of hydro thermal problems containing large dimensionality, the computational time of the system increases. In case of the classical methods the outcome signifies that the convergence rate is very slow and the error in the outcome is due to assumptions that are adopted to make the problem more traceable [35].

Development and advancement in research led to application of global search techniques where the conventional technique assumptions are not considered for achieving optimal solution in hydrothermal systems. It reduces computational time and provides optimum solution globally. PSO and its improved methods are applied to hydrothermal scheduling for better results. Zhang *et al*. [36] proposed multi elite guide PSO; several other sub techniques under PSO have been used for better efficient results. Development and advancement in search led to different new techniques utilised in optimizing hydrothermal systems. Swain *et al*. [37] proposed a new algorithm CSA from global techniques family which is fast and robust tool for hydrothermal scheduling problems. Liao *et al*. [38] presents a novel adaptive artificial bee colony (AABC) algorithm and it has been intended for long-term transmit of cascaded hydropower systems the efficiency has been compared with other algorithms. The formulation of economic dispatch of hydropower for long term is a non linear complicated optimization problem.

Salama *et al*. [39] proposed techniques for getting best possible solution for the pumped storage hydro thermal scheduling problem, such as, a GA and constriction factor based PSO technique. The performance in the output for the proposed techniques is confirmed and analysed on hydrothermal test system and on pumped storage power plant. Hota *et al*. [40] presents EP techniques to solve the scheduling problem of hydro thermal system as generation or pumping with pumped Storage plants. Chen [41] proposed EPSO technique combining PSO and encode/decode techniques to optimize pumped storage problems. The Encoding/decoding technique has been analysed the discrete characteristic of a pump storage plant. Kanakasabapathy [42] has investigated to what extent pumped storage plants impacts on the electricity market during energy trading. Kazempour *et al*. [43] referred the problem of optimal scheduling of a pumped-storage plant so as to participate in the energy and regulation market. The pumped-storage unit is also capable of participating in the energy services market [44] to make sure that the system security is been added to the quality of service provided by the system in the energy market. The effect of pumped-storage unit in the pool based energy market for making economical and optimal energy locating strategies [45]. To strategically bid the pumped-storage power plant with multiple number of unit cascaded and additional evolutionary tri-state PSO is exploited in day to day electricity market [46].

Particle swarm optimization, the heuristic search technique due to its good performance and flexibility has become a proficient technique for optimization applications in research fields. The PSO technique has been acknowledged through the social behaviour of bird while searching for food [47]. This technique is based on maximizing the species survival by imitating the behaviour of swarm individuals. The successful application of PSO in various areas such as reactive power dispatch [48], distribution state estimation [49], electromagnetic devices design [50] and discrete binary problem, has given credibility to its efficient existence. PSO has been effectively useful for a lot of optimization problems in hydropower system [51–53].

Several features of PSO are [36]:

- No overlapping and mutation calculation.
- Speed of the particle is helpful in search.
- Most optimal particle is useful in sending information to other particles during generation.
- Preconditions are not required such as differentiability or continuity of objective functions.
- Its coding is simpler than other heuristic techniques such as artificial bee colony (ABC), bacterial foraging optimization algorithm (BFOA) etc...
- Parameters to be tuned are few.

The premature convergence and sensitivity of search ability are disadvantages of PSO. Hence in optimisation of little complex problems as multimodal problems, this PSO technique becomes problematic. Therefore new PSO variants with high explorative capability are important and valuable. Many researchers worked significantly to improve PSO performance by applying different variants as random number generation techniques [54-55], mutation [56], introduction of particle repulsion [57], time varying acceleration coefficients [58-59], inertia weight variation [60], and craziness [61] on optimisation problems.

In PSO, optimal solution search is conducted by considering particles population guided by two random acceleration components. While the local search is controlled by the component known as cognitive component, global exploration of particles is controlled by social learning component. For achieving the global best solution these two components needs to be controlled efficiently. As explained by Keneddy and Eberhart [62], the excessive movement of particles occurs with high value of cognitive component and premature convergence occurs due to higher value of social component. Time varying acceleration coefficient (TVAC) becomes helpful in overcoming problems related to non convex models. This application strikes a balance between the two components during initial and latter part of search, thereby avoiding the premature convergence problems. The intent of this paper is to optimally schedule the hydrothermal thermal plants considering the presence of pumped storage unit by using heuristic optimization techniques combining PSO and its variants.

1.3 Objective of Work

The objective of dissertation is to optimally schedule the hydrothermal system considering the presence of pumped storage unit by implementing heuristic optimization techniques and presenting the improved results. The technique implemented in this dissertation utilises different combination of PSO variants such as variation in inertia weight and social learning factors (acceleration coefficients), DE based mutation strategy, probability distribution based mutation like Gaussian and Cauchy distribution, opposition based mutation for optimizing the problem. There are two heuristic techniques implemented in this dissertation among which heuristic optimization technique-I deals with variation in inertia weight and comparison among the upgraded best fitness value by using Gaussian, Cauchy, DE and opposition based mutation operators also known as leader enhancement technique. In the heuristic optimization technique-II the combination of TVAC-PSO and leader enhancement techniques used simultaneously to improve the results obtained in heuristic optimization technique-I. The significant improvement in performance of PSO technique has been recognized.

1.4 Organization of Dissertation

The dissertation titled as “Applying Heuristic Optimization Techniques for Optimal Scheduling of Pumped Storage Hydrothermal System” has been explained in five chapters. In **Chapter 1** dissertation detailed overview is mentioned, problem related literature survey and dissertation objective is provided. **Chapter 2** introduces about hydrothermal system, types of the hydrothermal system (HTS), description of pumped storage plant and scheduling problem formulation of HTS problem. In **Chapter 3** the overview of classical PSO technique, heuristic optimization technique-I and heuristic optimization technique-II have been discussed and implemented on pumped storage STHTS problem. **Chapter 4** highlights and discuses the results for test system-I comprising of three thermal, four hydro unit and one pumped storage unit. The dissertation conclusion and potential scope of work has been mentioned in **Chapter 5** followed by the publications, references and also the appendix.

Chapter-2

Short Term Pump Storage Hydrothermal Scheduling

2.1 Hydrothermal Plants

According to present scenario where we are prevailing with power balance problems optimal scheduling of hydrothermal plants is a necessity. The Power generation process in hydro unit is emission free and input fuel is obtained at zero cost. Moreover hydro electric plant shares the load of thermal units and help in meeting demand with low cost of fuel and emission. The better planning and preparation for optimally scheduling the power generation could save us the cost required for fuel as input to the plant. Therefore, important question is the method by which or how is the optimal schedule of hydro and thermal Units are achieved. The complexity in the operation of hydrothermal system can't be equated with the operation of independent thermal system due to presence of electrical as well as mechanical coupling in the hydrothermal system [63]. The hydro and thermal units are consolidated for improving economical efficiency of power system and efficient utilisation of energy resources. Hence hydro units are considered as the peak load plants. The importance of hydro plants occurs because of its nature to behave as base load as well as peak load plants. The response rate of hydro electric plant is faster and has higher reliability which leads to plant capability of withstanding fluctuating loads.

In scheduling hydrothermal system for short period of time interval, the scheduling horizon needs to be considered for one day to one week thereby involving hour-by-hour generation during the scheduling horizon to obtain the minimum cost of production for the power generation. The solution for the required quantity of water that is needed to be utilized for operation during the scheduling problem of short span of time is derived from the long span scheduling problem. A predefined data for reservoirs storage conditions for hydroelectric plants is provided and the optimal schedule of each horizon or period for the desired objective i.e. fuel cost minimization, while satisfying the hydro system constraints, is achieved [64]. Hydroelectric plants also have prohibited generating limits due to physical limitations and the hydroelectric unit can operate above or below these limits called prohibited discharge limits.

The idea of hydrothermal coordination is to utilize all energy resources in most economic and efficient manner. The scheduling of hydroelectric plant is more intricate 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, the cost of fuel associated with the power generated is very less nearly free 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 cost associated with fuel for thermal generation is minimized [2].

Thus the hydrothermal scheduling is important as the cost for the operation of thermal plant is not economical but very high, though their initial investment cost is low. On the other side, the cost of operation for the hydroelectric plant is low, but their initial installation cost is high. So, difference between the operation and installation of both types of conventional plant has made us clear that it has to be economically convenient when both thermal as well as hydroelectric plants are to be used in the same grid. The advantage of fast response time so that hydroelectric plant can be started in small period of time and provide better response to load fluctuations with higher reliability has associated hydroelectric plants as most reliable energy generation source [65]. Hence hydro plants can carry and balance the intermittent loads. In contrast to hydro plants, initial start period of thermal plant is slow and has the slow speed of response.

The hydroelectric plants needs to be classified on the basis of types, available water head, amount of water available, nature of the load and site of the hydro units.

Based on the position of the hydro plants on the water stream, hydroelectric plants can be classified as [65]:

a) Hydro plants on the different stream.
b) Hydro plants on same stream.
c) Multi-reservoir hydro plants.

Based on the height of water head available in the reservoir, these are:

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

On the basis of their type, they are classified as:

a) Pumped storage plants.
b) Conventional plants.

2.2 Pumped Storage Plant

This is one of the types of hydroelectric plant which has storage reservoir at its lower end and hence saves the fuel input. It is design to save the cost disburse over the fuel input by providing the power to load when the demand is high (a high power demand) with hydroelectric energy (generating mode) and then pump the water back to the upper reservoir of the stream at time of off peak load (low power demand) [2]. These types of plants generally use break up pumps and turbines or further recently in use the reverse pump motor turbines. Difference from the normal hydro plant is that pump storage plant consist of upper and lower reservoirs. Under off peak load hours PSP pumps the water back from lower to upper reservoir by utilising energy from other sources and during peak load hours PSP generates energy by utilising the water [66]. Due to this difference PSP helps in reducing the thermal power generation cost during peak load hours and maximum utilisation of available water source. Pump storage plant needs to be in operation till the cost added due to pumping mode exceeds the saving in thermal fuel cost during the load sharing.

Pumped storage hydroelectric plant is one of the oldest types of energy storage methodology on the large scale basis [67]. They are in operation since 1904 because of their ability to operate flexibly provide fast response to variation in load demand and electricity prices. For vertically incorporated integrated system, coordination of hydrothermal plants [64] is used where the pumped storage unit during mode of generation serves the increased load demand and during the mode in which water needs to be pumped back to store the energy when system is lightly loaded so the cost of generating the power needs to be reduced. Pumped storage plant helps in sharing the load of hydrothermal units and thereby meeting the scarcity of supply during the peak demand. Due to restructuring of power system networks in recent years, investments in generation and operation of power plants have introduced a greater impact on the energy market. In this era of competition in the electricity market, pumped-storage plant came as handful for the owner of energy production who can now buy and sell electricity in energy market.

Another effect of pumped storage plant has seen in energy trading where it helps in increasing the social welfare of overall population in the energy markets, by having various cost-effective implications on power market generators and consumers depending on whether energy is being imported or exported from the market. Operation of the pumped storage plant can significantly lead to changes in the customer and produce excess of energy in the individual power market because trading of pumped storage energy can significantly alter the prices of energy in the market and its efficiency in the market.

2.3 Potential Energy Storage Techniques.

a) Sea water: This is one of the sources of storing the energy for future generation purpose. The benefit of using sea water is when it is allowed to flow during time of high tide into the barrage considering the equal level of water on both sides, maintain the potential energy difference equals to zero. During the low tide after building of the head water is allowed to release and a greater potential difference occurs between two water bodies. Now the energy utilised for pumping is entirely depends on the head height and this pumped energy needs to be recovered during the generation. Therefore during the high tide more amount of water needs to be pumped back to gain the energy [68].

b) Underground reservoirs: The advantage of using underground reservoir is that energy cost for these technologies is lower than for the ground projects by utilising mine space. The underground mine space provide very limited opportunity but pumped storage opportunity using underground reservoir increases if these abandoned mines are utilised [68].

c) Direct pumping: wind turbines and solar power came in handy as new source to pump water back, effective as solar dam or wind energy storage. This provides more useful process to store the energy from wind or sun with the smoothest variation possible, hence minimising the cost of the plant and environmental effect [68].

d) Decentralised systems: Pumped storage plants are effective as these can be built on running water streams and drinking water networks. In the pumped storage plant operation the water reservoirs used as input can be unused portions of mines, natural or artificial lakes, hilly terrain and structures made for irrigation purposes. This plant provides flexible distributed energy production and storage which can be utilised with decentralized incorporation of renewable energy systems such as; solar and wind power [68].

All the types of methodologies generally use the difference in height between artificial reservoirs or two natural bodies of water. Basically shifting of water between reservoirs takes place in pure pumped storage plant and pumping back approach takes place when natural stream flow is utilised during the combination of hydroelectric plant and pumped storage plant.

Considering the evaporation losses that take due to water exposed to solar heat and conversion losses during energy conversion, still 80% of energy can be recovered known as round trip efficiency of a pumped storage plant. This technique in the present scenario of energy problems has been the most effective for energy storage and meeting power demands on daily operation basis, besides this pumped storage plants also provides an additional support to proper working of renewable energy systems.

The advantage of using pumped storage plant besides dealing with energy management is:

- Pumped storage units facilitate in providing reserve generation and control the frequency of electrical network.
- Level the variable output of the energy sources that starts and stops at irregular intervals.
- The pump storage unit provide a load in the moment of high electricity output and low electricity demand, allowing the supplementary capacity of system to be raised.
- Pumped storage unit will turn out to be vital as a balance system for very large size photovoltaic generation.

2.4 Mathematical Modelling of Pump Storage Hydrothermal System

The total cost need to be minimized and considering that as objective function the mathematical modelling is done. The sub-interval is taken for 24 hours with 1 hour interval. The cost of generation of power from hydro units is almost negligible as the power is generated from water. The loading effect of the valve in case of thermal plant is considered as non linear factor. The ripple effect is expressed as sinusoidal part in the equation.

Objective Function:

The total cost for the equivalent Hydro thermal and pumped storage unit over the scheduled horizon is given by f_1. The total cost function of quadratic nature is expressed as [69]:

$$f_1 = \sum_{t=1}^{T}\sum_{i=1}^{ng}\left[a_i + b_i \times P_{git} + c_i \times P_{git}^2 + \left|d_i \times \sin\left\{e_i \times \left(P_{gi}^{\min} - P_{git}\right)\right\}\right|\right] + \sum_{t=1}^{T} K_1 + K_2.\left(P_{pslt}^{g} + P_{pslt}^{p}\right) \quad (2.1)$$

where K_1 *and* K_2 represent the maintenance and operational cost coefficient for the pump-storage unit.

The principal intention is to minimize the cost by satisfying the inequality and equality constraints to meeting the demand. The foremost constraint for this problem is power balance constraint. The full amount of power generated by hydro, thermal and pump-storage unit satisfy's the demand in each sub-interval [69].

$$\sum_{i=1}^{ng} P_{git} + \sum_{j=1}^{nh} P_{hjt} + \eta_g \times P_{pslt}^{g} = P_d + \eta_p \times P_{pslt}^{p} \qquad (i \in n_g, \quad j \in n_h, \quad t \in T, \; l = 1) \tag{2.2}$$

Here in the above equation η_g *and* η_p is the round trip efficiency for pump storage plant. An additional constraint declares the continuity equation of hydro reservoir network, volume of the reservoir which is defined and evaluated by the water level of the reservoir in the previous interval and the delay in the transport of water from the upstream reservoir at certain height to the reservoir at the down side of the stream. The total volume of water in the reservoir [69] is given by:

$$V_{hj}^{t+1} = V_{hjt} + F_{hjt} - q_{hjt} - S_{hjt} + \sum_{n=1}^{Ruj} \left(q_{hn,t-dkj} + S_{hn,t-dkj} \right) \qquad (j \in n_h, \quad t \in T) \tag{2.3}$$

The next constraint is the power generated through the hydro-electric units which depends on discharge rate of water and head of the water reservoir. Hydrothermal power from the hydro unit in multi reservoir hydrothermal system is given by:

$$P_{hjt} = C_{1j} \times V_{hjt}^2 + C_{2j} \times q_{hjt}^2 + C_{3j} \times V_{hjt} \times q_{hjt} + C_{4j} \times V_{hjt} + C_{5j} \times q_{hjt} + C_{6j} \quad (j \in n_h, \; t \in T) \tag{2.4}$$

The multi chain hydrothermal scheduling problem has to be solved within decision variables and also to satisfy both equality constraints and inequality constraints.

For STHTS decision variables are rate of discharge of water and power generated from thermal units. These variables should be set aside within the limit during the iterative process.

a) Water discharge rate is given as:

$$q_{hj}^{\min} \le q_{hjt} \le q_{hj}^{\max} \quad (j \in n_h, \, t \in T) \tag{2.5}$$

b) Thermal power of each thermal unit can be represented as:

$$P_{gi}^{\min} \le P_{git} \le P_{gi}^{\max} \quad (i \in n_g, t \in T) \tag{2.6}$$

c) The equality constraint associated with the storage volume of the reservoir is being presented as:

$$V_{hjt}^{0} = V_{hjt}^{init} \quad (j \in n_h\,,\, t \in T) \tag{2.7}$$

$$V_{hjt}^{T} = V_{hjt}^{end} \quad (j \in n_h\,,\, t \in T) \tag{2.8}$$

d) The output power generated by hydro unit and volume of the reservoir forms the inequality constraint. They must lie within the maximum and minimum limit for optimal solution.

d.1) Inequality constraint associated with the hydro power of each hydro unit is represented as:

$$P_{hj}^{\min} \le P_{hjt} \le P_{hj}^{\max} \qquad (j \in n_h\,,\, t \in T) \tag{2.9}$$

d.2) inequality constraint associated to reservoir volume of hydro unit is being presented as:

$$V_{hj}^{\min} \le V_{hjt} \le V_{hj}^{\max} \quad (j \in n_h\,,\, t \in T) \tag{2.10}$$

The constraints related to the pump-storage unit can be defined as [70]:

$$0 \le P_{pslg} \le Y_{glt} \times P_{pslg}^{\max} \quad (l = 1,\, t \in T) \tag{2.11}$$

$$0 \le P_{pslp} \le Y_{plt} \times P_{pslp}^{\max} \quad (l = 1,\, t \in T) \tag{2.12}$$

The pump-storage unit being discrete in nature deals with numerous type of constraints. One of them is its limitation to remain either in generating or pumping mode. During this phase of decision making regarding the switching of modes a time period of an hour is required during the changeover. Therefore, when the pump-storage unit is working in the generating mode and required to alter its condition to the mode of pumping or vice versa, the pumped storage unit must be switched off about an hour because of its physical limitation of being in either of the mode [69]. This switching off time is known as change-over time or change-over period. The constraints during switching period are defined using binary variables $Y_{glt}\ and\ Y_{plt}$, which defines the condition of generating and pumping mode of the pump storage unit for each sub-interval, respectively.

$$Y_{glt} + Y_{plt} \le 1 \qquad (l = 1,\, t \in T) \tag{2.13}$$

$$Y_{glt} + Y_{pl}^{t-1} \le 1 \qquad (l = 1,\, t \in T) \tag{2.14}$$

$$Y_{plt} + Y_{gl}^{t-1} \le 1 \quad (l = 1,\, t \in T) \tag{2.15}$$

The one mode of working for pumped storage unit that is pumping, generating or zero operating modes is been approved by equation (2.13). In succession to this, there is a time gap of 1-hr involving two modes of action where Equation (2.14) and (2.15) ensures the changeover time.

Since the pumped storage unit besides pumping mode can also be operated in generating mode therefore generated power should be associated with pumped storage unit. The power generated by pumped-storage unit is shown as below:

$$P_{plt} = L_{1l} \times V_{hlt}^2 + L_{2l} \times q_{hlt}^2 + L_{3l} \times V_{hlt} \times q_{hlt} + L_{4l} \times V_{hlt} + L_{5l} \times q_{hlt} + L_{6l} \ \left(l = 1,\ t \in T\right) \qquad (2.16)$$

As represented in equation (2.16) pumped storage power for generating as well pumping mode is shown. The volume and discharge will be utilised accordingly depending on the type of mode pumped storage unit is working. When pump storage unit need to be working in generating mode depending on the value of binary variable whether 0 or 1 the discharge and volume of hydro unit 1 is considered and when pump storage unit works in pumping mode discharge and volume of unit 3 is considered.

e) Inequality constraint related to pumped storage hydro units considering its generating as well as pumping mode.

$$P_{pslt}^{g} \geq 0 \quad \left(l = 1,\ t \varepsilon T\right) \qquad (2.17)$$

$$P_{pslt}^{p} \geq 0 \quad \left(l = 1,\ t \varepsilon T\right) \qquad (2.18)$$

$$S_{jt} \geq 0 \quad \left(l = 1,\ t \varepsilon T\right) \qquad (2.19)$$

Chapter-3

Implementation of Heuristic Optimization Techniques

3.1 Overview of PSO

In PSO the swarm of particles is initialized in the provided search space. Each of the particle stores two different values in space provided in its memory which are particles best experienced position and objective function value which are called as local best value and after that the best value out of whole swarm is represented as global best position of particle and global best objective function value respectively [48]. The position of the particle P_{kd} and the velocity of particle V_{kd} in dimension d (includes position and sub-interval of a particle) forming an array of (24×7) particles where 24 subintervals and 7 (decision variables) units particle position are represented by the following:

$$P_{kd} = \left(P_{k1}, P_{k2}, P_{k3}, \ldots\ldots, P_{kd}\right) \tag{3.1}$$

$$V_{kd} = \left(V_{k1}, V_{k2}, V_{k3}, \ldots\ldots, V_{kd}\right) \tag{3.2}$$

The velocity of the particle and the position of the particles are updated in iteration according to the subsequent equations [49]:

$$V_{kd}^{iter+1} = \omega \times V_{kditer} + C_1 \times rand_{kd} \times \left(Plb_{kd} - P_{kd}\right) + C_2 \times rand_{kd} \times \left(Pb_{kd} - P_{kd}\right) \tag{3.3}$$

$$P_{kd}^{iter+1} = P_{kditer} + V_{kd}^{iter+1} \tag{3.4}$$

In the above Equation (3.3) variation obtained in the velocity is based on three components. The earliest being its preceding velocity V_{kd} scale by ω as an inertia weight. The second one is a linear movement toward its preceding best position Plb_{kd}, raised by the product of constant value of acceleration C_1 and a generated random number $rand_{kd}$. Note that a diverse random number is assigned for the entire dimension [49]. The third component is derived from a linear attraction carried towards the best position in the swarm of particles Pb_{kd}, raised by the product of constant value of acceleration C_2 and a random number. Where ω is inertial weight factor, C_1 and C_2 are social learning rates factors. $rand$ is a three dimension uniformly distributed random number array in the range of [0, 1]. Plb_{kd} is the three dimension value of the particle's personal best position. Pb_{kd} is the global best position value of the particle in the search region of d dimension. K is the particles population. While Considering the problem of optimization for different number of variables. A swarm of particles is initiated in which random position of each particle is assigned d-dimensional search region such that each particle's position is related to a candidate solution for the problem of optimization. Let P_{kd} denotes a particle's position (coordinate) and V denotes the flight velocity of the particle for the solution over a search space. Each individual particle P_{kd} in the swarm is obtained and placed in a position using a scoring function that obtains a fitness value representing the better solution of the problem and the efficiency of the particle in the swarm [36]. The best preceding position of a particle is Plb_{kd}. The index of the best particle among all particles in the swarm is Pb_{kd}. The individual best position own by each and every particle is recorded during the searching period; this recorded personal best position of individual particle is known as Plb_{kd}, and aware about the particles best positions found by all the particles in the swarm Pb_{kd}. The rules that are updated for the new positions are helpful for the particles that are flying over the d-dimensional solution space and are subjected to updated rules until the global optimal position of the particle is found. Velocity of the particle and position of the particle are stochastically and deterministically updated by updating the rules.

In the algorithm the term C_1 and C_2 known as acceleration constants are being represented as the product of the stochastic acceleration terms that drive a particle toward individual best and the global best in a swarm, respectively. These small constant values of acceleration multipliers help in allowing the particle to wander far as of the target regions. On the other hand, big value of the acceleration multipliers gives the outcome for the unexpected movement of particles toward target regions.

In conventional PSO, at hand exist two decisive issues; first issue is that while all particles are drawn in towards swarm leader, they may converge prematurely not including enough exploration of search space that is, conventional PSO is adapted to premature convergence. The latter concern is that if the particles are spellbound in local optima, then we have [51]:

$$V_{kd}^{iter+1} = \omega \times V_{kd} \tag{3.5}$$

Since $\omega < 1, V \rightarrow 0$, that is, the particle velocities are inclined to be zero. Therefore, the particles are not able to skip away from local optimum implication that in conventional PSO, there is no method for jumping out from local optima.

3.2 Different strategies of PSO modification:

3.2.1 Transformation: There are various possibilities of PSO variants even for a basic PSO algorithm. Considering an example for initializing the particles position and velocities, controlling the velocities, updating only local best and global best after updating the swarm etc, there are number of different ways for directing the algorithm. Some of these ways and their impact after performing have been analysed in the literature.

A continuous implementation of different ways have been done by researchers for performance testing of technique improvements, improvising new methods for implementing PSO as suitable and effective optimization technique in the soft computational techniques community [52]. The strictly-defined well known standard algorithm inhibits an important point of differentiation which can be utilised for improvement in advanced research work.

3.2.2 Hybridization: New and more refined PSO variants also being frequently introduce for improving the performance during course of optimization. Different trends are there regarding performance improvement [52]. Firstly, to optimize the system using hybridized method where PSO technique is combined with other optimization methods e.g., PSO combined with biogeography-based optimization, incorporating an effective learning technique.

3.2.3 Mitigate Premature Convergence: This is the real problem with PSO and an efficient hard work is given to mitigate premature convergence (optimization stagnation). This is attempted by perturbing particle movement in PSO or another attempt is done by using multiple swarms which can also be used for implementing multiobjective optimization problem [52]. Last but not least, major development is achieved during optimization process by acclimatizing the various behavioural parameters of PSO.

3.2.4 Simplifications: Another method of modification in PSO is that without impairing its performance possible simplification needs to be performed, PSO simplification was initially offered by Kennedy and has been researched and studied more rigorously. Where it is arrived that the performance of technique during optimization was refined, and the parameters were facile to tune and they appeared more consistent over various problems during optimization [52].

For simplifying PSO different argument that occurred in favour is meta-heuristic technique that only has efficiency demonstrated factually by doing computational demonstration over the optimization problem for finite times. Therefore meta-heuristic technique such as PSO cannot be improved or analysed efficiently and there always remains the error making risks either in implementation or in describing the optimization process. For example considering the famous variant of GA, which was ineffective in its optimization process since same values are in search space for different dimensions, which describes the highest possible problem happening during the optimization and the most frequently rated.

There is the requirement of extra input during velocity initialization at the input. The variant implemented for improved velocity initialization is the accelerated particle swarm optimization (APSO), TVAC-PSO and so on. These variants normally do not use particle velocity at all and improved the efficiency or accelerates the convergence process in each and every application.

3.3 Heuristic Optimization Technique-I

In PSO, swarm leader is the efficient particle towards whom all particles are attracted. This heuristic optimization technique achieves the success by enhancing the swarm leader obtained from PSO. This enhancement of swarm leader would be more efficient and streamlined. In this technique inertial weight (w) is modified and further on swarm leader four-stage mutation strategy is applied. Now the obtained objective value at mutated Pb_{kd} (particle best value) is compared with current best value and if the mutated Pb_{kd} has enhanced fitness value than the current best value, it occupies the position of current value. This strategy is better and efficient since at each stage enhanced value is compared [70].

Modification in inertial weight:

$$\omega = (\omega_{\max} - \omega_{\min}) \times \exp^{(-b \times iter)} + \omega_{\min} \tag{3.6}$$

Where $\omega_{\max}$ *and* $\omega_{\min}$ are initial and final inertia weight factors, b is a shrink factor; $iter_{\max}$ is the maximum iteration number.

Four stage mutation strategies are applied in the iteration process. After application of mutation strategies, if the mutated value has better fitness than the current, it occupies the position of the current value of particle. Swarm leader has been enhanced by application of mutation strategies in iterations for more efficient search process.

In first stage of the mutation strategy, implementation of Gaussian mutation to the swarm leader as below:

$$Pb_{kd1} = Pb_{kd} + \left(P_{kd}^{\max} - P_{kd}^{\min}\right) \times gau(0,h) \tag{3.7}$$

$$gau_d = \frac{1}{\sqrt{6.28}} \times \exp^{\left(\frac{-r_d^2}{2\times h^2}\right)} \tag{3.8}$$

Where $P_{kd}^{\max}$ *and* $P_{kd}^{\min}$ represent maximum and minimum limit of the particle in dimension d, gau is for Gaussian distribution method, r is the random number from 0 to 1 and h is defined standard deviation of Gaussian distribution. If the objective value f_1 at Pb_{kd1} is better (minimum) than the objective value obtained at Pb_{kd} then Pb_{kd1} takes the position of Pb_{kd}. There is a linear decrement in standard deviation during iterative process according to equation (3.9), to make sure of strong exploration capability in beginning and exploitation in later iterations.

$$h_{iter+1} = h_{iter} - \frac{1}{iter_{\max}} \tag{3.9}$$

In the second stage mutation of particles best value is shown by equation (3.10);

$$Pb_{kd2} = Pb_{kd} + \left(P_{kd}^{\max} - P_{kd}^{\min}\right) \times cau(0,s) \tag{3.10}$$

$$cau_d = \frac{1}{3.14 \times \left(r_d - s\right)^2} \tag{3.11}$$

$$s_{iter+1} = s_{iter} - \frac{1}{iter_{\max}} \tag{3.12}$$

This is called as Cauchy mutation strategy. Here s is the scale parameter of Cauchy distribution function linearly decreasing in iterative process as equation (3.12).

In third stage DE based mutation strategy is applied.

$$Pb_{kd3} = sf \times \left(Pb_{k(d-1)} - Pb_{k(d+1)}\right) + Pb_{kd} \tag{3.13}$$

Here sf is the scale factor.

Considering particles random position (d-1) and (d+1) the best optimal solution is updated. Here k represents population index.

In the stage four opposition-based mutations is applied.

$$Pb_{kd4} = \left(Pb_{kd}^{\max} + Pb_{kd}^{\min}\right) - Pb_{kd} \tag{3.14}$$

Here in equation (3.14) the maximum and minimum value of i^{th} generating unit in thermal plant is compared and difference is been reduced from previous best value to attain the new best position.

3.4 Heuristic Optimization Technique-II.

This technique adopts combination of TVAC-PSO and different mutation strategies describe in heuristic optimization technique-I. The need and importance related behind using of TVAC is to upgrade the global explore in the initial fraction of the optimization and provide consent to the particles to come collectively towards the global best at the end of the search. This is gained by varying the acceleration coefficients $C_1 \; and \; C_2$ with time in such a way that the cognitive component is descended while the social component is ascended as the search gains momentum. With higher value of cognitive component and lower value of social component at the beginning, particles move around the search space rather than moving toward the swarm best during initial stages. On the other hand, a lower value of cognitive component and a higher value of social component permit the particles to congregate to the global optima in the final part of the optimization method.

The acceleration coefficients are expressed as [71]:

$$C_1 = \left(C_{1f} - C_{1i}\right) \times \left(\frac{iter}{iter_{\max}}\right) + C_{1i} \tag{3.15}$$

$$C_2 = \left(C_{2f} - C_{2i}\right) \times \left(\frac{iter}{iter_{\max}}\right) + C_{2i} \tag{3.16}$$

Where $C_{1i}, C_{2i}, C_{1f} and C_{2f}$ are the initial and final values for cognitive and social learning acceleration coefficient. Here $iter \; and \; iter_{\max}$ are the running iteration number and maximum iteration value.

3.5 Heuristic Optimization Techniques for Pumped Storage HTS Problem.

The decision variables for pumped storage hydrothermal scheduling are water discharge and thermal power. In short term multi reservoir pumped storage hydrothermal scheduling; two types of constraints are present categorised as inequality constraint and equality constraint.

Decision variables match up to the position of the particles which is primarily generated arbitrarily within the limits.

(i) Decision Variable:

Water discharge generated randomly within maximum and minimum limits is represented as Follows:

$$q_{hjt} = q_{hj}^{\min} + \left(q_{hj}^{\max} - q_{hj}^{\min}\right) \times rand_{tj} \tag{3.17}$$

The maximum and minimum range of thermal power generated at random is represented as Follows:

$$P_{gti} = P_{gi}^{\min} + \left(P_{gi}^{\max} - P_{gi}^{\min}\right) \times rand_{ti} \tag{3.18}$$

Equality and Inequality constraint is handled by the penalty factor technique in which when the inequality and equality constraints are violated the error is generated is multiplied with the high exterior penalty. The objective function is obtained finally by considering the integration of thermal units total fuel cost and the addition of square of all the errors obtained from violating the maximum and minimum limits.

(ii) Equality Constraints:

In multi-chain pumped storage hydrothermal scheduling on short term basis, the power demand to the power system contributes to the equality constraint. Equation (2.2) represents the power demand and equation (2.8) represents the reservoirs final storage volume.

Due to the unbalancing of the load demand error generated is represented as follows:

$$d_{er} = P_{dt} - \sum_{i=1}^{ng} P_{git} - \sum_{j=1}^{nh} P_{hjt} - P_{psgtl} + P_{psptl} \tag{3.19}$$

where, d_{er} represents the error generated from the unbalance of the demand .

The unbalancing of the final reservoir storage volume generates the error which is represented as:

$$e_{vr} = \left(V_j^{end} - V_{hjt}^{T}\right) \tag{3.20}$$

where, e_{vr} represents the error generated from the unbalancing of the final reservoir storage volume.

(iii)Inequality Constraints:

In analysis of the short term multi reservoir pumped storage hydrothermal scheduling, the storage volume of reservoir mention in equation (2.10) represents the inequality constraints, equation (2.9) represent the hydro generation inequality constraints and equation (2.11 and 2.12) represents pumped storage power inequality constraint either in generating or in pumping mode.

The generated error for reservoir storage volume inequality constraint is represented as follows:

$$V_{er} = \begin{cases} V_j^{\max} - V_{hjt}, & V_{hjt} \geq V_j^{\max} \\ V_{hjt} - V_j^{\min}, & V_{hjt} \leq V_j^{\min} \end{cases} \tag{3.21}$$

The generated error from the limits violation for the hydroelectric generation inequality constraint is represented as follows:

$$P_{h\,er} = \begin{cases} P_{hj}^{\max} - P_{hjt}, & P_{hjt} \geq P_{hj}^{\max} \\ P_{hjt} - P_{hj}^{\min}, & P_{hjt} \leq P_{hj}^{\min} \end{cases} \tag{3.22}$$

The generated error from the violation of pumped storage generation constraint relating to inequality constraint is represented as follows:

$$P_{pser} = \begin{cases} P_{psl}^{\max} - P_{pstl}, & P_{pstl} \geq P_{psl}^{\max} \\ P_{pstl} - P_{psl}^{\min}, & P_{pstl} \leq P_{psl}^{\min} \end{cases} \tag{3.23}$$

Overall value of the objective function is obtained by integrating total value of errors in consideration with their penalty factor i.e. r and the calculation related to the fuel cost is done as:

Objective function = $f_1 + r \times \left(e_{vr}^2 + V_{er}^2 + d_{er}^2 + P_{her}^2 + P_{pser}^2\right)$ (3.24)

The algorithm-I represents procedural steps to solve HTS problem considering pumped storage unit by applying heuristic optimization technique-II.

Algorithm-I: Scheduling of hydro-thermal system considering pumped storage units with heuristic optimization technique-II.

Step1: Set all the parameters in relation to the applied technique i.e. maximum iteration, standard deviation, population size, scale factor and other factors or constants.

Step2: Initialize the position and velocity of the particle for pumped storage STHTS problem using the equation (3.1) and (3.2) respectively.

Step3: Computational analysis of reservoir storage volume.

The reservoir storage volume is attained by means of equation (2.3). If the value of storage volume of the reservoir violates the maximum and minimum limits, error is generated and evaluated by means of equation (3.21).

Step4: Calculating the Hydro power generation.

The total generation by the hydroelectric units is attained using the equation (2.4). If hydro power generated violates the maximum and minimum limit, the error is generated and calculated by using the equation (3.22).

Step5: Generate the random binary variable (Y) for both pumping and generating mode of pumped storage unit to provide a changeover period by using equations (2.13), (2.14) and (2.15).

Step6: Compute the pumped storage power using equation (2.16) considering either generating or pumping mode.

Step7: Evaluating total useful power:

Total useful productive power is the sum of the thermal power, hydro power and pumped storage unit power either in generating or pumping mode. If total useful productive power doesn’t meet the load demand, the error generated is evaluated by means of equation (3.19).

Step8: The objective function is evaluated using equation (3.24).

Step9: Generate the inertia weight (w) from equation (3.6), social learning and cognizant factors (C_1 and C_2) from equation (3.15 and 3.16).

Step10: Velocity of the particle is updated by using equation (3.3).

Step11: Position of the particle is updated using equation (3.4).

Step12: Step (3) to Step (11) are repeated till maximum iteration for PSO is reached.

Step13: Compute Gaussian distribution from equation (3.8) and Cauchy distribution from equation (3.11).

Step14: Update the global best position of particles obtained from PSO by applying Gaussian distribution using equation (3.7), Cauchy distribution using equation (3.10) and other DE based mutation strategies using equations (3.13 and 3.14).

Step15: comparison among the global best values obtained to achieve the global best solution.

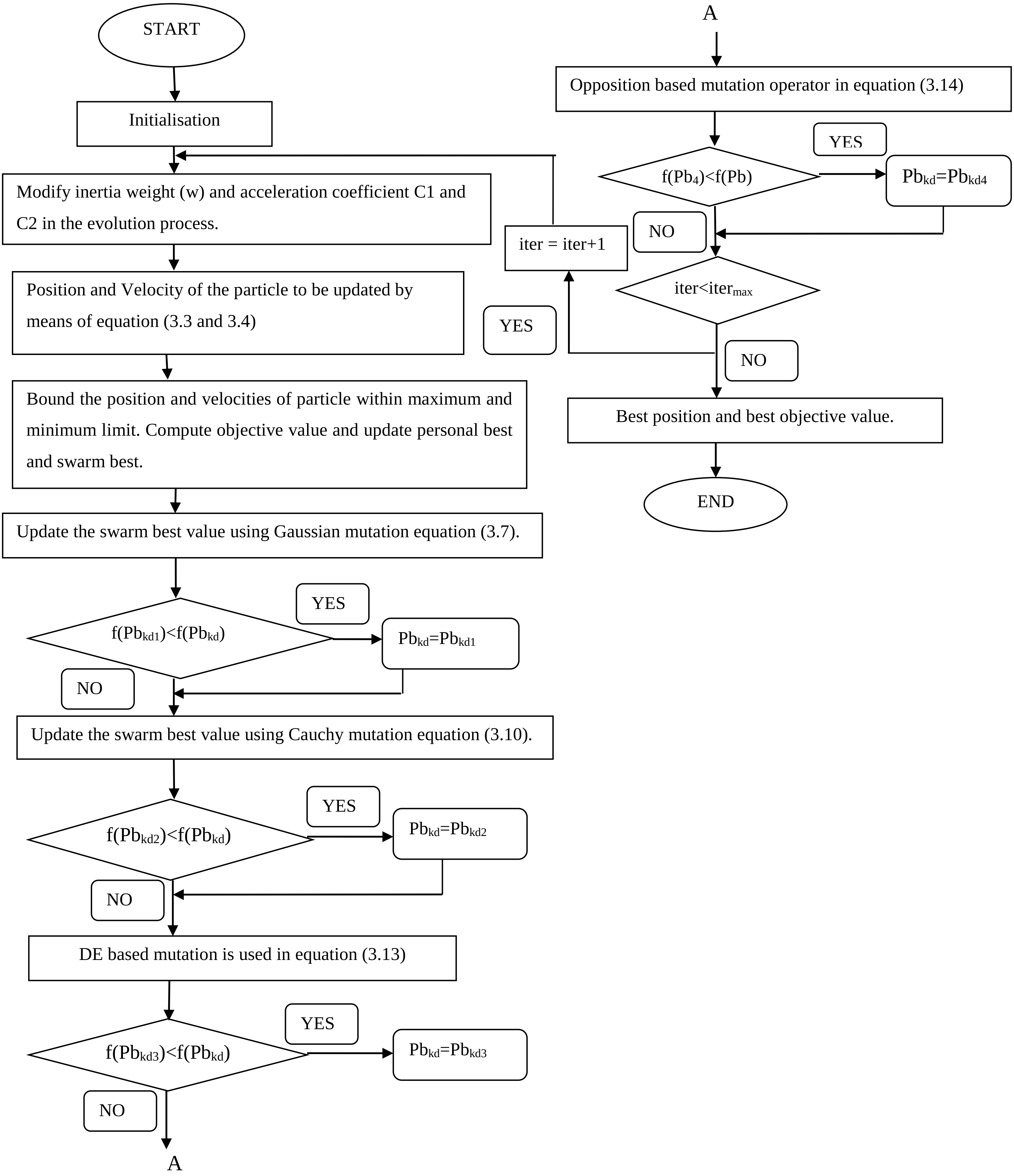

Figure 3.1. Flowchart of heuristic optimization technique- II.

Chapter-4

Results and Discussion

The proposed heuristic optimization techniques adopting TVAC-PSO and different mutation strategies has been implemented over the pumped storage hydrothermal problem in the test system. The test system involves multi-storage cascaded reservoir of hydroelectric units having different inflow rate and water transport delay involving reservoirs considered for the integrated hydroelectric plants [72]. The related input data for the test system have been depicted in Appendix A.

4.1 Test System

4.1.1 Depiction of Pumped Storage Hydrothermal System

As shown in figure 4.1, test system-I consist of four multi-reservoir cascaded hydro units, three thermal units and one pumped storage unit connected linking hydro unit 1 and 3. The valve point loading effect has been undertaken and losses have been neglected. Apart from this the water inflow rate, thermal plant fuel cost coefficient, hydro and thermal generation limits, load demand, water discharge limit, Reservoir volume storage limit, and hydro power generation coefficient are listed in appendix A. The scheduled time interval considered is 1 day consisting 24 sub-intervals with time period of 1 hour in between two sub-intervals.

4.1.2 Parameter Setting

The proposed technique utilised for solving pumped storage hydrothermal scheduling problem has been implemented using the FORTRAN 90 compiler. The parameters associated to propose heuristic optimization technique (TVAC and mutation strategies) which has to be prearranged are size of population N, shrink factor b, pump storage cost coefficients and the social learning factors initial and final values. On the basis of several numbers of attempts with altered values of the parameter associated to propose heuristic optimization technique (TVAC and mutation strategies) is given in the table 4.1.

Table 4.1 Parameter setting in the techniques for test system-I.

S. No	Parameter	Value
1.	Size of Population	100
2.	Shrink factor	0.001
3.	Scale factor	1.2
4.	K_1, K_2	0.8, 0.7
5.	$C_{1i}, C_{1f}, C_{2f}, C_{2i}$	2.5, 0.5,2.5,0.5

4.1.3 Simulation Results for Heuristic Optimization Techniques

The proposed heuristic optimization technique has been utilised for solving pumped storage STHTS problem with the help of FORTRAN 90 complier. Using the standards of the parameters specified in table 4.1, the pumped storage hydrothermal power generated to meet the power demand using heuristic optimization technique-I and II algorithm are given in table 4.2 and 4.3 respectively. The trajectory of the optimal discharge of water every hour for heuristic optimization technique-I and II algorithm are shown in the figure 4.2 and 4.3 respectively. Similarly, storage reservoir volume in case heuristic optimization technique-I and II are shown in figure 4.4 and 4.5 respectively. The cost attained using heuristic optimization technique-II (TVAC-PSO and mutation strategies) algorithm is 43,678.69$. The optimal cost obtained using heuristic optimization technique-II is compared with heuristic optimization technique-I and other ingrained global search technique as PSO specified in table 4.4 show that heuristic optimization technique-II delivered the improved results than the heuristic optimization technique-I and PSO technique.

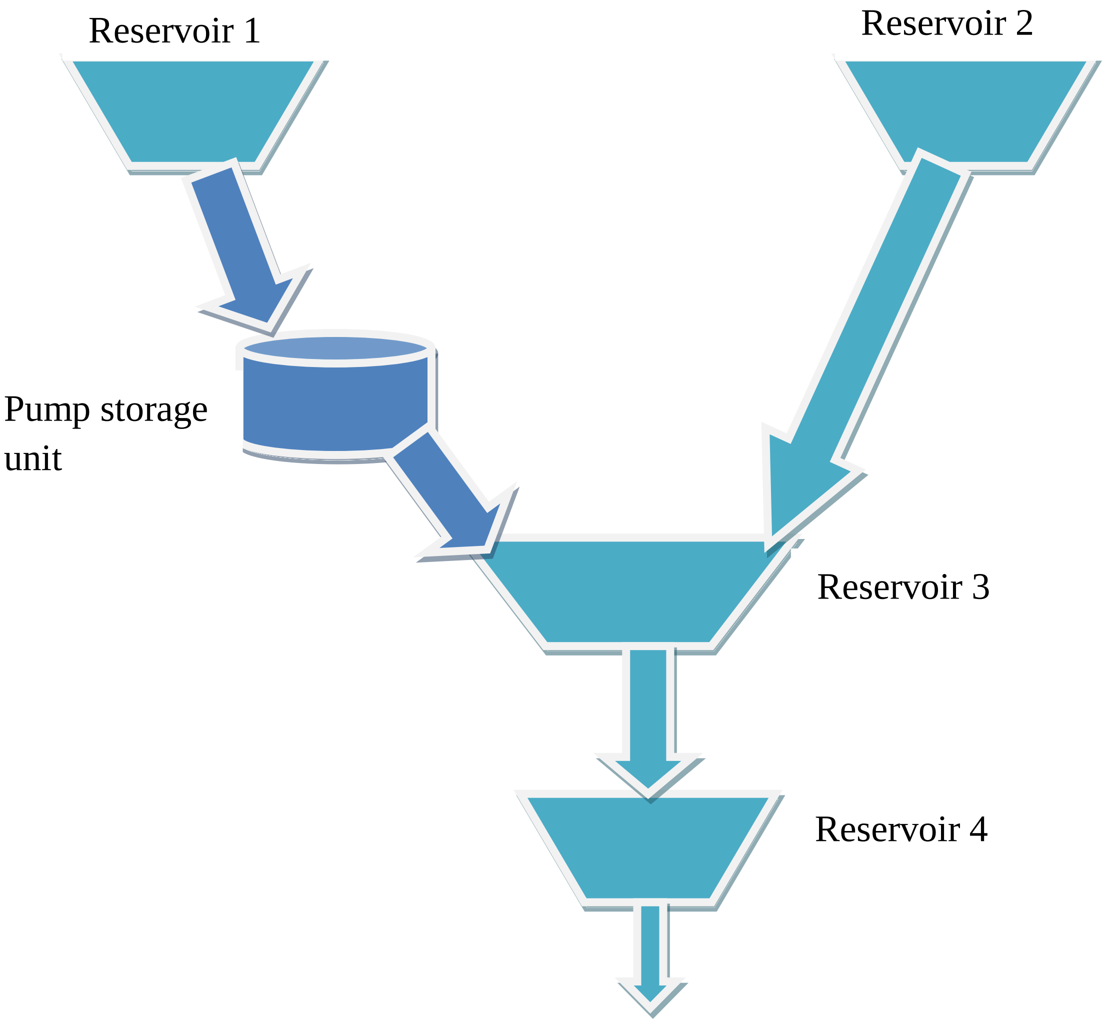

Figure 4.1 **Multi chain cascade of pumped storage hydrothermal system.**

TABLE 4.2 **Optimal hydrothermal power generation using Heuristic optimization technique-I: Test system-I**

Sub Interval (Hr)	**Thermal Generation** (MW)			**Hydro Generation** (MW)			
	P_{g1}	P_{g2}	P_{g3}	P_{h1}	P_{h2}	P_{h3}	P_{h4}
1	31.0335	125.0172	184.9130	91.9296	58.9719	37.9487	219.9992
2	113.6238	136.0152	270.2885	94.1184	79.4735	52.4252	116.2758
3	66.1302	126.5696	203.6318	103.0608	58.5828	44.7682	184.8241
4	102.8390	143.7381	101.9765	108.2186	69.4667	43.1901	164.9620
5	69.2667	117.7816	198.4420	74.2745	49.0824	2.1031	159.0324
6	29.4820	62.5869	280.3972	88.7530	64.4911	13.2185	172.0012
7	103.6912	276.3560	107.2144	97.8960	51.7114	28.5019	186.5304
8	60.1413	223.8415	319.2710	96.0601	47.1555	0	167.7584
9	116.3393	198.0050	281.1073	98.9767	48.3685	47.5664	200.9437
10	102.6602	168.9976	321.7845	97.0386	70.3524	50.3475	171.6357
11	105.6899	200.5219	270.6850	93.1522	49.6766	51.2027	235.7230
12	76.4423	259.0550	288.3414	86.7675	71.2449	46.3329	234.7819
13	87.3055	176.0922	323.2484	91.9555	62.3779	53.9186	223.1405
14	101.9719	180.3152	238.4696	99.3817	69.7844	26.6659	213.9719
15	99.8320	150.4411	245.7196	95.9834	65.8914	57.4030	198.7548
16	92.7306	181.7744	253.2349	97.3062	49.4522	58.2210	229.8493
17	112.766	187.7541	259.1855	76.3538	77.7123	58.8920	200.9295
18	96.7919	159.6474	318.7859	94.4239	53.5926	58.7840	243.6339
19	88.4956	179.9663	257.2486	85.3641	58.6233	52.5550	261.9827
20	70.9670	214.1151	217.7841	93.6913	67.2751	56.9570	235.3940
21	97.3918	153.7271	149.5182	95.9835	49.7519	60.7630	206.9294
22	124.708	117.8904	168.8449	92.4744	75.6033	45.1003	235.7910
23	43.7732	219.9373	223.6420	95.2773	56.5324	61.8272	233.5280
24	86.2128	133.9107	319.9277	99.4120	54.9457	50.9985	148.2917

TABLE 4.3 **Optimal hydrothermal power generation using heuristic optimization technique-II: Test system-I**

Sub Interval (Hrs)	**Thermal Generation** (MW)			**Hydro Generation** (MW)			
	P_{g1}	P_{g2}	P_{g3}	P_{h1}	P_{h2}	P_{h3}	P_{h4}
1	102.6810	148.6122	139.7544	95.8434	67.3123	0	195.7223
2	93.0423	145.1913	229.5678	97.7922	65.5433	47.1033	188.5622
3	33.9445	159.3615	168.9034	103.2015	64.7733	45.6744	207.1813
4	79.2612	162.3156	187.0923	98.6067	77.2655	42.6256	86.6824
5	89.7081	124.4067	139.6631	103.9988	52.5288	47.8812	112.0322
6	72.4012	124.7044	139.7526	88.0598	47.6399	47.4023	192.0445
7	124.5018	143.9934	229.5239	67.9287	56.3577	54.2245	205.4567
8	94.6875	209.8138	271.9445	88.3865	61.8378	26.7467	168.2978
9	102.6744	240.5888	293.1749	94.5444	47.0166	52.5888	164.8456
10	77.7243	124.9097	389.9687	91.0645	48.8278	53.4677	203.6545
11	102.6742	209.8112	319.2077	93.1456	61.7911	0	220.2233
12	102.7941	143.5622	409.0388	74.6467	50.6332	51.2118	243.4166
13	102.7033	146.1524	361.7586	97.6878	72.9833	53.6144	177.3678
14	68.5212	209.8234	229.5265	93.3589	53.8089	53.3733	228.1789
15	36.5818	209.8132	229.5225	90.6445	75.4499	56.5344	221.0888
16	77.3099	294.7239	229.5156	68.7344	56.3387	56.8666	207.7612
17	102.6476	209.7887	267.3888	95.0144	51.4976	22.2677	206.3333
18	102.6766	209.9376	229.9221	99.652	73.9477	59.3888	244.7845
19	102.6555	130.9168	319.3222	92.4599	54.8078	35.1313	242.1769
20	44.8343	223.7889	229.5433	99.0689	50.3078	57.6624	245.6098
21	109.8457	124.8899	229.5544	94.0378	71.6988	27.4245	158.5777
22	102.6778	209.8199	139.6855	86.2267	57.9390	38.4444	225.1268
23	98.9366	40.055	319.3088	93.7455	86.1309	57.2823	246.4855
24	102.6754	163.3345	187.7399	97.2233	80.6708	56.4507	185.8198

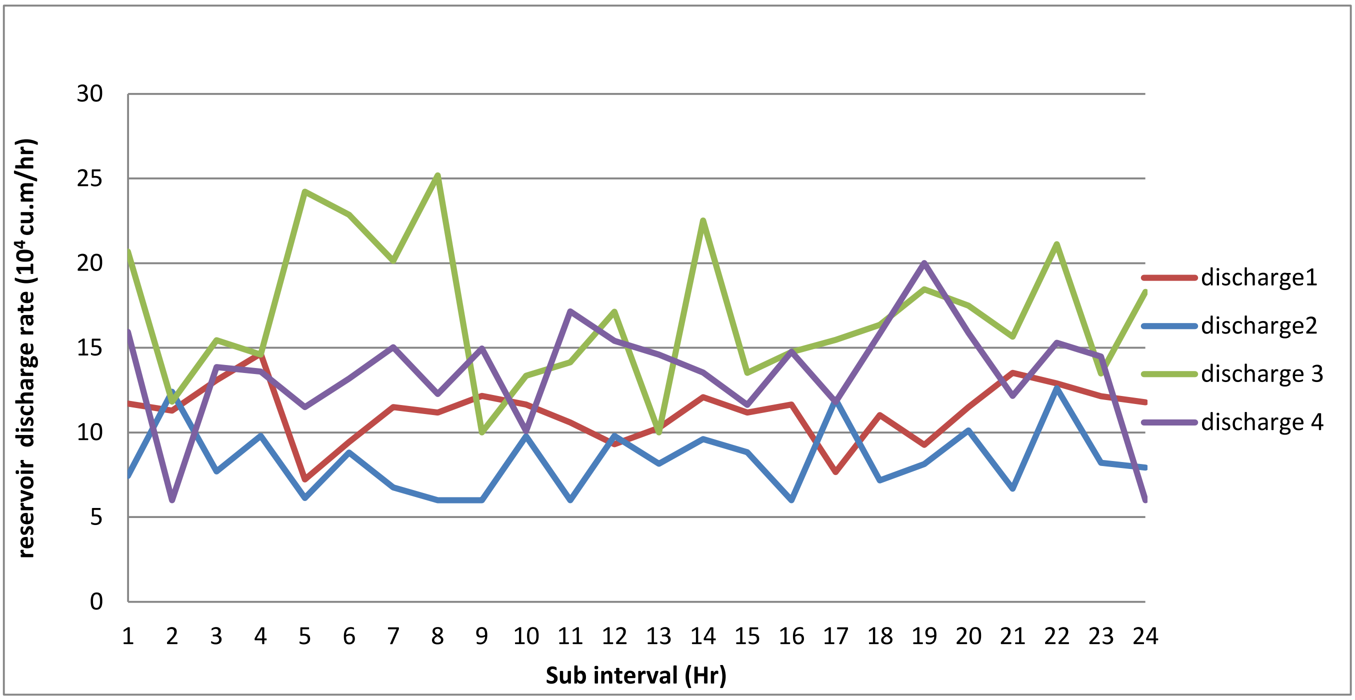

Figure 4.2: Reservoir discharge rates for test system-I with heuristic optimization technique-I

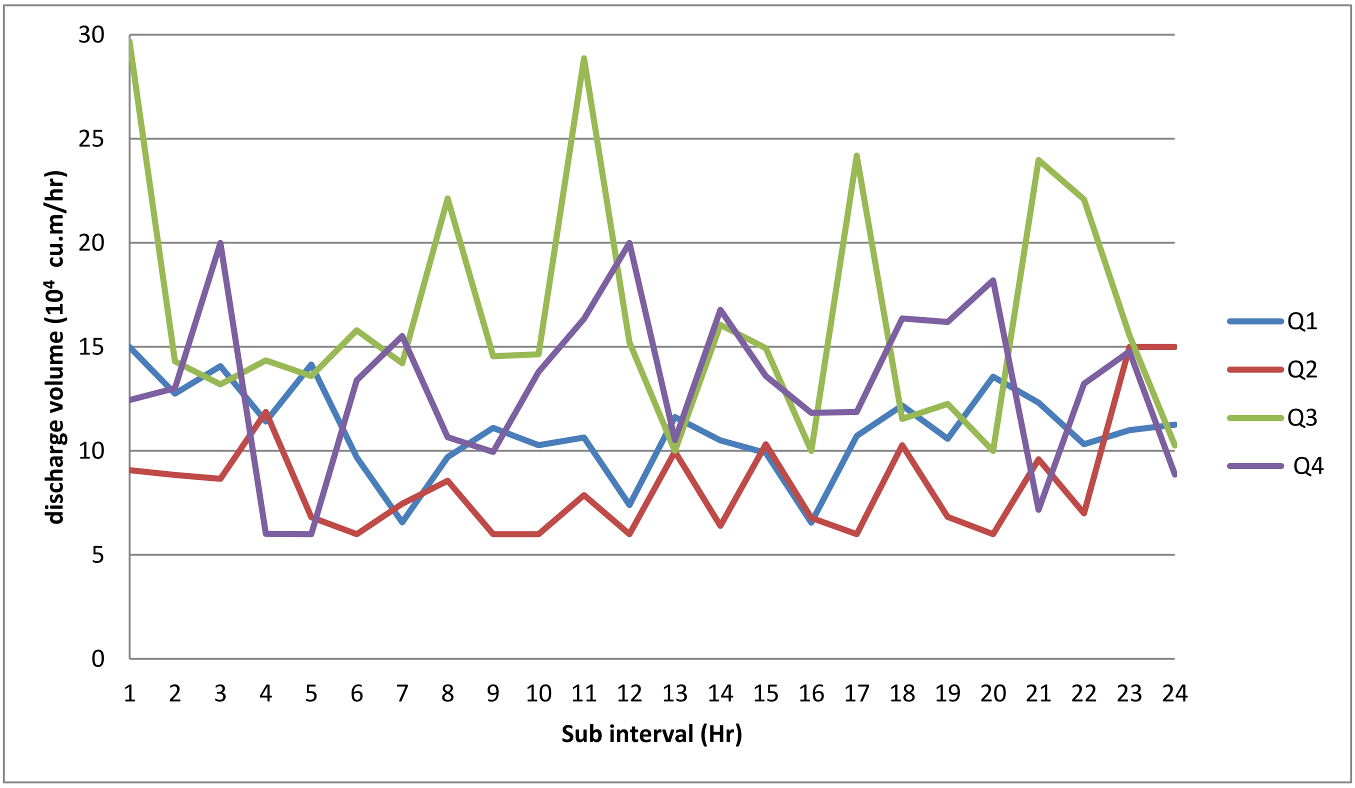

Figure4.3: Reservoir discharge rates for test system-I using heuristic optimization technique-II

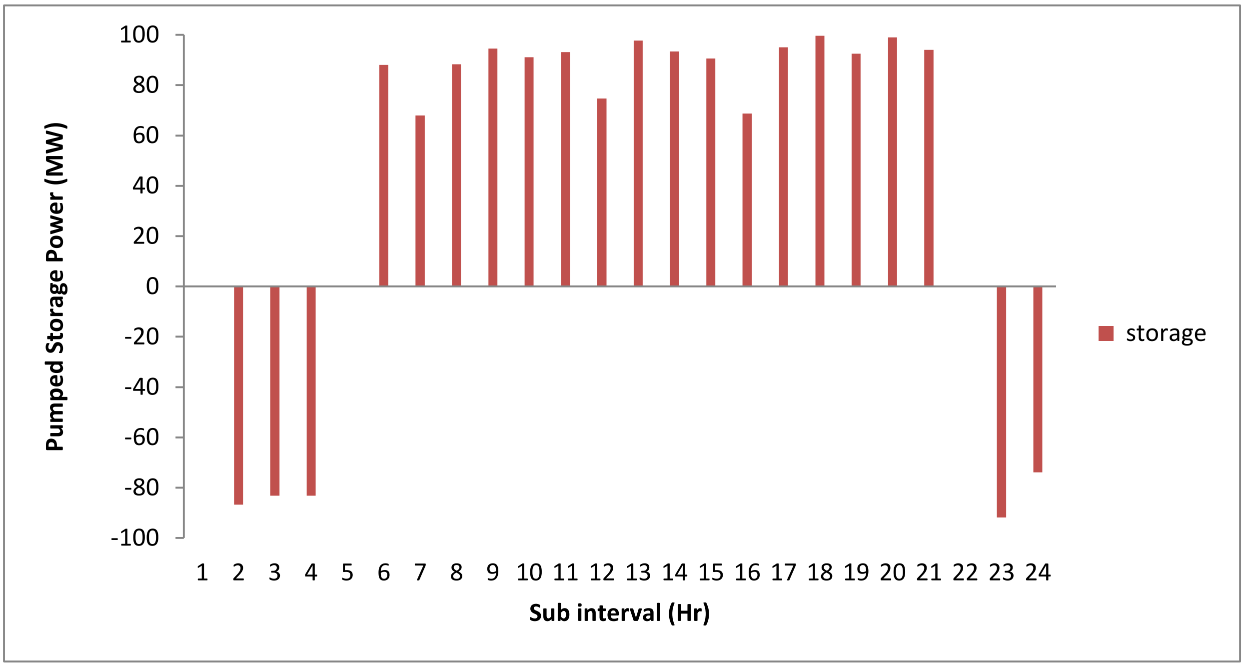

Figure4.4: Pumped storage unit power output for test system-I using heuristic optimization technique-II.

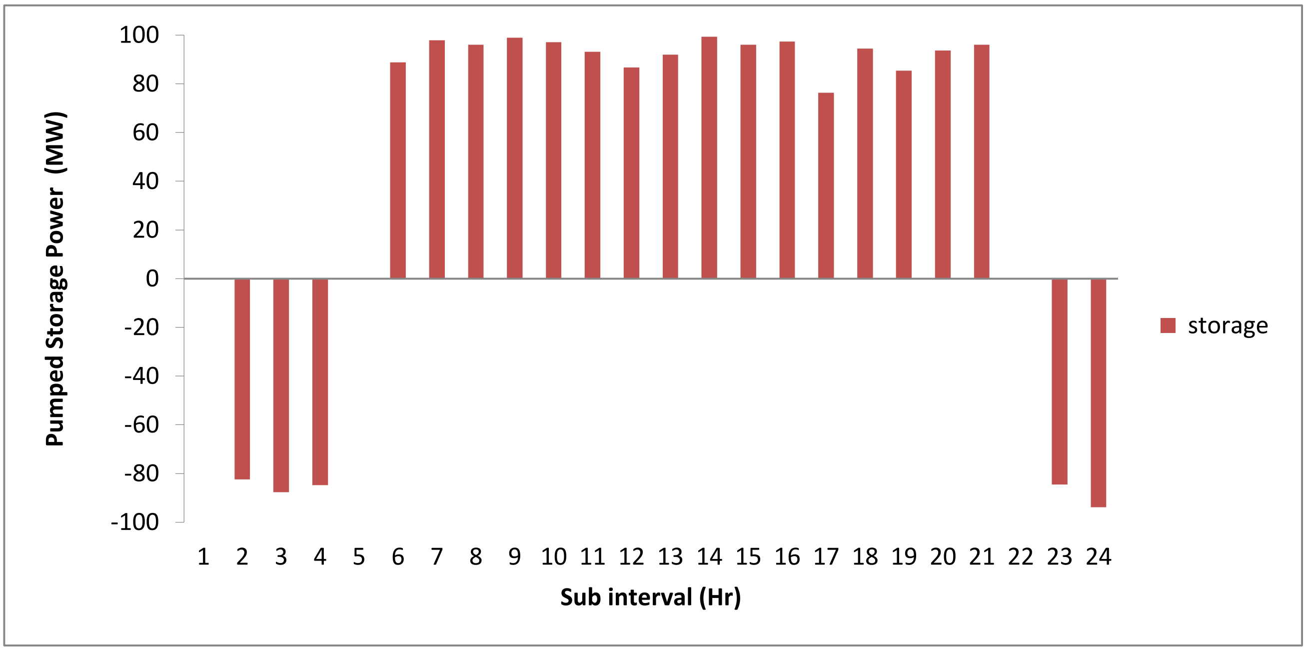

Figure4.5: Pumped storage unit power output for test system-I using heuristic optimization technique-I.

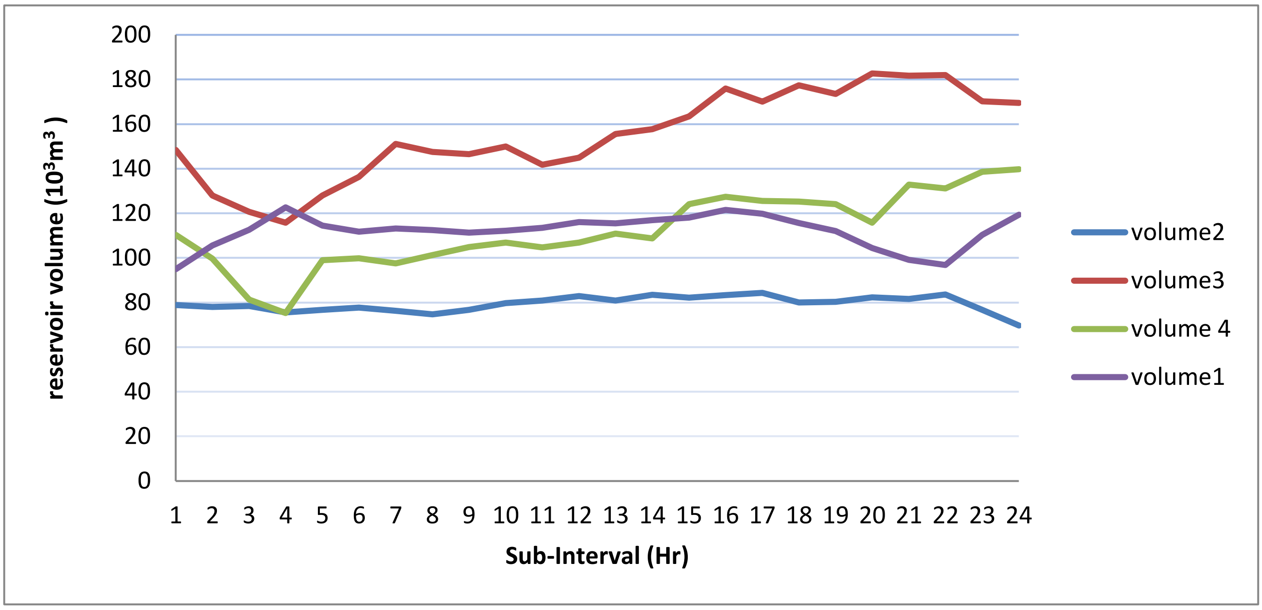

Figure 4.6 Reservoir storage volumes for test system-I using heuristic optimization technique-II

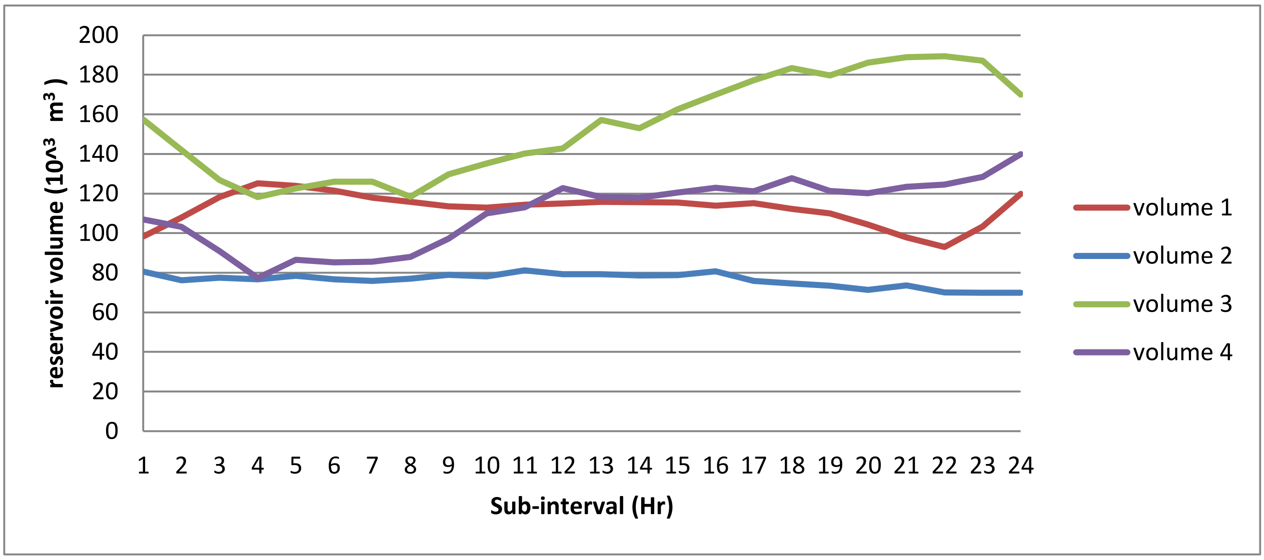

Figure 4.7 Storage reservoir volumes for test system-I using heuristic optimization technique-I

Table 4.4 comparison of cost for test system-I

S.No	Optimization Technique	Cost ($)
1	PSO	47779.29
2	Heuristic optimization technique-I	46192.40
3	Heuristic optimization technique-II	43678.69

Chapter- 5

Conclusion and Future Scope of the Work

5.1 Conclusion

The heuristic optimization techniques have been proposed for solving HTS problem considering pumped storage unit. In the proposed techniques, heuristic optimization technique adopts time varying acceleration coefficient PSO which controls the alternation and restricts the deviation of the particles in the search space. The acceleration factors i:e social learning and cognizant factors controls the exploration and exploitation of particle in search space. The proposed heuristic optimization technique works by considering combination of two different variants of PSO. The first variant controls the social learning and cognizant factors where as the second variant upgrades and compares the best evaluated objective value in a bid to locate global best solution. The usefulness of the proposed technique is demonstrated by means of a test system.

5.2 Future Scope

The possibility for the upcoming work in the dissertation is acknowledged as:

- In the dissertation, pumped storage hydrothermal scheduling is prepared for short term period. The proposed approach can also be implemented for optimal scheduling on medium term HT and long term HT systems.
- The problem of hydrothermal scheduling can be solve by taking into consideration the effects of ramp rate, transmission losses and prohibited zone.
- The problem of hydrothermal scheduling can be extended from single objective to multi objective by taking into consideration the secretion of gases as an objective.

PUBLICATIONS

I. International Conference

Presented a paper in the IEEE International Conference on the Power Electronics, Intelligent Control and the Energy Systems.

R.S. Patwal and N. Narang. “Heuristic Optimization technique for Hydrothermal Scheduling Considering Pumped Storage Unit”, IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems, New Delhi 2016.

II. International Journal

Published a paper in International Journal of Scientific Research and Development.

1. R.S. Patwal and N. Narang. “Applying Time Varying Acceleration Coefficient PSO for Pumped Storage Hydrothermal Scheduling Problem”, International Journal of Scientific Research and Development, vol. 4, no. 3, pp. 1677-81, 2016.

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APPENDIX-A

SYSTEM DATA FOR TEST SYSTEM I

Table A.1: Water transport delay between the connected reservoirs.

Plant	1	2	3	4
R_{uj}	0	0	2	1
d_{lj}	2	3	4	0

R_{uj} : Number of upstream hydro power plant

d_{lj} : Time delay to immediate downstream hydro power plant

Table A.2: Reservoir storage capacity limit, plant discharge limits, plant generation limits and reservoir end conditions.

Plant (j)	$V_{hj}^{\min}$ $\left(m^3\right)$	$V_{hj}^{\max}$ $\left(m^3\right)$	V_{hj}^{init} $\left(m^3\right)$	V_{hj}^{end} $\left(m^3\right)$	$q_{hj}^{\min}$ $\left(m^3/hr\right)$	$q_{hj}^{\max}$ $\left(m^3/hr\right)$	$P_{hj}^{\min}$ $\left(MW\right)$	$P_{hj}^{\max}$ $\left(MW\right)$
1	80	150	100	120	5	15	0	500
2	60	120	80	70	6	15	0	500
3	100	240	170	170	10	30	0	500
4	70	160	120	140	6	20	0	500

Table A.3: Hydro power generation coefficient.

Plant (j)	C_1 $\left(\frac{MW}{(m^3)^2}\right)$	C_2 $\left(\frac{MW}{(m^3/hr)^2}\right)$	C_3 $\left(\frac{MW}{m^3 \times (m^3/hr)}\right)$	C_4 $\left(\frac{MW}{m^3}\right)$	C_5 $\left(\frac{MW}{m^3/hr}\right)$	C_6 $\left(MW\right)$
1	-0.0042	-0.4200	0.0300	0.9000	10.000	-50.000
2	-0.0040	-0.3000	0.0150	1.1400	9.5000	-70.000
3	-0.0061	-0.3000	0.0140	0.5500	5.5000	-40.000
4	-.00300	-0.3100	0.0270	1.4400	14.000	-90.000

Table A.4: Fuel cost coefficient and operating limits of thermal units.

Plant (i)	a_i (MW)	b_i (MW)	c_i (MW)	d_i (MW)	e_i (MW)	$P_{gi}^{\min}$ (MW)	$P_{gi}^{\max}$ (MW)
1	0.0012	2.45	100	160	0.038	20	175
2	0.0010	2.32	120	180	0.037	40	300
3	0.0015	2.10	150	200	0.035	50	500

Table A.5: Reservoir inflows of the multi chain hydro plants (x 10^4m^3).

Sub-interval (Hr)	**Reservoir**				Sub-interval (Hr)	**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 A.6: Load demand for 24 hours.

Sub-interval (Hr)	Power Demand (MW)	Sub-interval (Hr)	Power Demand (MW)	Sub-interval (Hr)	Power Demand (MW)	Sub-interval (Hr)	Power Demand (MW)
1	750	7	950	13	1110	19	1070
2	780	8	1010	14	1030	20	1050
3	700	9	1090	15	1010	21	910
4	650	10	1080	16	1060	22	860
5	670	11	1100	17	1050	23	850
6	800	12	1150	18	1120	24	800

Table A.7: Pump storage power generation coefficient.

Plant (l)	L_1 $\left(\frac{MW}{(m^3)^2}\right)$	L_2 $\left(\frac{MW}{(m^3/hr)^2}\right)$	L_3 $\left(\frac{MW}{m^3 \times (m^3/hr)}\right)$	L_4 $\left(\frac{MW}{m^3}\right)$	L_5 $\left(\frac{MW}{m^3/hr}\right)$	L_6 (MW)	η_g and η_p
1	-0.00042	-0.04200	0.00300	0.09000	1.000	-5.000	0.8 (P_{psg}) 1.0 (P_{psp})

$P_{pspl}^{\max}$ =Maximum generating power and utilised pumping power for pump storage plant =100 MW.

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I. Personal background

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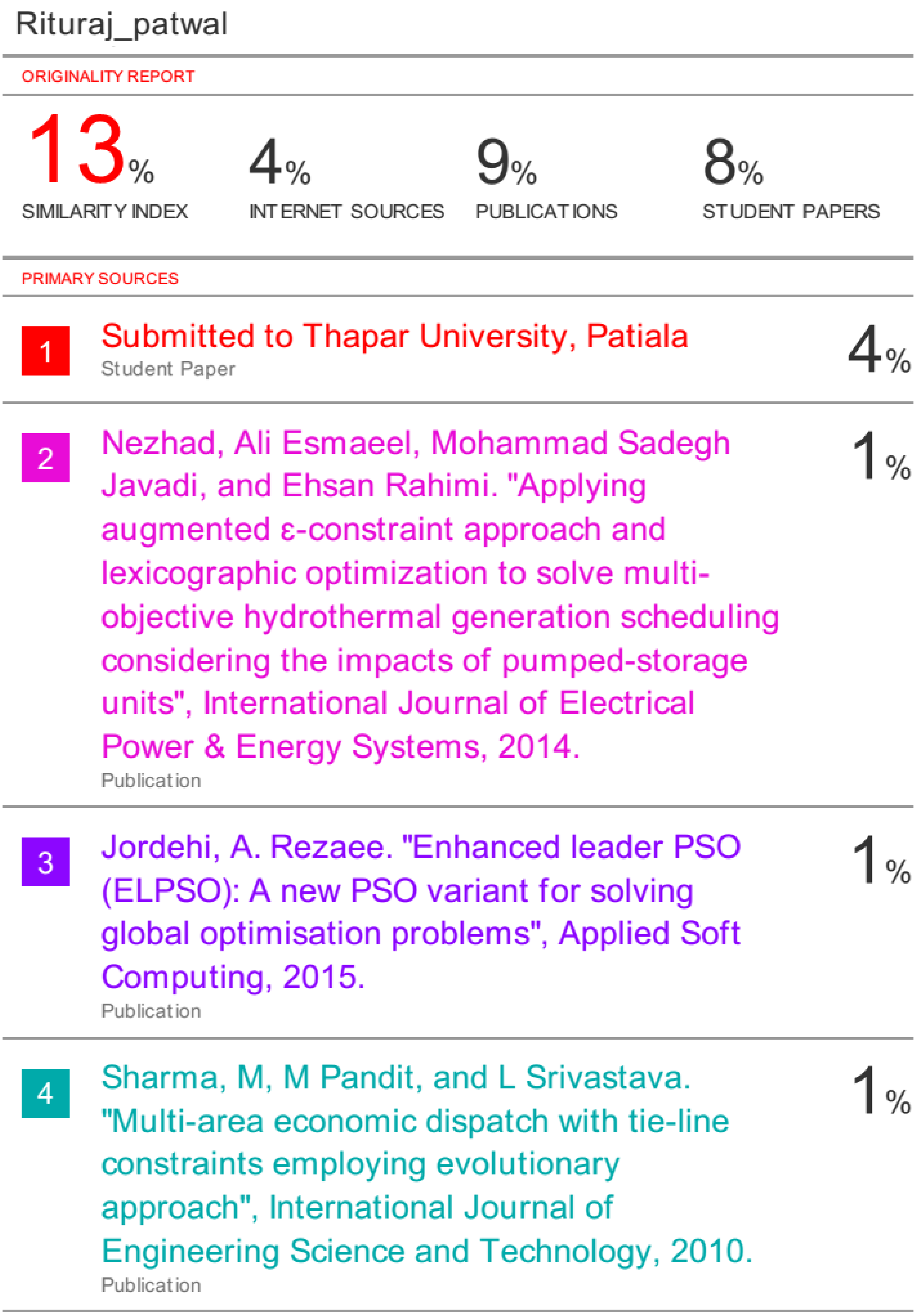
Degree	Subject	Institute	Board/University	Marks(%)
S.S.C	Science	St. Theresa Sen.Sec. School Nainital.	CBSE	86.2
H.S.C	Science(PCM)	St. Theresa Sen.Sec. School Nainital.	CBSE	83
B.Tech.	Electrical Engineering	Dehradun Institute of Technology	Uttarakhand Technical University	71.83

III. List of Publications

1. R.S. Patwal and N. Narang. "Heuristic Optimization technique for Hydrothermal Scheduling Considering Pumped Storage Unit", IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems, New Delhi 2016.

2. R.S. Patwal and N. Narang. "Applying Time Varying Acceleration Coefficient PSO for Pumped Storage Hydrothermal Scheduling Problem", International Journal of Scientific Research and Development, vol. 4, no. 3, pp. 1677-81, 2016.

PLAGIARISM CERTIFICATE



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ORIGINALITY REPORT

13%	4%	9%	8%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Submitted to Thapar University, Patiala Student Paper	4%
2	Nezhad, Ali Esmaeel, Mohammad Sadegh Javadi, and Ehsan Rahimi. "Applying augmented ε-constraint approach and lexicographic optimization to solve multi-objective hydrothermal generation scheduling considering the impacts of pumped-storage units", International Journal of Electrical Power & Energy Systems, 2014. Publication	1%
3	Jordehi, A. Rezaee. "Enhanced leader PSO (ELPSO): A new PSO variant for solving global optimisation problems", Applied Soft Computing, 2015. Publication	1%
4	Sharma, M, M Pandit, and L Srivastava. "Multi-area economic dispatch with tie-line constraints employing evolutionary approach", International Journal of Engineering Science and Technology, 2010. Publication	1%