

Hybridization of Modified Gravitational Search Algorithm and SQP for Multi Chain Hydrothermal System

A Dissertation submitted in fulfillment of the requirements for the Degree
of

MASTER OF ENGINEERING
in
Power Systems

Submitted by

SAURABH SHARMA
801341023

Under the Guidance of
Dr. Nitin Narang
Assistant Professor, EIED



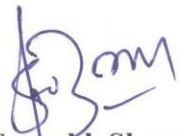
2015

Electrical and Instrumentation Engineering Department
Thapar University, Patiala
(Declared as Deemed-to-be-University u/s 3 of the UGC Act., 1956)
Post Bag No. 32, Patiala – 147004
Punjab (India)

DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "Hybridization of Modified Gravitational Search Algorithm and SQP for Multi-Chain Hydrothermal System", in partial fulfillment 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.

Place: Patiala
Date: 15-07-2015


(Saurabh Sharma)
Roll No.: 801341023

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

Date: 15-07-2015


(Dr. Nitin Narang)
Assistant Professor
Electrical & Instrumentation Engineering Department
Thapar University, Patiala

Countersigned by:

Head 
Electrical & Instrumentation Engineering Department
Thapar University, Patiala


Dean (Academic Affairs)
Thapar University, Patiala

ACKNOWLEDGEMENT

It is a great pleasure for me to take this opportunity to express my profound sense of gratitude to all those who assisted me in the completion of this dissertation work.

I gratefully acknowledge my supervisor **Dr. Nitin Narang** for his understanding, encouragement and personal attention which have provided good and smooth basis for my dissertation tenure. This work would not have been possible without his guidance, support and encouragement. Under his guidance I successfully overcame many difficulties and learned a lot.

I am also thankful to **Dr. Prakash Gopalan**, Director of Thapar University, Patiala for providing the facilities for the completion of M.E. I express my deep sense of gratitude towards **Dr. Ravinder Agarwal**, Head of the Department of Electrical & Instrumentation Engineering, Thapar University, Patiala who has been a constant source of inspiration for me throughout this work.

I am also thankful to my batch mates who devoted their valuable time for the successful completion of dissertation. I extend my gratitude to the researchers and scholars whose hours of toil have produced the papers that I have used in the dissertation.

Words are short to express my deep sense of gratitude towards my family members and friends for their encouragement, inspiration, emotional support and love. Finally, I bow to the Almighty who gave me strength to carry out this work with sincerity and dedication.

SAURABH SHARMA

801341023

TABLE OF CONTENTS

	Page
DECLARATION	i
ACKNOWLEDGEMENTS	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	v
LIST OF FIGURES	vi
NOMENCLATURE	vii
ABBREVIATIONS	viii
ABSTRACT	ix
CHAPTER-1 INTRODUCTION	1-5
1.1 Overview	1
1.2 Literature review	2
1.3 Objective of work	5
1.4 Organization of Dissertation	5
CHAPTER - 2 SHORT-TERM HYDROTHERMAL SCHEDULING	6-10
2.1 Introduction	6
2.2 Classification of Hydrothermal Scheduling Problem	7
2.2.1 Long-term hydrothermal scheduling	7
2.2.2 Mid-term hydrothermal scheduling	7
2.2.3 Short-term hydrothermal scheduling	7
2.3 Problem formulation of short term hydrothermal scheduling	8
CHAPTER – 3 IMPLEMENTATION OF HYBRID MGSA-SQP FOR STHTS	11-22
3.1 Gravitational search algorithm	12
3.2 Modified Gravitational search algorithm	15

TABLE OF CONTENTS (Continued)

3.3	Sequential quadratic programming	17
3.5	Hybrid MGSA-SQP algorithm for STHTS problem	18
CHAPTER - 4	RESULTS AND DISCUSSION	23-33
4.1	Test system I	23
4.1.1	Description of hydrothermal system	23
4.1.2	Parameter setting	24
4.1.3	Simulation results for hybrid MGSA-SQP algorithm	24
4.2	Test system II	28
4.2.1	Description of hydrothermal system	28
4.2.2	Parameter setting	29
4.2.3	Simulation results for hybrid MGSA-SQP algorithm	29
CHAPTER - 5	CONCLUSION AND FUTURE SCOPE	34
5.1	Conclusion	34
5.2	Future scope	34
PUBLICATIONS		35
REFERENCES		36
APPENDIX A		44
APPENDIX B		46
CURRICULUM VITAE OF AUTHOR		48
PLAGIARISM CERTIFICATE		49

LIST OF TABLES

Table No.	Caption	Page
4.1	Parameter setting for MGSA-SQP algorithm for test system I	24
4.2	Optimal hydrothermal power generation using MGSA algorithm : test system I	25
4.3	Optimal hydrothermal power generation using MGSA –SQP algorithm : test system I	25
4.4	Cost comparison for test system I	28
4.5	Parameter setting for MGSA-SQP algorithm for test system II	29
4.6	Optimal hydrothermal power generation using MGSA algorithm : test system II	30
4.7	Optimal hydrothermal power generation using MGSA –SQP algorithm : test system II	30
4.8	Cost comparison for test system II	33

LIST OF FIGURES

Figure No.	Caption	Page
3.1	Flowchart of Modified GSA algorithm	16
4.1	Multi-chain cascade of four hydro plants	23
4.2	Water discharge rate for test system I using MGSA algorithm	26
4.3	Water discharge rate for test system I using hybrid MGSA-SQP algorithm	27
4.4	Reservoir storage volume for test system I using MGSA algorithm	27
4.5	Reservoir storage volume for test system I using hybrid MGSA-SQP algorithm	28
4.6	Water discharge rate for test system II using MGSA algorithm	31
4.7	Water discharge rate for test system II using hybrid MGSA-SQP algorithm	32
4.8	Reservoir storage volume for test system II using MGSA algorithm	32
4.9	Reservoir storage volume for test system II using hybrid MGSA-SQP algorithm	33

NOMENCLATURE

F_T	Total fuel cost of thermal units (\$).
a_i, b_i, c_i, e_i, f_i	Fuel cost coefficients of i^{th} thermal unit.
P_{gik}	Output power of i^{th} thermal unit in k^{th} sub-interval.
P_{gi}^{min} and P_{gi}^{max}	Lower limits and upper generating limits on the i^{th} thermal unit.
N and M	Number of thermal and hydro units.
P_{hjk}	Hydro power generated of the j^{th} hydro unit in k^{th} sub-interval.
P_{Dk} and P_{Lk}	Power demand and transmission line losses in k^{th} sub-interval.
P_{hj}^{min} and P_{hj}^{max}	Lower and upper limits of the j^{th} hydro power generated.
V_{hj}^{min} and V_{hj}^{max}	Minimum and maximum storage limit of the reservoir j.
q_{hj}^{min} and q_{hj}^{max}	Minimum and maximum limit of the water discharge rate of reservoir j.
V_{hj}^{begin} and V_{hj}^{end}	Initial and final storage volume of the reservoir j.
I_{hjk} and S_{hjk}	Inflow and spillage of the reservoir j in k^{th} sub-interval.
d_{lj}	Water transport delay from the l 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 coefficient of the hydro plant j.
q_{hjk}	Water discharge of hydro plant j in k^{th} sub-interval.
V_{hjk}	Volume storage of the hydro plant j in k^{th} sub-interval.
T	Scheduling period
r	Exterior penalty factor

ABBREVIATIONS

STHTS	Short term hydrothermal scheduling
LTHTS	Long term hydrothermal scheduling
MTHTS	Medium term hydrothermal scheduling
GSA	Gravitational search algorithm
MGSA	Modified gravitational search algorithm
SQP	Sequential quadratic programming
EP	Evolutionary programming
GA	Genetic algorithm
DE	Differential evolution
BFGS	Broyden-Fletcher-Goldfarb-Shanno

ABSTRACT

Hydrothermal scheduling is an important aspect in power system operation. The main objective of the hydrothermal scheduling is to minimize the total operating cost while satisfying all the operational constraints. Over the years, many researchers have used several optimization techniques to solve hydrothermal scheduling problem in order to achieve a better result. In this dissertation, hybrid modified gravitational search and SQP algorithm has been proposed for solving short term hydrothermal scheduling problem. The proposed hybrid technique is the combination of the global search technique and the local search technique that works in two stages. The first stage employees global search technique MGSA to explore the search space and obtain a near to global solution. The second stage employees local search technique SQP for the exploitation of the of the explored search space to obtain the final solution. In order to show the effectiveness of the proposed hybrid MGSA-SQP algorithm, it is applied on the two standard systems. The results have been compared with other well established results mentioned in the literature and found satisfactory.

1.1 OVERVIEW

In modern world, electrical energy is considered as one of the most important factor in economic development of the country. With increase in the number of consumers and load, need of electrical energy is increasing day by day. To meet the increasing electrical energy requirement, power system is becoming complex. A complex power system comprises of large number of the hydro and thermal power plants connected to the various load via transmission network. The integration of the hydro power plant and the thermal power plant helps in optimal utilization of all energy resources in economical manner [1]. The generation cost of the thermal plant is very high but its capital cost is very low whereas the generation cost of the hydro plant is very low but its capital cost is very high. Therefore the objective of the hydro thermal system is the minimization of the total generation cost of the hydro thermal system by minimizing the generation cost of the thermal plant satisfying all the hydraulic and operational constraint [2].

Hydrothermal scheduling problem is solved for different time periods namely *long term hydrothermal scheduling* (LTHTS), *medium term hydrothermal scheduling* (MHTS) and *short term hydrothermal scheduling* (STHTS) [1]. In LTHTS [3], the time period varies from 1 year to several years, divided into monthly steps. In MHTS [4], time period corresponds a year, divided into monthly or weakly steps. In STHTS [5], time period corresponds a week or a day, divided into hourly steps. A number of classical methods such as Newton Raphson method [2], Lagrangian method [6-7], and interior point method [8], mixed integer programming [9] have been used for solving STHTS problem. In classical methods, some assumptions are considered to make the optimization problem more traceable which results in increase in computational time with increase in dimensionality of the problem [10]. Recently, global search technique techniques such as evolutionary programming [11-12], simulated annealing [13-14], differential evolution [15], artificial neural network [16] has been used for solving STHTS problem.

In 2009, Rashedi *et al.* [17] introduced a global search technique *gravitational search technique* (GSA) based on Newton's law of gravity and law of motion. In GSA, all agents interact with each other through gravitational force. Swain *et al.* applied GSA for solving economic load dispatch problem. In GSA, constant magnitude of maximum velocity is used for the exploration of the search space but after few iterations small movement of the agents is required for the exploitation of the search space. In 2012, Khajedzadeh *et al.* [18] proposed *modified gravitational search algorithm* (MGSA) algorithm for analysis of slope stability. In MGSA, time varying maximum velocity is utilized which limits the area of the search in the later stages of the iteration and strengthen the exploitation capability of the algorithm offering rapid convergence rate. Global search techniques have non-smooth characteristics in the search space which improves the convergence rate and make it less dependent on the initial solution points [19] but have a drawback of local trapping into the later stages of the iteration [20].

In order to overcome the drawbacks of the global search techniques, hybrid techniques are introduced. Victoire *et al.* [21] applied hybrid PSO-SQP for solving economic dispatch with valve point effect. Narang *et al.* [22] applied hybrid predator pray optimization and powell method for STHTS problem. Nallasivan *et al.* [23] presented hybrid evolutionary programming and tabu search technique for solving STHTS problem.

1.2 LITERATURE REVIEW

Hydrothermal scheduling is the scheduling of the thermal power and hydro power to get a feasible solution by satisfying all the constraints. It has been the area of interest for many years by the researchers. In past, hydrothermal problem was divided into two stages. Hydro problem was solved in the first stage. In the second stage thermal problem was solved which depends on the solution of the first stage [24]. The drawback of this approach was the incoherency between the two stages which resulted in a non-feasible solution. To assure that final solution obtained is the feasible solution, the overall all hydrothermal problem was divided into two sub problems: a thermal sub problem and a hydro sub problem [25-26] which are solved iteratively to get a feasible solution.

During past several decades, various classical methods have been used to solve STHTS problem. Tang *et al.* [27] and Yang *et al.* [28] used the dynamic programming to solve the STHTS problem. The drawback of this technique was the dimensionality leading to a larger computational time and memory storage [29]. Piekutowski *et al.* [30] used the linear programming method to find the STHTS for a large scale cascaded hydro system. Linear programming is always applied to the linear system, which resulted in the linear approximation of the objective function and the constraint of the hydro thermal problem leading to the errors in result [31]. Kumar *et al.* [32] applied non-linear programming to operation planning. The shortcoming of this technique was slow convergence and it requires a continuously differentiable function [33]. Salam *et al.* [34] applied Lagrange relaxation to the hydrothermal coordination. Lagrange Relaxation is considered more flexible for handling the different constraints. The drawback of this technique was the oscillation and accuracy of the solution and slow convergence [35]. The main disadvantages of the classical methods are dimensionality, convergence rate and assumption made during the implementation of these techniques on the hydrothermal problem. For hydro thermal problems having large dimensionality, computational time increases. The convergence rate of the classical methods are slow and assumptions made to make the problem more traceable introduces error in the results [10].

In recent years, global search techniques has been developed and used by the researchers because of their fast convergence rate and ability to determine almost global solution for the problem. Orero and Irving [36] used genetic algorithm to STHTS problem. The final volume of the reservoir was treated as the soft constraint which resulted in improvement of the total fuel cost but increased the computational time by eighty percent [37]. Sinha *et al.* [38] applied improved fast evolutionary technique for the hydrothermal problem. The final reservoir level constraint was satisfied by calculating the hydro discharge of the dependent time interval randomly. This method does not ensure whether the value of the water discharge might not be in limits [39]. Lakshminarasimman *et al.* [39] proposed the use the differential evolution to solve STHTS problem with cascaded reservoirs. The dependent hydro discharge is used to satisfy the constraint of the initial and final reservoir volume but lacks the handling of the power load balance constraint [40]. Mandal *et al.* [41] applied particle swarm optimization and Basu [42] applied artificial bee colony to solve STHTS

problem. These optimization techniques suffer premature convergence and require the memory to store the previous best value [43].

In 2009, Rashedi *et al.* [17] introduced *gravitational search algorithm* (GSA) based on the Newton's law of gravity in which the motion of all the agents is towards the heavier agent because of the gravitational force from the other agents. Advantage of the GSA over other global search technique is that it is inspired by the physical phenomenon of the gravitational force between the agents and doesn't require memory to store the previous value as it requires only the current position of the agent to update the velocity [17]. Many researchers has used GSA on large number of problems such as multi-objective optimal reactive power dispatch problem [44], reactive power planning [45], designing of power system stabilizer [46], optimal energy management of microgrid [47], unit commitment [48]. However GSA suffers problem of premature convergence or may trap into the local optimum in the final stages of the iteration [18]. Khajehzadeh *et al.* [18] used modified GSA for the slope stability analysis in which time varying maximum velocity to help global exploration and strengthens the exploitation. The drawbacks of global search method is that they do not always provide the global optimum solution, requires a large computational time for the large scale problems and trapping in the local optimum in the later stages [49].

In order to overcome the drawbacks of the global search techniques, hybrid techniques were introduced. Hybrid technique is a combination of the global search technique and local search technique. It is divided into two steps. First step employees global search technique to explore and obtain near to global optimum solution in the feasible space. Second stage employees local search technique to exploit and obtain final solution [50]. Harman and Phil [51] proposed the combination of the global search and local search technique for solving complex problem. Basu [50] applied the hybridization of the bee colony optimization and SQP for solving economic dispatch. Sivasubramani *et al.* [52] applied the hybrid DE-SQP technique to solve STHTS problem and showed that the results obtained using the hybrid technique are better quality solutions.

In this dissertation work, a new hybridization technique is used, which is the integration of modified GSA and SQP used to solve the short term multi chain hydrothermal scheduling. modified GSA is used as the global search technique to explore the feasible space and obtain

a near to global optimum solution. SQP is used as the local search technique which is used to exploit and obtain the final solution.

1.3 OBJECTIVE OF WORK

The objective of the dissertation is to propose a new hybrid technique for solving STHTS problem. The proposed hybrid technique is the combination of the global search technique MGSA and local search technique SQP. In proposed hybrid MGSA-SQP algorithm, MGSA helps in exploration of the search space and gives a direction towards global optimal region and SQP helps in the exploitation of the search space and find the final optimal solution.

1.4 ORGANIZATION OF THE DISSERTATION

The dissertation titled as -“Hybridization of modified gravitational search algorithm and SQP for multi chain hydrothermal system” has been elaborated in five chapters. **Chapter 1** provides the detailed overview of the dissertation, brief literature survey related to the problem and objective of the dissertation. **Chapter 2** introduces various configurations in hydrothermal system, types of the hydrothermal scheduling and problem formulation of STHTS problem. The proposed modified gravitational search algorithm and SQP algorithm and its implementation on STHTS problem has been discussed in **Chapter 3**. **Chapter 4** presents the results and discussion for two test systems. Test I comprises of one thermal and four hydro units whereas test system II consists of three thermal and four hydro units. The results for test system obtained by using proposed algorithm is compared with other established techniques in the literature. The conclusion of the dissertation work and scope for the future work has been mentioned in **Chapter 5** followed by the publications, references and appendix.

SHORT TERM HYDROTHERMAL SCHEDULING

2.1 INTRODUCTION

In a modern power system consisting of a large number of the hydro and thermal generating units, efficient scheduling of thermal and hydro units are required in order to minimize the total generating cost of the thermal unit and to meet the load demand while maintaining stability of the system by operating within the boundaries. The study of the hydrothermal system is much more complex than the operation of independent thermal system as hydrothermal system is coupled both electrically as well as mechanically. Due to the scarce of the hydel resources and high cost of the thermal generation, the integration of the hydro and thermal units is done for the optimum utilization of all the energy resources in most economical way [1]. Thermal units have high operating cost, low capital cost and slow speed of response to the change in load. Hence thermal units are preferred as the base load plants. Hydro units have low operating cost, high capital cost and quick speed of response to meet the change in demand. Hence hydro units are considered as the peak load plants. As there is no generation cost associated with the hydro units, hydro units are utilized at the maximum level in order to minimize the generation cost of the thermal plant. The hydro plants can be classified into different types on the basis of types, amount of water available, available water head, and nature of the load and location of the hydro units. On the basis of the location of the hydro plants on the stream [53], hydro plants can be classified as

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

a) Hydro plants on the different stream

In hydro plants on different stream [1], hydro plants are situated on the different streams and are independent of each other.

b) Hydro plant on same stream

In hydro plants on the same stream [1], hydro plants are situated on the same stream, the downstream plant depends upon the immediate upstream plant.

c) Multi chain hydro plants

In multi chain hydro plants [54], hydro plants are situated on the same stream as well as on the different stream. The volume of the reservoir during a sub-interval depends upon the inflow rate and the delay between the cascaded reservoirs.

2.2 CLASSIFICATION OF THE HYDROTHERMAL SCHEDULING

Depending on the different time scopes and system representation, hydrothermal scheduling problem is divided into three types:

1. Long term hydrothermal scheduling
2. Mid-term hydrothermal scheduling
3. Short term hydrothermal scheduling

2.2.1 LONG TERM HYDROTHERMAL SCHEDULING

Long term hydrothermal scheduling [55] has a scheduling period ranging from several weeks to several years. It considers the dynamic of the head variation using water flow equation and involves meteorological and statistical analysis. Long term hydrothermal problem is a complex problem because of the size, long scheduling period and randomness of the water inflow over a long span. The benefits of the LTHTS are minimization of the cost of generation and helps in meeting the agricultural and irrigational requirement.

2.2.2 MID TERM HYDROTHERMAL SCHEDULING

Mid-term hydrothermal scheduling [55] has a scheduling period ranging from few months to a year. In mid-term hydrothermal scheduling [56], scheduling period is divided into two parts having different time spans. Modeling of the generating units and scheduling is done differently for the first week and differently for the remaining weeks. For the starting week,

sequential load model is utilized whereas for the remaining weeks load duration curve is utilized.

2.2.3 SHORT TERM HYDROTHERMAL SCHEDULING

Short term hydrothermal scheduling [55] has a scheduling period ranging from one day to one week. As the scheduling period is small, head can be assumed fairly constant. In STHTS, load demand, unit availabilities and water inflow are assumed to known. Short term hydrothermal problem has hour by hour scheduling of the generating units in order to minimize the total operating cost of the hydrothermal system.

The STHTS based on the characteristics of the hydrothermal system can be divided into three groups:

- a) Fixed head hydrothermal scheduling
- b) Variable head hydrothermal scheduling

a) Fixed head hydrothermal Scheduling

In fixed head hydrothermal scheduling [53], head of the reservoir is considered as fixed when the capacity of the reservoir in a hydro plant is very large.

b) Variable head hydrothermal Scheduling

In variable head hydrothermal scheduling [57], head of the reservoir is considered as the variable when the capacity of the reservoir in a hydro plant is small. In multi-chain hydrothermal system , the volume of the reservoir is variable for each sub-interval which depends upon the inflow and upstream reservoir.

2.3 PROBLEM FORMULATION OF THE SHORT TERM HYDRO THERMAL SYSTEM

The principal objective of STHTS is the minimization of the operating cost of the thermal unit and to meet the load while satisfying all operational constraints [58]. Total operating cost of the thermal unit considering the valve point loading effect [10] is given by:

$$F_T = \sum_{k=1}^T \sum_{i=1}^N a_i P_{gik}^2 + b_i P_{gik} + c_i + |e_i \times \sin(f_i \times (P_{gik}^{min} - P_{gik}))| \quad (2.1)$$

For hydro units, volume of the reservoir depends upon the level of the reservoir in the previous interval and the delay in the transport of water from the upstream reservoir to the downstream reservoir. Reservoir volume [10] of the j^{th} reservoir in multi chain hydrothermal system is given by:

$$V_{hj}^{k+1} = V_{hjk} + I_{hjk} - q_{hjk} - S_{hjk} + \sum_{l=1}^{R_{uj}} (q_{hl,k-d_{ij}} + S_{hl,k-d_{ij}}), (j \in M, k \in T) \quad (2.2)$$

Hydro power generated by the hydro unit is calculated by using water discharge rate and reservoir volume which in turn is the function of the net hydraulic head. Hydrothermal power of the j^{th} hydro unit in multi chain hydrothermal system [10] is given by:

$$P_{hjk} = C_{1j} V_{hjk}^2 + C_{2j} q_{hjk}^2 + C_{3j} V_{hjk} q_{hjk} + C_{4j} q_{hjk} + C_{5j} q_{hjk} + C_{6j} \quad (j \in M, k \in T) \quad (2.3)$$

The short term multi chain hydrothermal scheduling problem is solved within bound on decision variables and has to satisfy both equality constraints and inequality constraints.

1) Bound on decision variables

For short term multi chain hydrothermal scheduling, decision variables are water discharge rate and thermal power. The water discharge rate and thermal power should be kept within the limit after each iteration.

a) The limit on the water discharge rate [10] is represented as:

$$q_{hj}^{min} \leq q_{hjk} \leq q_{hj}^{max} \quad (j \in M, k \in T) \quad (2.4)$$

b) The limits related to the thermal power of each thermal unit [10] can be represented as:

$$P_{gi}^{min} \leq P_{gik} \leq P_{gi}^{max} \quad (i \in N, k \in T) \quad (2.5)$$

2) Equality constraints

In STHTS, sum of the thermal power and hydro power has to meet the load demand. The initial and final volume of the reservoir should be equal to the specified limit of the reservoir for a given hydro model.

a) The equality constraint related to the load demand [10] can be represented as :

$$\sum_{i=1}^N P_{gik} + \sum_{j=1}^M P_{hjk} = P_{Dk} + P_{Lk} \quad (k \in T) \quad (2.6)$$

b) The equality constraint related to the storage volume of the reservoir [10] is represented as:

$$V_{hjk}^0 = V_{hj}^{begin} \quad (j \in M, k \in T) \quad (2.7)$$

$$V_{hjk}^T = V_{hj}^{end} \quad (j \in M, k \in T) \quad (2.8)$$

3) Inequality constraint

Inequality constraints for STHTS problem are related to hydro power and volume of the reservoir. The output power generated by the hydro unit and reservoir volume should lie between its minimum and maximum limit.

a) The inequality constraint related to the hydro power of each hydro unit [10] can be represented as:

$$P_{hj}^{min} \leq P_{hjk} \leq P_{hj}^{max} \quad (j \in M, k \in T) \quad (2.9)$$

b) The inequality constraint related to the reservoir storage volume [10] is represented as:

$$V_{hj}^{min} \leq V_{hjk} \leq V_{hj}^{max} \quad (j \in M, k \in T) \quad (2.10)$$

IMPLEMENTATION OF HYBRID MGSA-SQP FOR STHS

The objective of STHS is to calculate the optimal amount of the water release for hydro units and generation output of the thermal unit in order to minimize the total operating cost of the thermal unit while satisfying all the equality and inequality constraints [59]. In past, several global search techniques such as PSO [60], genetic algorithm [61], evolutionary programming [62] etc. has been used for solving the STHS problem. Global search techniques use probabilistic set of rules which allows them to have large possibility to explore the search space [63]. The drawback related to the global search technique is premature convergence and slow convergence rate. Global search algorithm does not always provide the global best solution but provides a fast and near global optimum solution [59]. During the later stages of the iteration, global search algorithm takes more computational time for obtaining the small improvements in results [63]. In order to overcome the limitations of the global search techniques, hybrid optimization techniques are introduced by the researchers. In hybrid optimization techniques, exploration capability of the global search algorithm helps in finding near optimal solution and exploitation ability of the local search technique improves the convergence to find global best solution [64]. Basu [50] applied hybrid BCO-SQP for dynamic economic dispatch problem. Sivasubramani [52] *et al.* applied hybrid DE-SQP on the STHS problem in which DE is used as the global search technique and SQP is used as the local search technique.

In this desertion, hybrid modified GSA and SQP has been proposed for solving short term multi chain hydrothermal scheduling problem in which MGSA algorithm has been used as global search technique for the exploration of the search space to get near to a global solution and SQP has been used as local search technique for the exploitation of the search space to get global best solution.

3.1 GRAVITATIONAL SEARCH ALGORITHM

Gravitational search algorithm (GSA) is a population based global search technique introduced by Rashedi *et al.* in 2009 [17]. GSA is based on the Newton's law of gravity according to which all particles attracts at each other with the help of gravitational force. The gravitational force between the agents is directly proportional to the product of their masses and inversely proportional to the square of the distance between them represented by the equation (3.1).

$$F = G \left(\frac{M_1 \times M_2}{R^2} \right) \quad (3.1)$$

where, F represents gravitational force, G is gravitational constant, M_1 and M_2 are the masses of the objects and R is the distance between the objects.

In GSA, all the agents are the considered as the objects and the performance of each agent is based on their masses. Each agent is associated with four parameters: position, inertial mass, active mass and gravitational mass [17]. The masses related to each agent are defined as:

- (a) **Active gravitational mass (M_a):** Active gravitational mass [17] represents the magnitude of the gravitational field related to each object. An object with smaller magnitude of active gravitational mass has a weaker gravitational field than the agent with a bigger gravitational mass.
- (b) **Passive gravitational mass (M_p):** Passive gravitational mass [17] represents the magnitude with which the gravitational field exerts force on the object. For a given gravitational field, an object with a larger passive gravitational mass experiences a large force than the object with the smaller passive gravitational mass.
- (c) **Inertial mass (M_i):** Inertial mass [17] is the measure of the resistance offered by the object to change its motion when a force is applied. An object with the larger inertial mass changes its motion gradually than an object with smaller inertial mass.

The position of the object represents the decision variable of the optimization problem, gravitational and inertial masses help the agents for navigation in the search space and reaching the global optimum solution. All agents are attracted towards each other with the

help of gravitational force and global movement is towards the object with heavier mass. The agent with the heavier mass moves slowly than the agent with lighter mass. The slow movement of the heavier mass guarantees the exploitation [18].

The steps of the conventional GSA [17] are given as follows:

Step 1: Initializing the position and velocity of each agent

Position and velocity of the N number of agents are initialized randomly.

$$X_i = (x_i^1, x_i^2, \dots, x_i^d, \dots, x_i^n), (i \in N) \quad (3.2)$$

$$V_i = (V_i^1, V_i^2, \dots, V_i^d, \dots, V_i^n), (i \in N) \quad (3.3)$$

where, x_i^d and V_i^d represents the position and velocity of the i^{th} agent in the d^{th} dimension.

Step 2: Computation of best and worst value of the objective function

For a minimization problem:

$$best(t) = \min fit_i(t) \quad (3.4)$$

$$worst(t) = \max fit_i(t) \quad (3.5)$$

fit_i represents the objective function of the i^{th} agent at iteration t , $best(t)$ and $worst(t)$ represents the best and the worst value of the fitness at iteration t .

Step 3: Computation of Gravitational constant (G):

At iteration t , Gravitational constant G is computed as [17]:

$$G(t) = G_0 e^{(-\alpha t/t_{max})} \quad (3.6)$$

G_0 and α are initialized at the beginning. t_{max} is the maximum iteration.

Step 4: Computation of Inertial and Gravitational masses

At iteration t , Gravitational and Inertia masses for each agents are calculated as follows[17]:

$$M_{ai} = M_{pi} = M_{ii} = M_i, \quad (i \in N) \quad (3.7)$$

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \quad (3.8)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^N m_j(t)} \quad (3.9)$$

M_{ai} and M_{pi} are the active and passive gravitational masses respectively, while M_{ii} is the inertia mass of the i^{th} agent

Step 5: Calculation of total force on the agent

At iteration t, force acting on the i^{th} agents at the d^{th} dimension is computed as [17] :

$$F_i^d(t) = \sum_{j \in Kbest, j \neq i} rand_i F_{ij}^d(t) \quad (3.10)$$

where, $F_i^d(t)$ is the total magnitude the force acting on i^{th} agent at d^{th} dimension . $Kbest$ is the group of agents with bigger masses. The value of the $Kbest$ decreases linearly with time and it lasts with 2% of the total agents.

$F_{ij}^d(t)$ is computed as the following equation:

$$F_{ij}^d(t) = G(t) \times (M_{pi}(t) \times M_{aj}(t) / R_{ij}(t) + \varepsilon) \times (x_j^d(t) - x_i^d(t)) \quad (3.11)$$

$F_{ij}^d(t)$ is the force applied on the agent i from the agent j at d^{th} dimension at iteration t. $R_{ij}^d(t)$ is the euclidian distance between i^{th} and j^{th} agent at t^{th} iteration. $G(t)$ is the magnitude of gravitational constant at iteration t, while ε is small algorithm constant.

Step 6: Calculation of the acceleration

Acceleration on the i^{th} agents at the d^{th} dimension at iteration t is computed as [17]:

$$a_i^d(t) = F_i^d(t) / M_{ii}(t) \quad (3.12)$$

Step 7 : Updating the position and velocity of agents:

The new value of position and velocity of the agents at the end of each iteration are computed based on the following equations:

$$v_i^d(t+1) = rand \times v_i^d(t) + a_i^d(t) \quad (3.13)$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad (3.14)$$

Step 8 : Termination Criteria

Step 2 to Step 7 repeated till maximum iteration is achieved.

3.2 MODIFIED GRAVITATIONAL SEARCH ALGORITHM (MGSA)

In GSA, the direction and motion of all the agents in the search space is decided by the magnitude of the velocity. Conventional GSA uses constant maximum velocity which defines the maximum change in the position of the agent from one position to next position in the search space [17]. If the magnitude of maximum velocity is too large, movement of the agent will be beyond the global best solution and if the magnitude of the constant velocity is too small, movement of the agent will be restricted and optimal solution will not be reached [18]. During the initial stages, in order to facilitate the global search in the search space (exploration) magnitude of the maximum velocity should be large and during the later stages ,in order to facilitate the local search in the search space (exploitation) magnitude of the maximum velocity should be small. Hence a time varying maximum velocity is used which facilitates the global search during the early stages and with passage of time exponentially decreases the magnitude of the maximum velocity resulting in smaller search space facilitating the local search [18]. Time varying maximum velocity is gives as:

$$V^{max} = \left[1 - \left(\frac{itr}{it} \right)^h \right] \times V^{max0} \quad (3.15)$$

where, h is a small positive constant and V^{max0} is the initial maximum velocity limit of the agent. The MGSA algorithm is represented as flowchart shown in figure 3.1.

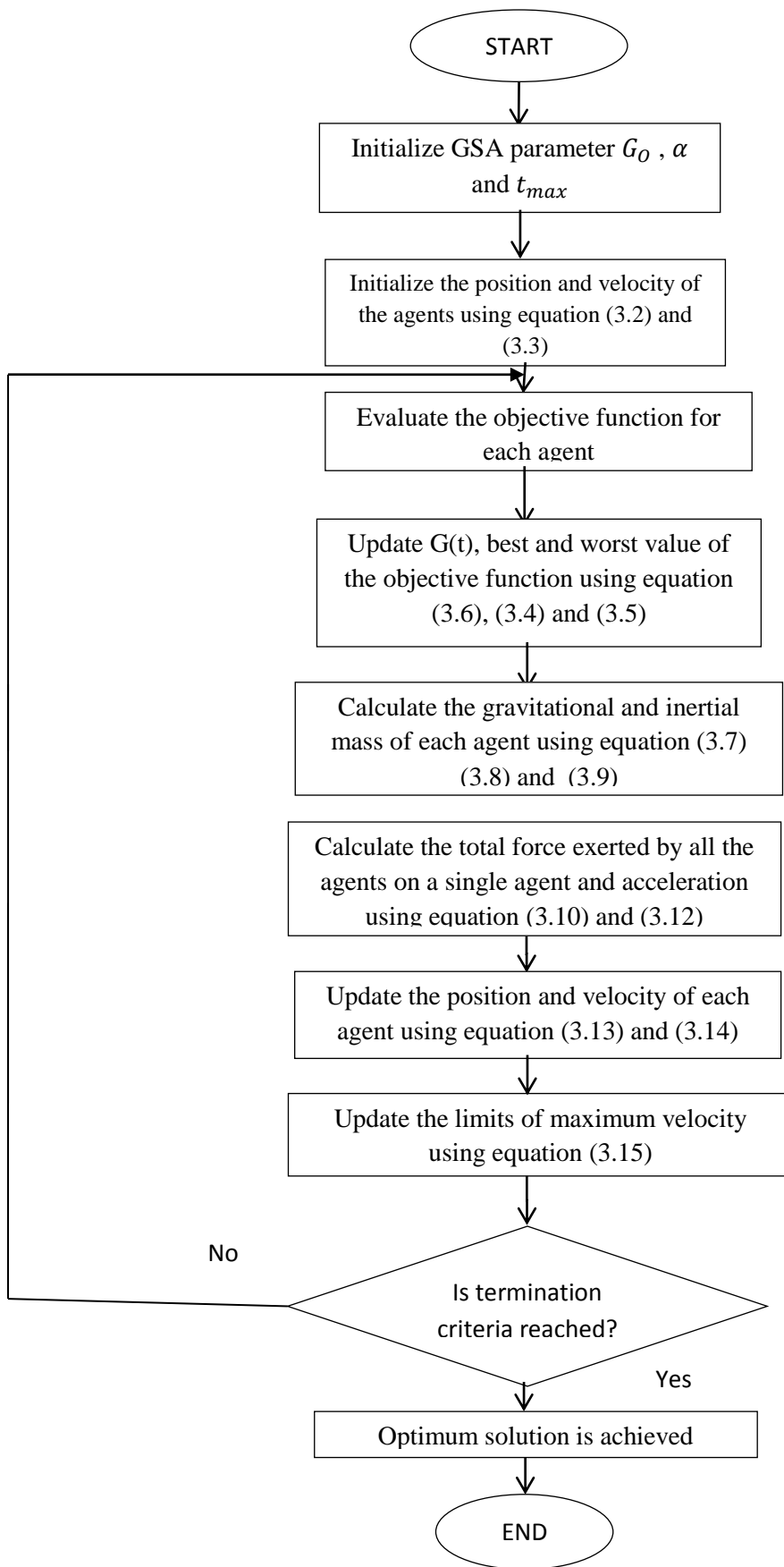


Figure 3.1 : Flowchart of Modified GSA

3.3 SEQUENTIAL QUADRATIC PROGRAMMING

Sequential Quadratic Programming is a non-linear programming method used for solving constraint problems [65]. SQP is considered as the generalization of the Newton's method for optimization of the constrained problems, which is used for solving the quadratic problem having quadratic objective function and linear constraints [66]. At each iteration, an approximation is considered for the updating the hessian matrix of the lagrangian functions using BFGS quasi-newton updation method. The results obtained from the approximation made for updating hessian matrix is used for generating a quadratic program (QP) sub-problem whose solution gives the direction for the line search method. As objective function is of non-convex nature, SQP confirms a local minimum [67].

At each iteration, QP is solved for obtaining the search direction. QP sub-problem can be defined as follows [64].

Minimize the following

$$\frac{1}{2}(d^t)^T B^t d^t + \nabla f(x^t)^T d^t \quad (3.16)$$

Subjected to

$$g_i(x^t) + [\nabla g(x^t)]^T d^t = 0 \quad (i \in m_c) \quad (3.17)$$

$$g_i(x^t) + [\nabla g(x^t)]^T d^t \leq 0 \quad (i = m_c+1 \dots m) \quad (3.18)$$

where, B^t is the hessian matrix, $g(x)$ is constraints, $f(x)$ is objective function, m_c is number of equality constraints, m is number of constraints, d^t is search direction at t^{th} iteration.

The STHTS is non-convex and non-differentiable problem. Hence the approximate differentiation method is employed in order to calculate the gradient of the STHTS problem [64]. At the start of the iteration, hessian matrix B^0 is initialized as the unity matrix which matrix helps in calculating the search direction d^t .

In summary, SQP can be divided into three steps [64]:

(1) Update the hessian matrix

At each iteration t , hessian matrix is calculated using BFGS quasi newton method as represented in the given equation [64]:

$$B^{t+1} = B^t + \frac{q^t(q^t)^T}{(q^t)^T(x^{t+1}-x^t)} - \frac{(B^t(x^{t+1}-x^t))(B^t(x^{t+1}-x^t))^T}{(x^{t+1}-x^t)^T B^t (x^{t+1}-x^t)} \quad (3.19)$$

(2) Quadratic programming problem

At iteration t , direction of the search d^t is calculated by solving the QP sub problem described in equation (3.16)

(3) Line search calculation

The search direction d^t obtained by solving QP sub problem is used to update the decision variable

$$x^{t+1} = x^t + \alpha d^t \quad (3.20)$$

where, α represents the step length.

3.4 HYBRID MGSA - SQP ALGORITHM FOR STHS PROBLEM

In short term multi chain hydrothermal scheduling, there are two decision variables and two types of constraints namely, equality constraint and inequality constraint. Decision variables correspond to the position of the agents which is initially generated randomly within the limits.

(i) Decision Variable: Decision variable related to the STHS problem are water discharge and thermal power [58].

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

$$q_{hjk} = q_{hj}^{min} + rand \times (q_{hj}^{max} - q_{hj}^{min}) \quad (j \in M, k \in T) \quad (3.21)$$

Thermal power generated randomly within maximum and minimum limits is represented as follows:

$$P_{gik} = P_{gi}^{min} + rand \times (P_{gi}^{max} - P_{gi}^{min}) \quad (i \in N, k \in T) \quad (3.22)$$

Equality and Inequality constraint handling is done by the penalty method in which a high exterior penalty is multiplied with the error generated from the violation of the equality and inequality constraints. The summation of the total fuel cost of the thermal units and sum of square of all the errors forms the objective function of the problem.

(ii) Equality constraint: In short term multi-chain hydrothermal scheduling, equality constraints are related to the demand mentioned in equation (2.6) and the final storage volume of the reservoir mentioned in equation (2.8).

Error generated from the mismatch of load demand is represented as follows:

$$e_{peq} = (P_{Dk} + P_{Lk} - \sum_{i=1}^N P_{gik} - \sum_{j=1}^M P_{hjk}) \quad (k \in T) \quad (3.23)$$

where, e_{peq} represents the error generated from the mismatch of demand .

Error generated from the mismatch of the final storage volume is represented as:

$$e_{Veq} = (V_{hj}^{end} - V_{hjk}^T) \quad (3.24)$$

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

(iii) Inequality constraint: In short term multi-chain hydrothermal scheduling, inequality constraint is related to the reservoir storage volume inequality mentioned in equation (2.10) and hydro generation inequality mentioned in equation (2.9).

Error generated from the violation of reservoir storage volume inequality is represented as follows:

$$e_{Vinq} = \begin{cases} (V_{hj}^{max} - V_{hjk}) , & V_{hjk} > V_{hj}^{max} \\ (V_{hjk} - V_{hj}^{min}) , & V_{hjk} < V_{hj}^{min} \end{cases} \quad (3.25)$$

Error generated from the violation of hydro generation inequality is represented as follows:

$$e_{P_{inq}} = \begin{cases} (P_{hj}^{max} - P_{hjk}) , & P_{hjk} > P_{hj}^{max} \\ (P_{hjk} - P_{hj}^{min}) , & P_{hjk} < P_{hj}^{min} \end{cases} \quad (3.26)$$

Overall objective function formed is by adding all the errors with their penalties i.e. r and fuel cost is calculated as:

$$\text{Objective function} = F_T + r \times (e_{P_{eq}}^2 + e_{V_{eq}}^2 + e_{V_{inq}}^2 + e_{P_{inq}}^2) \quad (3.27)$$

The steps involved for solving STHTS problem using hybrid MGSA-SQP are represented as follows:

- Step 1: Read all the parameters related to proposed algorithm i.e. maximum iteration, population size, gravitational constant and other algorithm constant.
- Step 2: Initializing the position and velocity of the agent

For STSH problem, position and velocity of the agent is initialized using the equation (3.2) and (3.3) respectively.

- Step 3: Computation of Storage reservoir volume

The storage reservoir volume is calculated from the equation (2.2). If the value of storage reservoir volume violates the limits, errors generated are calculated using equation (3.24) and (3.5)

- Step 4: Computation Hydro power generation

The hydro power is generated using the equation (2.3). If the value of the hydro power violates the limit , error generated is calculated using the equation (3.26).

Step 5: Calculate the total active power

Total active power is the sum of the thermal power and hydro power. If total active power doesn't meet the load demand, error is generated is calculated using equation (3.23).

Step 6: Evaluate the objective function

Objective function is calculated using equation (3.27).

Step 7: Computation of best and worst value of the objective function.

The best and the worst value of the objective function is calculated using equation (3.4) and (3.5) respectively.

Step 8: Computation of the gravitational constant

Gravitational constant decreases exponentially to control the search direction and is computed using equation (3.6)

Step 9: Computation of mass of the agents

Gravitational and inertial is calculated with the help of objective function using equation (3.7), (3.8) and (3.9)

Step 10: Computation of total force

The magnitude of the forces acting on an agent applied by other agents calculated using equation (3.11). Total force on the agent is calculated by equation (3.10).

Acceleration acting on the agent is calculated by equation (3.12)

Step 11: Update the velocity of the agent

The velocity of the agent is updated using equation (3.13)

Step 12: Update the limit of maximum velocity

The limit of maximum velocity is time varying quantity which decreases with time and is updated equation (3.15)

Step 13: Update the position of the agent

At each iteration, the velocity of each agent is calculated using equation (3.14)

Step 14: Step (3) to Step (13) are repeated till maximum iteration for MGSA is reached.

Step 15: The best solution obtained from MGSA algorithm acts as the input for SQP.

Step 16: Read all the parameters related to SQP i.e. maximum iteration, initialize hessian matrix, and step size.

Step 17: Obtain the search direction for SQP algorithm

Obtain the search direction by computing QP sub-problem using equation (3.16).

Step 18: Update the position of the agent for SQP algorithm

The position of the agent is updated using equation (3.20).

Step 19: Update the hessian matrix for SQP algorithm

The hessian matrix is updated using equation (3.19)

Step 20: Step (17) to Step (19) are repeated till maximum iteration for SQP is reached.

Step 21: Global best optimal solution is obtained.

The proposed hybrid MGSA-SQP algorithm has been implemented on the two hydrothermal test systems. These test system consists of multi-chain cascade hydro units having variable inflow rate and reservoir water transport delay between the cascaded hydro plants. Input data related to both test systems has been mentioned in Appendix A and B.

4.1 TEST SYSTEM I

4.1.1 DESCRIPTION OF HYDROTHERMAL SYSTEM

The test system I consists of multi-chain cascade of four hydro units shown in figure 4.1 and equivalent thermal plants neglecting the effect of valve point loading and power transmission losses. The thermal plant fuel cost coefficient, water inflow rate, water discharge limit, hydro and thermal generation limits, hydro power generation coefficient, reservoir volume storage limit and load demand taken from [36] are listed in appendix A. The time interval considered is 1 day with 24 sub-intervals each of 1 hour.

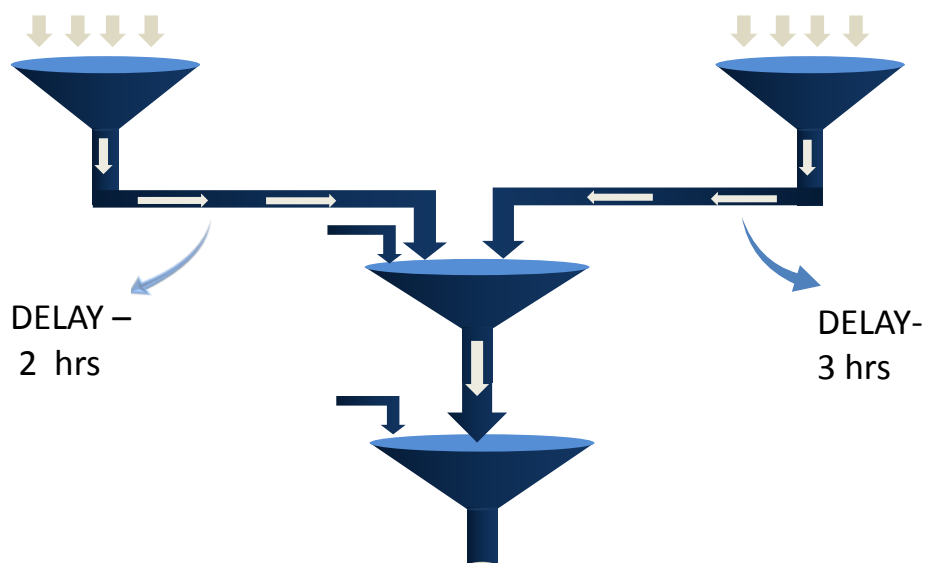


Figure 4.1: Multi-chain cascade of four hydro plant

4.1.2 PARAMETER SETTING

The proposed hybrid algorithm used for solving STHTS problem has been implemented using FORTRAN 90 compiler. The parameters related to proposed hybrid MGSA-SQP algorithm which has to be predetermined are population size N , gravitational constant G_0 and a constant α and step size. Based on the number of trials with different values of the parameter related to proposed MGSA-SQP algorithm is given in the table 4.1.

Table 4.1 Parameter setting for MGSA-SQP algorithm for test system I

S.no.	Parameter	Value
1.	Population Size (N)	60
2.	Gravitational Constant (G_0)	200
3.	Constant (α)	10
4.	Step size for SQP	.001

4.1.3 SIMULATION RESULTS FOR MGSA-SQP ALGORITHM

The proposed hybrid MGSA-SQP algorithm has been employed for solving STHTS problem using FORTRAN 90 compiler. Using the values of the parameters given in table 4.1, the hydrothermal generation obtained to meet the load demand using MGSA and hybrid MGSA-SQP algorithm are given in table 4.2 and 4.3 respectively. The trajectories of the optimal hourly discharge for MGSA algorithm and hybrid MGSA-SQP algorithm are shown in the figure 4.2 and 4.3 respectively. Similarly, reservoir storage volume for MGSA and hybrid MGSA-SQP are shown in figure 4.4 and 4.5 respectively. The cost obtained using MGSA algorithm is 921562.40 \$. The optimal cost obtained using hybrid MGSA-SQP is compared with MGSA and other well-established global search techniques given in table 4.4 shows that hybrid MGSA-SQP algorithm provides better results than other global search techniques.

Table 4.2: optimal hydrothermal power generation using MGSA algorithm: test system I

Hours	Hydro Power (MW)				Thermal Power (MW)
	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{g1}
1	53.445	50.164	36.949	135.659	1093.653
2	80.836	54.159	19.825	134.300	1100.408
3	63.719	57.810	13.130	129.607	1095.595
4	80.516	53.860	30.934	144.085	980.6842
5	80.438	64.794	35.952	172.961	936.3459
6	70.748	67.543	42.682	173.668	1055.695
7	73.586	66.462	37.306	177.859	1294.704
8	76.274	62.060	31.954	252.781	1576.536
9	84.991	60.207	27.720	254.992	1811.952
10	69.041	63.659	41.851	240.312	1904.447
11	87.772	62.379	39.493	255.626	1784.804
12	89.000	67.206	32.212	246.370	1874.600
13	74.930	68.779	42.934	288.138	1754.688
14	95.096	75.716	43.540	270.182	1715.530
15	95.345	60.735	49.184	296.577	1627.730
16	66.569	77.527	44.031	292.750	1588.800
17	95.852	66.709	51.575	283.828	1632.317
18	86.494	74.749	50.476	267.523	1672.508
19	83.500	69.757	54.922	285.620	1746.397
20	69.657	68.125	55.539	274.265	1811.662
21	83.398	78.837	52.865	294.772	1729.964
22	78.432	75.932	51.492	272.534	1641.357
23	67.445	68.073	55.506	291.832	1367.301
24	65.412	73.987	58.935	284.889	1106.428

Table 4.3: optimal hydrothermal power generation using MGSA-SQP algorithm : test system I

Hours	Hydro Power (MW)				Thermal Power (MW)
	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{g1}
1	80.081	68.059	32.963	131.880	1065.393
2	76.798	62.748	0	141.577	1113.573
3	65.838	48.206	31.417	158.098	1064.831
4	53.159	49.972	0	169.109	1026.486
5	70.559	51.666	32.718	152.666	967.9481
6	68.532	63.437	38.994	173.790	1049.391
7	72.109	72.292	45.057	218.303	1236.570
8	81.222	58.216	41.879	196.999	1607.259
9	92.297	62.065	29.202	246.675	1807.489

Table 4.3: optimal hydrothermal power generation using MGSA-SQP algorithm : test system I (cont.)

10	74.735	60.528	32.869	259.241	1889.362
11	77.116	56.202	38.936	236.444	1816.773
12	82.764	66.901	39.516	261.060	1857.677
13	70.194	67.683	45.417	279.513	1761.307
14	87.271	58.269	40.998	290.818	1720.079
15	86.061	74.316	44.342	296.554	1629.827
16	81.806	74.089	46.278	273.328	1592.308
17	87.317	53.039	34.891	260.304	1694.809
18	85.615	53.568	49.513	280.007	1667.983
19	89.531	77.237	49.538	277.035	1747.475
20	79.212	84.540	52.916	298.757	1769.658
21	86.042	83.984	53.691	302.471	1715.378
22	61.773	76.309	52.737	284.136	1649.652
23	64.349	73.180	55.727	298.012	1363.224
24	94.410	69.263	57.132	292.743	1086.346

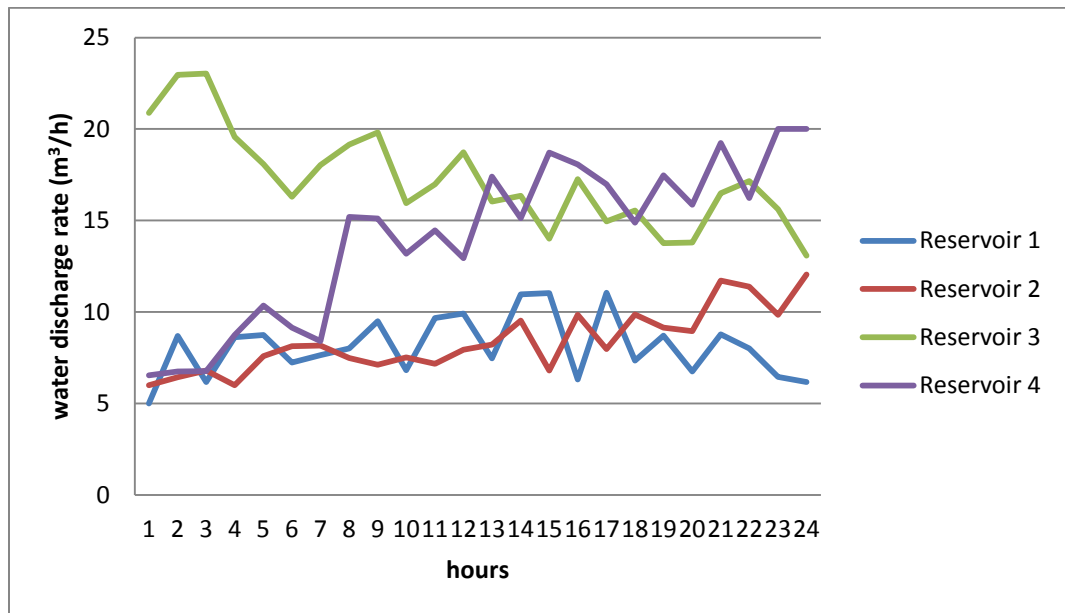


Figure 4.2 Water discharge rates for test system I with MGSA algorithm

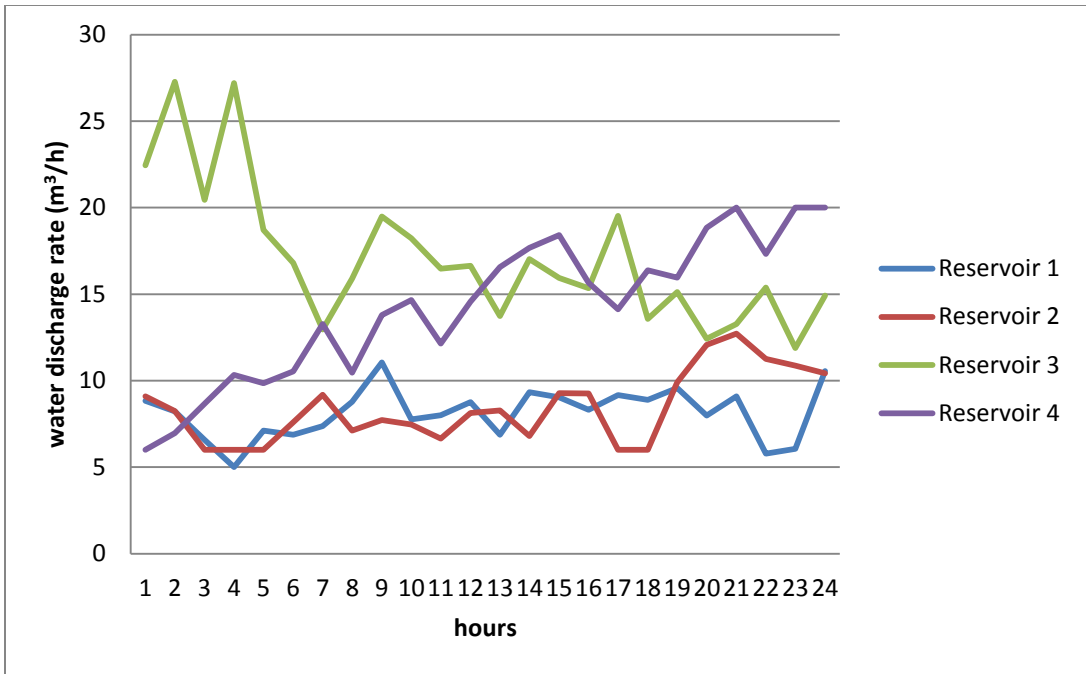


Figure 4.3 Water discharge rates for test system I using MGSA-SQP algorithm

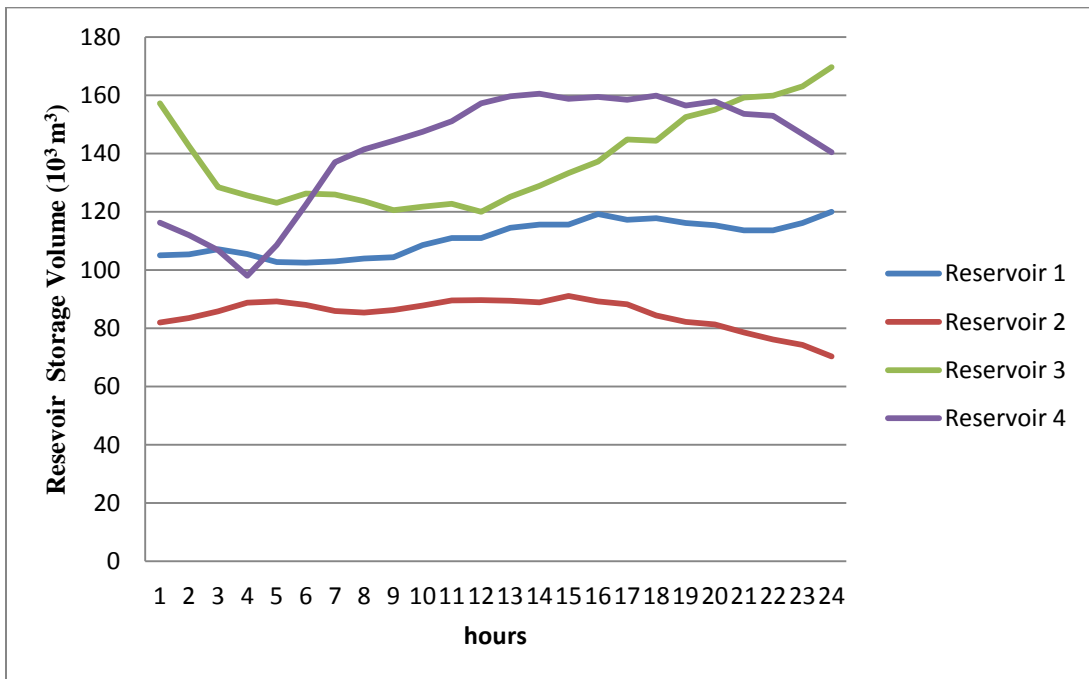


Figure 4.4 Reservoir storage volumes for test system I using MGSA algorithm

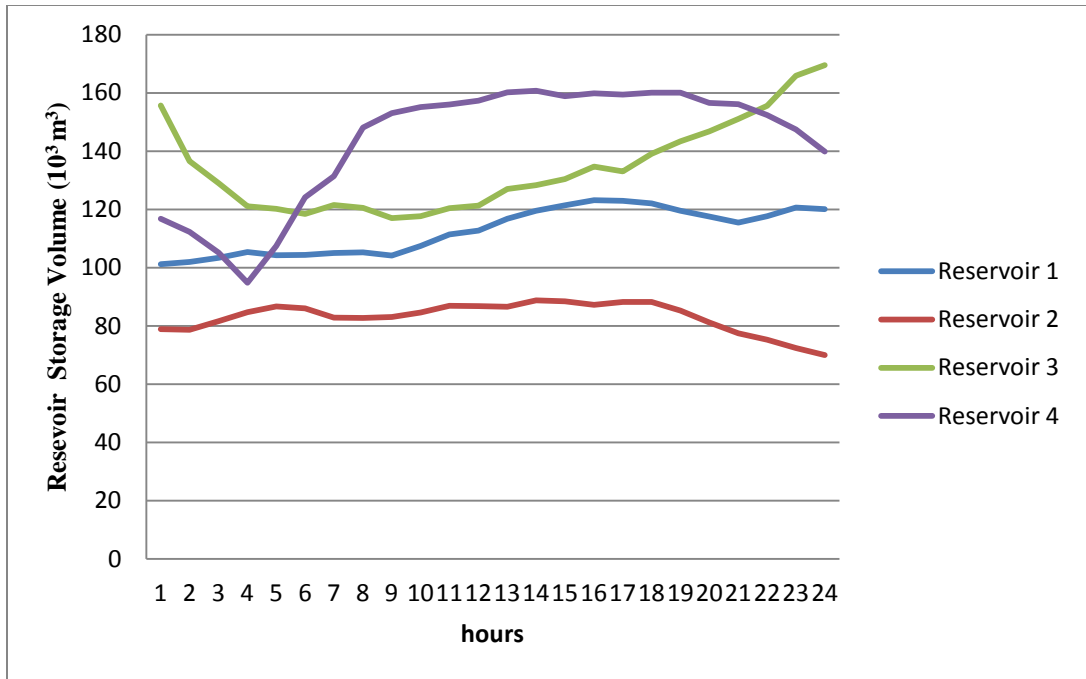


Figure 4.5: Reservoir storage volumes for test system I using MGSA-SQP algorithm

Table 4.4: Cost comparison for test system I

Method	Total Fuel cost (\$)
TLBO [68]	9,22556.44
IPSO[69]	9,22553.49
MIDE[39]	9,22556.44
GA[36]	9,26707.00
MGSA	9,21562.40
MGSA-SQP	9,21403.45

4.2 TEST SYSTEM II

4.2.1 DESCRIPTION OF HYDROTHERMAL SYSTEM

The test system II consists of multi-chain cascade of four hydro units as shown in figure 4.1 and three thermal units considering the effect of valve point loading and neglecting power transmission losses. The maximum and minimum value of the thermal and hydro power ,

thermal fuel coefficients , hydro power coefficients , water inflow rate , water discharge rate , reservoir storage volume and load demand taken from [58] are listed in of the appendix B.

4.2.2 PARAMETER SETTING

In order to obtain a global best solution, a number of trails are made with different values of the parameters related to the algorithm. The values of the parameters related to MGSA-SQP for the Test system II are given in table 4.5.

Table 4.5: Parameter setting for MGSA-SQP algorithm for test system II

S.no.	Parameter	Value
1.	Population Size (N)	80
2.	Gravitational Constant (G_0)	200
3.	Constant (α)	12
4.	Step size for SQP	.001

4.2.3 SIMULATION RESULTS FOR MGSA-SQP ALGORITHM

For solving STHTS problem, proposed MGSA-SQP algorithm has been implemented in FORTRAN 90 compiler. Using the value of the parameter given in table 4.5, the optimal hydrothermal generation calculated using MGSA and proposed hybrid MGSA-SQP are given in table 4.6 and 4.7 respectively. The optimal hourly discharges obtained using MGSA and hybrid MGSA-SQP are shown in figure 4.6 and 4.7 respectively. The reservoir storage volume for MGSA and hybrid MGSA-SQP algorithm are shown in the figure 4.8 and 4.9 respectively. The total fuel cost obtained using MGSA algorithm for test system II is 42,305.38 \$. The optimal cost obtained using hybrid MGSA-SQP are compared with MGSA and other well-established global search techniques given in table 4.8 shows that the results obtained from hybrid MGSA-SQP algorithm is better results than other global search techniques.

Table 4.6: Optimal hydrothermal power generation using MGSA algorithm : test system II

Hours	Hydro Power (MW)				Thermal Power (MW)		
	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{g1}	P_{g2}	P_{g3}
1	81.132	61.584	0	140.415	164.965	252.029	50.000
2	88.955	51.630	0	134.280	143.624	40.000	321.561
3	78.334	51.772	0	134.632	85.174	148.789	201.211
4	62.273	57.319	0	141.496	117.924	119.909	151.091
5	81.111	57.873	39.768	179.215	46.1149	129.171	136.758
6	67.963	66.874	40.452	226.936	82.4527	89.458	225.795
7	64.258	61.366	41.424	266.773	102.983	196.480	216.759
8	52.823	53.106	44.398	292.348	122.211	237.297	207.775
9	77.714	54.153	45.112	258.282	144.613	249.998	260.139
10	79.812	67.272	31.956	264.257	103.365	258.109	275.364
11	99.911	74.736	45.169	255.608	102.275	250.641	271.661
12	86.333	69.218	27.572	254.829	175.000	238.564	298.376
13	54.047	67.763	42.128	229.871	148.634	300.000	267.446
14	76.377	68.031	46.827	255.146	107.302	228.947	247.351
15	75.273	72.517	44.811	234.159	130.988	260.205	192.021
16	86.023	80.960	50.691	303.813	100.934	225.502	212.243
17	87.609	75.156	43.524	268.102	121.504	211.928	242.165
18	81.365	67.436	48.552	278.193	175.000	254.044	215.430
19	76.608	71.580	47.641	277.191	121.263	228.455	247.406
20	74.259	75.948	54.681	273.260	59.555	300.000	212.162
21	68.443	76.107	0	297.242	113.591	160.700	193.997
22	86.641	66.530	52.598	293.466	128.925	40.000	191.769
23	74.098	66.577	54.297	290.511	99.630	40.000	224.825
24	62.048	68.853	56.089	284.092	101.111	177.750	50.000

Table 4.7: Optimal hydrothermal generation using hybrid MGSA-SQP algorithm: test system II

Hours	Hydro Power (MW)				Thermal Power (MW)		
	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{g1}	P_{g2}	P_{g3}
1	68.651	50.164	42.148	129.026	117.115	135.501	207.487
2	81.724	51.296	48.512	125.743	95.690	190.772	186.174
3	80.576	59.110	0.000	121.625	72.479	138.297	227.891
4	82.225	54.001	0.000	115.822	70.529	40.000	287.564
5	79.788	61.400	0.000	143.231	119.253	112.371	153.969
6	73.261	60.494	43.273	250.812	47.646	123.041	201.489
7	52.339	65.021	41.140	219.148	81.798	252.086	238.374
8	79.127	54.253	42.931	243.822	95.275	240.257	254.317
9	84.614	61.316	36.256	278.097	131.452	227.582	270.722

Table 4.7 : Optimal hydrothermal generation using hybrid MGSA-SQP algorithm :test system II (Cont.)

10	76.993	67.643	43.893	239.359	112.202	300.000	239.8515
11	81.973	56.838	33.244	252.714	151.125	207.349	316.868
12	89.241	65.093	29.580	271.670	163.168	230.059	301.3196
13	75.933	74.062	36.199	283.631	120.451	236.240	283.1673
14	76.278	69.283	35.584	269.486	150.234	201.708	227.4051
15	86.621	78.684	47.074	302.976	92.352	181.187	221.0354
16	91.515	77.017	41.352	282.222	111.352	213.268	243.3422
17	74.928	75.241	46.484	289.233	116.125	213.172	234.9737
18	84.238	80.632	50.957	287.022	91.463	231.495	294.2985
19	81.085	74.631	0	276.618	34.706	102.703	500
20	73.319	75.119	49.322	295.666	133.185	238.681	184.7428
21	54.660	78.212	51.933	290.866	175.000	107.603	151.7847
22	69.410	78.772	53.774	284.416	36.484	157.185	179.9346
23	73.758	78.270	54.869	295.515	49.742	94.902	202.9115
24	77.955	73.843	56.102	284.416	59.411	198.333	50

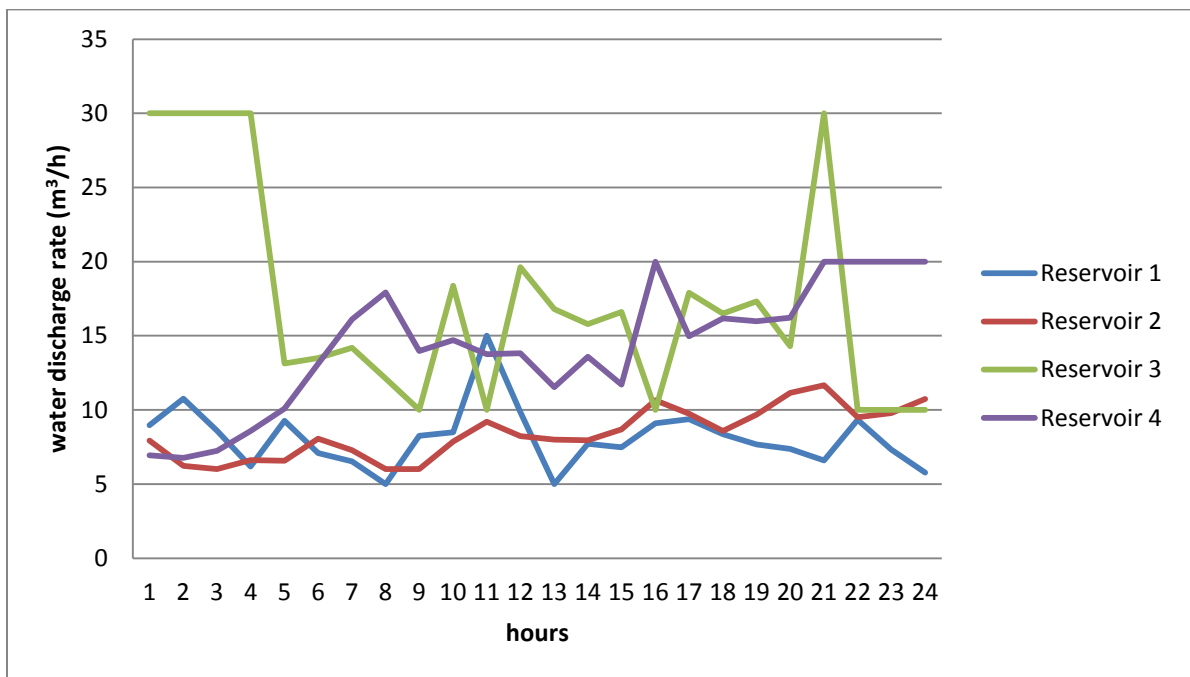


Figure 4.6 Water discharge rates for test system II with MGSA

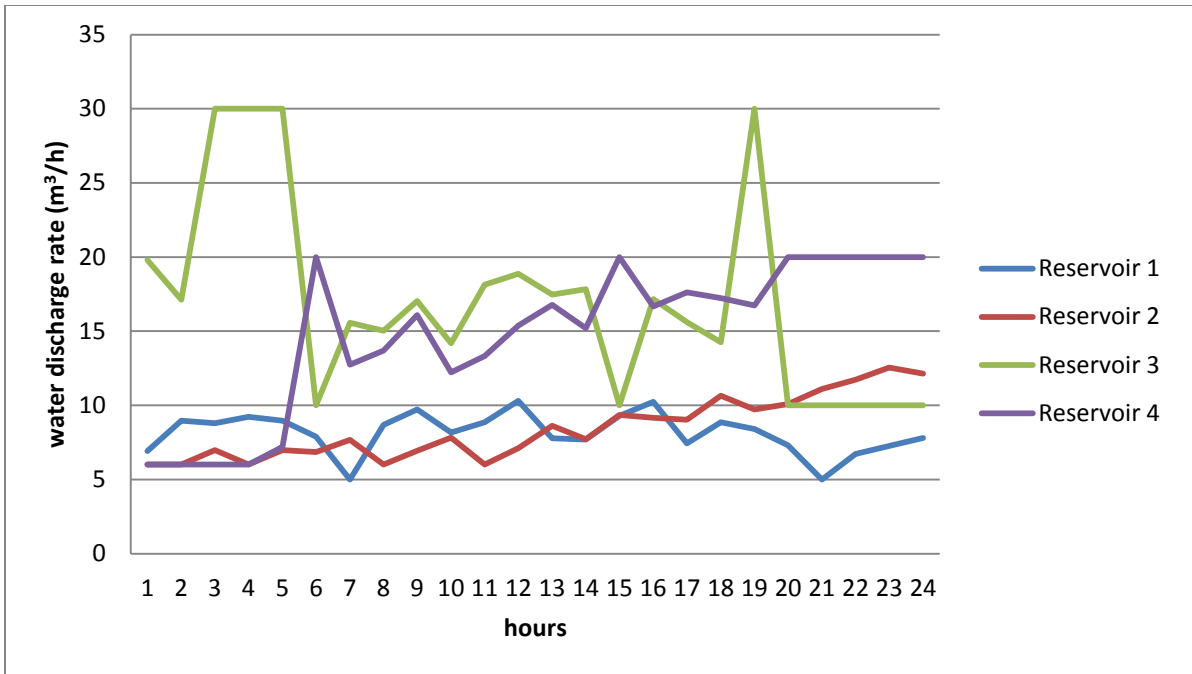


Figure 4.8 Water discharge rates for test system II for hybrid MGSA-SQP

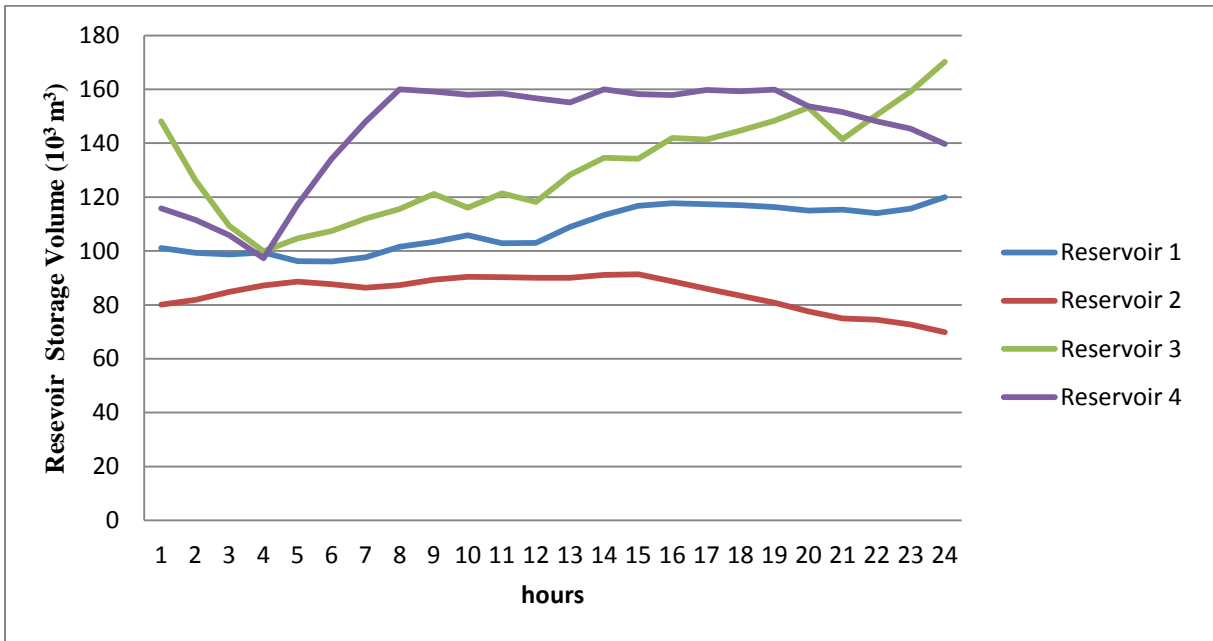


Figure 4.7 Reservoir storage volumes for test system II with MGSA

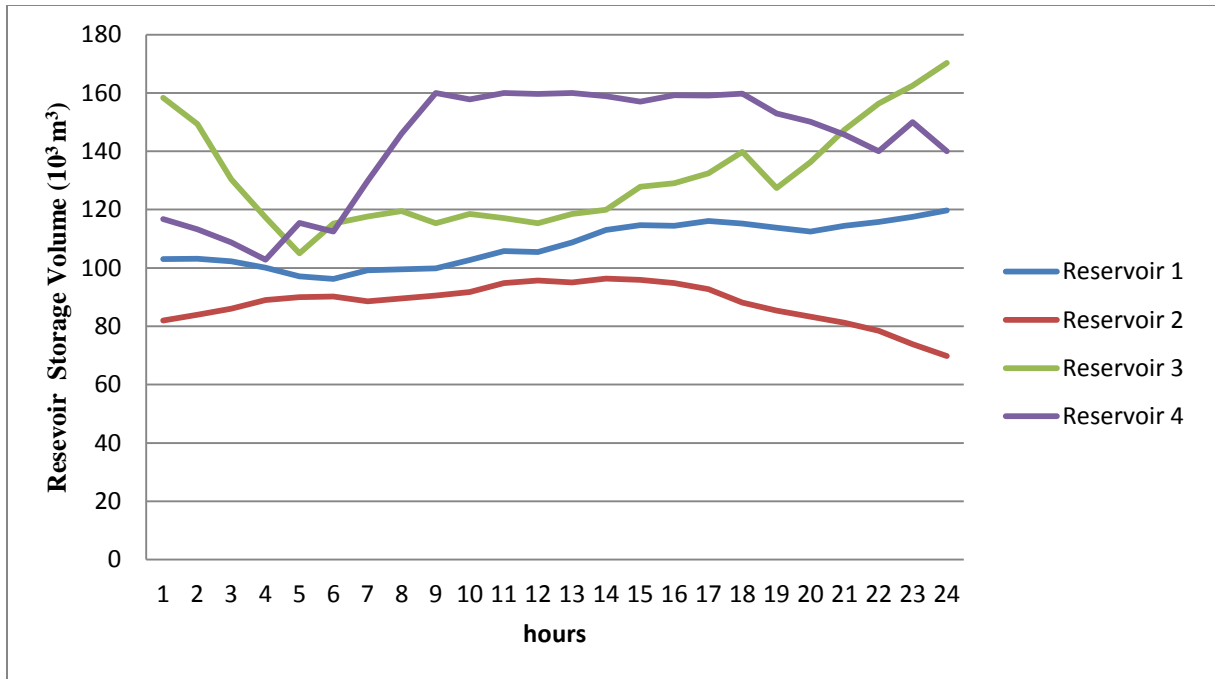


Figure 4.9 Reservoir storage volumes for test system II with hybrid MGSA-SQP

Table 4.8: Cost comparison for test system II

Method	Total Fuel cost (\$)
EP [12]	45,063.00
DE [15]	43,500.00
MDE [39]	43,453.41
PSO[41]	42,474.00
QPSO[70]	42,359.00
MGSA	41,540.40
MGSA-SQP	41,383.28

5.1 CONCLUSION

A hybrid MGSA-SQP algorithm has been proposed for solving STHTS problem over the scheduling time horizon of 24 hours with sub-interval of one hour. In the proposed algorithm, MGSA uses time varying maximum velocity constraint which controls the oscillation and avoids the divergence of the agents in the search space. The proposed hybrid MGSA-SQP works in two stages for solving STHTS problem. The first stage employees MGSA algorithm to explore the search space in order to finds near global solution. The second stage employees local search technique SQP for the exploitation of the explored search space and tunes the control variable in order to find global optimal solution. The effectiveness of the proposed algorithm is demonstrated by using two test systems. The results obtained show the effectiveness of the proposed algorithm on other well established techniques in modern power system.

5.2 FUTURE SCOPE

The scope for the future work in the dissertation is identified as:

- In the dissertation, hydrothermal scheduling is done for short term basis. In future, MTHTS and LTHTS can be performed.
- Hydrothermal scheduling problem can be solved considering the effects of transmission losses, ramp rate and prohibited zone.
- The hydrothermal scheduling problem can be extended from single objective to multi objective by considering emission as an objective.

PUBLICATIONS

I. INTERNATIONAL CONFERENCE

Presented and **published** a paper in International Conference on Advances in Electrical, Power Control, Electronics and Communication Engineering

1. S. Sharma and N. Narang, “Hybrid GSA-SQP for short term multi-chain hydrothermal scheduling”, *International Conference on Advances in Electrical, Power Control, Electronics and Communication Engineering*, New Delhi, 2015.
2. S. Sharma and N. Narang, “Hybrid GSA-SQP for short term multi-chain hydrothermal scheduling”, *Advance Research in Electrical and Electronics Engineering*, vol.2, no.10, pp.108-112,2015

II. INTERNATIONAL JOURNAL

Published a paper in International Journal of Advanced Research in Technology, Engineering and Science

1. S. Sharma and N. Narang, “Short term Multi Chain Hydrothermal Scheduling Using Modified Gravitational Search Algorithm”, *International Journal of Advanced Research in Technology, Engineering and Science*, vol. 2, no.3, pp. 1-8 ,2015

REFERENCES

- [1] A. Wood and B. Wollenberg, *Power generation, operation, and control*. New York: Wiley, 1984.
- [2] D. Kothari and J. Dhillon, *Power system optimization*. New Delhi: Prentice-Hall of India, 2004.
- [3] R. Ferrero, J. Rivera and S. Shahidehpour, "A dynamic programming two-stage algorithm for long-term hydrothermal scheduling of multireservoir systems", *IEEE Transactions on Power Systems*, vol. 13, no. 4, pp. 1534-1540, 1998.
- [4] R. Fuentes-Loyola and V. Quintana, "Medium-Term Hydro-Thermal Coordination by Semidefinite Programming", *IEEE Power Engineering Review*, vol. 22, no. 12, pp. 59-59, 2002.
- [5] K. Wong, "Short-term hydrothermal scheduling. II. Parallel simulated annealing approach, *IEE Proceedings - Generation, Transmission and Distribution*", vol. 141, no. 5, pp. 502, 1994.
- [6] Xiaohong Guan, Ernan Ni, Renhou Li and P. Luh, "An optimization-based algorithm for scheduling hydrothermal power systems with cascaded reservoirs and discrete hydro constraints", *IEEE Transactions on Power Systems*, vol. 12, no. 4, pp. 1775-1780, 1997.
- [7] S. Al-Agtash, "Hydrothermal Scheduling by Augmented Lagrangian: Consideration of Transmission Constraints and Pumped-Storage Units", *IEEE Power Engineering Review*, vol. 21, no. 8, pp. 58-59, 2001.
- [8] L. Kimball, K. Clements, P. Davis and I. Nejdawi, "Multi period hydrothermal economic dispatch by an interior point method", *Mathematical Problems in Engineering*, vol. 8, no. 1, pp. 33-42, 2002..
- [9] O. Nilsson and D. Sjelvgren, "Mixed-integer programming applied to short-term planning of a hydro-thermal system", *IEEE Transactions on Power Systems*, vol. 11, no. 1, pp. 281-286, 1996.

- [10] M. Salama, M. Elgazar, S. Abdelmaksoud and H. Henry, "Short term optimal generation scheduling of multi-chain hydrothermal system using Constriction Factor Based Particle Swarm Optimization Technique", *International Journal Of Scientific and Research Publication*, vol. 03, no. 04, pp. 01-09, 2013.
- [11] J. Maturana and M. Riff, "Solving the short-term electrical generation scheduling problem by an adaptive evolutionary approach", *European Journal of Operational Research*, vol. 179, no. 3, pp. 677-691, 2007.
- [12] M. Basu, "An interactive fuzzy satisfying method based on evolutionary programming technique for multi objective short-term hydrothermal scheduling", *Electric Power Systems Research*, vol. 69, no. 2-3, pp. 277-285, 2004.
- [13] K. Wong, "Short-term hydrothermal scheduling part. I. Simulated annealing approach", *IEE Proceedings - Generation, Transmission and Distribution*, vol. 141, no. 5, pp. 497-501, 1994.
- [14] K. Wong, "Short-term hydrothermal scheduling. II. Parallel simulated annealing approach", *IEE Proceedings - Generation, Transmission and Distribution*, vol. 141, no. 5, pp. 502-506, 1994.
- [15] K. Mandal and N. Chakraborty, "Differential evolution technique-based short-term economic generation scheduling of hydrothermal systems", *Electric Power Systems Research*, vol. 78, no. 11, pp. 1972-1979, 2008.
- [16] M. Basu, "Hopfield neural networks for optimal scheduling of fixed head hydrothermal power systems", *Electric Power Systems Research*, vol. 64, no. 1, pp. 11-15, 2003.
- [17] E. Rashedi, H. Nezamabadi-pour and S. Saryazdi, "GSA: A Gravitational Search Algorithm", *Information Sciences*, vol. 179, no. 13, pp. 2232-2248, 2009.
- [18] M. Khajehzadeh, M. Taha, A. El-Shafie and M. Eslami, "A modified gravitational search algorithm for slope stability analysis", *Engineering Applications of Artificial Intelligence*, vol. 25, no. 8, pp. 1589-1597, 2012.
- [19] I. Farhat and M. El-Hawary, "Optimization methods applied for solving the short-term

- hydrothermal coordination problem”, *Electric Power Systems Research*, vol. 79, no. 9, pp. 1308-1320, 2009.
- [20] X. Yuan, Y. Zhang, L. Wang and Y. Yuan, “An enhanced differential evolution algorithm for daily optimal hydro generation scheduling”, *Computers & Mathematics with Applications*, vol. 55, no. 11, pp. 2458-2468, 2008.
- [21] T. Victoire and A. Jeyakumar, “Hybrid PSO–SQP for economic dispatch with valve-point effect”, *Electric Power Systems Research*, vol. 71, no. 1, pp. 51-59, 2004.
- [22] N. Narang, J. Dhillon and D. Kothari, “Multiobjective fixed head hydrothermal scheduling using integrated predator-prey optimization and Powell search method”, *Energy*, vol. 47, no. 1, pp. 237-252, 2012.
- [23] C. Nallasivan, D. Suman, J. Henry and S. Ravichandran, “A Novel Approach for Short Term Hydrothermal Scheduling Using Hybrid Technique”, *2006 IEEE Power India Conference*, 2006.
- [24] G. Luo, H. Habibollahzadeh and A. Semlyen, “Short-Term Hydro-Thermal Dispatch Detailed Model and Solutions”, *IEEE Power Engineering Review*, vol. 9, no. 11, pp. 40-41, 1989
- [25] A. Bonaert, A. El-abiad and A. Koivo, “Optimal Scheduling of Hydro-Thermal Power Systems”, *IEEE Transactions on Power Apparatus and Systems*, vol. -91, no. 1, pp. 263-270, 1972.
- [26] R. Duncan, G. Seymore, D. Streiffert and D. Engberg, “Optimal Hydrothermal Coordination for Multiple Reservoir River Systems”, *IEEE Transactions on Power Apparatus and Systems*, vol. -104, no. 5, pp. 1154-1159, 1985.
- [27] J. Tang and P. Luh, “Hydrothermal scheduling via extended differential dynamic programming and mixed coordination”, *IEEE Transactions on Power Systems*, vol. 10, no. 4, pp. 2021-2028, 1995

- [28] J. Yang and N. Chen, "Short Term Hydrothermal Coordination Using Multi-Pass Dynamic Programming", *IEEE Power Engineering Review*, vol. 9, no. 8, pp. 50-50, 1989.
- [29] A. Rasoulzadeh-akhijahani and B. Mohammadi-ivatloo, "Short-term hydrothermal generation scheduling by a modified dynamic neighborhood learning based particle swarm optimization", *International Journal of Electrical Power & Energy Systems*, vol. 67, pp. 350-367, May 2015.
- [30] M. Piekutowski, T. Litwinowicz and R. Frowd, "Optimal short-term scheduling for a large-scale cascaded hydro system", *IEEE Transactions on Power Systems*, vol. 9, no. 2, pp. 805-811, 1994.
- [31] N. Fang, J. Zhou, R. Zhang, Y. Liu and Y. Zhang, "A hybrid of real coded genetic algorithm and artificial fish swarm algorithm for short-term optimal hydrothermal scheduling", *International Journal of Electrical Power & Energy Systems*, vol. 62, pp. 617-629, November 2014.
- [32] S. Kumar, J. Sharma and L. Ray, "A nonlinear programming algorithm for hydro-thermal generation scheduling", *Computers & Electrical Engineering*, vol. 6, no. 3, pp. 221-229, 1979.
- [33] N. Gouthamkumar, V. Sharma and R. Naresh, "Disruption based gravitational search algorithm for short term hydrothermal scheduling", *Expert Systems with Applications*, vol. 42, no. 20, pp. 7000-7011, 2015
- [34] M. Salam, K. Nor and A. Hamdam, "Hydrothermal scheduling based Lagrangian relaxation approach to hydrothermal coordination", *IEEE Transactions on Power Systems*, vol. 13, no. 1, pp. 226-235, 1998.
- [35] T. Nguyen and D. Vo, "Modified cuckoo search algorithm for short-term hydrothermal scheduling", *International Journal of Electrical Power & Energy Systems*, vol. 65, pp. 271-281, February 2015.

- [36] S. Orero and M. Irving, "A genetic algorithm modelling framework and solution technique for short term optimal hydrothermal scheduling", *IEEE Transactions on Power Systems*, vol. 13, no. 2, pp. 501-518, 1998.
- [37] L. Lakshminarasimman and S. Subramanian, "A modified hybrid differential evolution for short-term scheduling of hydrothermal power systems with cascaded reservoirs", *Energy Conversion and Management*, vol. 49, no. 10, pp. 2513-2521, 2008
- [38] N. Sinha, R. Chakrabarti and P. Chattopadhyay, "Fast evolutionary programming techniques for short-term hydrothermal scheduling", *Electric Power Systems Research*, vol. 66, no. 2, pp. 97-103, 2003.
- [39] L. Lakshminarasimman and S. Subramanian, "Short-term scheduling of hydrothermal power system with cascaded reservoirs by using modified differential evolution", *IEE Proceedings - Generation, Transmission and Distribution*, vol. 153, no. 6, pp. 693, 2006.
- [40] J. Zhang, "An Improved Differential Evolution Approach for Short-term Hydrothermal Scheduling", *Journal of Information & Computational Science.*, vol. 12, no. 5, pp. 1817-1829, 2015.
- [41] K. Mandal, M. Basu and N. Chakraborty, "Particle swarm optimization technique based short-term hydrothermal scheduling", *Applied Soft Computing*, vol. 8, no. 4, pp. 1392-1399, 2008
- [42] M. Basu, "Artificial Bee Colony Optimization for Short-Term Hydrothermal Scheduling", *Journal of The Institution of Engineers (India): Series B*, vol. 95, no. 4, pp. 319-328, 2014.
- [43] J. Kennedy, R. Eberhart and Y. Shi, *Swarm intelligence*. San Francisco: Morgan Kaufmann Publishers, 2001.
- [44] P. Roy, B. Mandal and K. Bhattacharya, "Gravitational Search Algorithm Based Optimal Reactive Power Dispatch for Voltage Stability Enhancement", *Electric Power Components and Systems*, vol. 40, no. 9, pp. 956-976, 2012.

- [45] B. Bhattacharyya and S. Kumar, "Reactive power planning with FACTS devices using gravitational search algorithm", *Ain Shams Engineering Journal*, 2015.
- [46] A. Ghasemi, H. Shayeghi and H. Alkhatib, "Robust design of multimachine power system stabilizers using fuzzy gravitational search algorithm", *International Journal of Electrical Power & Energy Systems*, vol. 51, pp. 190-200, October 2013.
- [47] T. Niknam, F. Golestaneh and A. Malekpour, "Probabilistic energy and operation management of a microgrid containing wind/photovoltaic/fuel cell generation and energy storage devices based on point estimate method and self-adaptive gravitational search algorithm", *Energy*, vol. 43, no. 1, pp. 427-437, 2012.
- [48] P. Roy, "Solution of unit commitment problem using gravitational search algorithm", *International Journal of Electrical Power & Energy Systems*, vol. 53, pp. 85-94, December 2013.
- [49] X. Yuan, Y. Zhang, L. Wang and Y. Yuan, "An enhanced differential evolution algorithm for daily optimal hydro generation scheduling", *Computers & Mathematics with Applications*, vol. 55, no. 11, pp. 2458-2468, 2008.
- [50] M. Basu, "Hybridization of bee colony optimization and sequential quadratic programming for dynamic economic dispatch", *International Journal of Electrical Power & Energy Systems*, vol. 44, no. 1, pp. 591-596, 2013.
- [51] M. Harman and P. McMinn, "A Theoretical and Empirical Study of Search-Based Testing: Local, Global, and Hybrid Search", *IEEE Trans. Software Eng.*, vol. 36, no. 2, pp. 226-247, 2010.
- [52] S. Sivasubramani and K. Shanti Swarup, "Hybrid DE-SQP algorithm for non-convex short term hydrothermal scheduling problem", *Energy Conversion and Management*, vol. 52, no. 1, pp. 757-761, 2011.
- [53] M. El-Hawary, R. Rao and G. Christensen, "Optimal hydrothermal load flow: Formulation and a successive approximation solution for fixed head systems", *Optimal Control Applications and Methods*, vol. 7, no. 4, pp. 337-354, 1986.

- [54] J. Nanda and P. Bijwe, "Optimal Hydrothermal Scheduling With Cascaded Plants Using Progressive Optimality Algorithm", *IEEE Power Engineering Review*, vol. 1, no. 4, pp. 76-76, 1981.
- [55] M. Pereira and L. Pinto, "Application of Decomposition Techniques to the Mid - and Short -Term Scheduling of Hydrothermal Systems", *IEEE Transactions on Power Apparatus and Systems*, vol. 102, no. 11, pp. 3611-3618, 1983.
- [56] V. Sherkat, K. Moslehi, E. Lo, G. Sanchez and J. Diaz, "Modular and flexible software for medium and short-term hydrothermal scheduling", *IEEE Transactions on Power Systems*, vol. 3, no. 3, pp. 1390-1396, 1988.
- [57] M. Salama, "Variable Head Hydrothermal Generation Scheduling Using Genetic Algorithm and Constriction Factor Based Particle Swarm Optimization Technique", *International Organization of Scientific Research Journal of Engineering*, vol. 03, no. 09, pp. 01-16, 2013.
- [58] N. Narang, J. Dhillon and D. Kothari, "Multi-objective Short-term Hydrothermal Generation Scheduling Using Predator-Prey Optimization", *Electric Power Components and Systems*, vol. 40, no. 15, pp. 1708-1730, 2012.
- [59] N. Fang, J. Zhou, R. Zhang, Y. Liu and Y. Zhang, "A hybrid of real coded genetic algorithm and artificial fish swarm algorithm for short-term optimal hydrothermal scheduling", *International Journal of Electrical Power & Energy Systems*, vol. 62, pp. 617-629, November 2014.
- [60] G. Sreenivasan, "PSO Based Short-Term Hydrothermal Scheduling with Prohibited Discharge Zones", *International Journal of Advanced Computer Science and Application*, vol. 2, no. 9, pp. 97-105, 2011.
- [61] V. Kumar and M. Mohan, "A genetic algorithm solution to the optimal short-term hydrothermal scheduling", *International Journal of Electrical Power & Energy Systems*, vol. 33, no. 4, pp. 827-835, 2011.

- [62] P. Yang, H. Yang and C. Huang, "Scheduling short-term hydrothermal generation using evolutionary programming techniques", *IEE Proceedings - Generation, Transmission and Distribution*, vol. 143, no. 4, pp. 371-376, 1996.
- [63] F. Neri, C. Cotta and P. Moscato, *Handbook of memetic algorithms*. Berlin: Springer, 2012.
- [64] P. Attaviriyanupap, H. Kita, E. Tanaka and J. Hasegawa, "A hybrid EP and SQP for dynamic economic dispatch with nonsmooth fuel cost function", *IEEE Transactions on Power Systems*, vol. 17, no. 2, pp. 411-416, 2002.
- [65] P. Boggs and J. Tolle, *Sequential Quadratic Programming, Acta Numerica*, vol. 4, pp. 1-52, 1995.
- [66] W. Shou, W. Fan, Z. Gao and B. Liu, "Hybrid Differential Evolution and Sequential Quadratic Programming Algorithm", *10th IEEE/ACIS International Conference on Computer and Information Science*, 2011.
- [67] J. Cai, Q. Li, L. Li, H. Peng and Y. Yang, "A hybrid FCASO-SQP method for solving the economic dispatch problems with valve-point effects", *Energy*, vol. 38, no. 1, pp. 346-353, 2012.
- [68] P. Roy, "Teaching learning based optimization for short-term hydrothermal scheduling problem considering valve point effect and prohibited discharge constraint", *International Journal of Electrical Power & Energy Systems*, vol. 53, pp. 10-19, December 2013.
- [69] P. Hota, A. Barisal and R. Chakrabarti, "An improved PSO technique for short-term optimal hydrothermal scheduling", *Electric Power Systems Research*, vol. 79, no. 7, pp. 1047-1053, 2009.
- [70] C.Sun and S.Lu , "Short term combined economics emission hydrothermal scheduling using improved quantum behaved particle swarm optimization", *Expert Syst. Appl.*, vol.37, no.6, pp.4232-4241, 2010.

APPENDIX A

SYSTEM DATA FOR TEST SYSTEM I

1. Water transport delay between the connected reservoir

PLANT	1	2	3	4
R_u	0	0	2	1
d	2	3	4	0

R_u : Number of upstream hydro power plant
 d : Time delay to immediate downstream hydro power plant

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

PLANT	V_h^{min}	V_h^{max}	V_h^{begin}	V_h^{end}	q_h^{min}	q_h^{max}	P_h^{min}	P_h^{max}
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

3. Hydro power generation coefficient

PLANT	C_1	C_2	C_3	C_4	C_5	C_6
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

4. Fuel cost coefficient and operating limits of thermal units

Unit	a_i	b_i	c_i	e_i	f_i	P_{gi}^{min}	P_{gi}^{max}
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

5. Reservoir inflows of the multi chain hydro plants ($\times 10^4 m^3$)

Hours	Reservoir				Hours	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

6. Load demand for 24 hours

Hours	P_D (MW)	Hours	P_D (MW)	Hours	P_D (MW)	Hours	P_D (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

APPENDIX B

SYSTEM DATA FOR TEST SYSTEM II

- Water transport delay between connected reservoir connected reservoir

PLANT	1	2	3	4
R_u	0	0	2	1
d	2	3	4	0

R_u : Number of upstream hydro power plant
 d : Time delay to immediate downstream hydro power plant

- Reservoir storage capacity limit, plant discharge limits ,plant generation limits and reservoir end conditions

PLANT	V_h^{min}	V_h^{max}	V_h^{begin}	V_h^{end}	q_h^{min}	q_h^{max}	P_h^{min}	P_h^{max}
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

- Hydro power generation coefficient

PLANT	C_1	C_2	C_3	C_4	C_5	C_6
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

4. Fuel cost coefficients and operating limits of thermal units

Unit	ai	bi	ci	P_{gi}^{min}	P_{gi}^{max}
1	0.002	19.2	5000	500	2500

5. Reservoir inflows of the multi chain hydro plants ($\times 10^4 m^3$)

Hours	Reservoir				Hours	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

6. Load demand for 24 hours

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

CURRICULAM VITAE OF AUTHOR

I. Personal background

NAME : Saurabh Sharma
FATEHR'S NAME : Mr. Vinod Kumar Sharma
DATE OF BIRTH : 01/04/1989
E-mail : s.saurabh3112@gmail.com

II. Educational Qualification

Degree	Subject	Institute	Board/ University	Marks(%)
S.S.C	Science	O.S.N, Rishikesh	I.C.S.E	73
H.S.C	PCM	O.S.N, Rishikesh	I.S.C	72.8
B.Tech	Electrical Engineering	U.I.T, Dehradun	U.K.T.U	75.08

III. List of Publications

1. S. Sharma and N. Narang, "Hybrid GSA-SQP for short term multi-chain hydrothermal scheduling", *Advance Research in Electrical and Electronics Engineering*, vol.2, no.10, pp.108-112,2015.
2. S. Sharma and N. Narang, "Short term Multi Chain Hydrothermal Scheduling Using Modified Gravitational Search Algorithm", *International Journal of Advanced Research in Technology, Engineering and Science*, vol. 2, no.3, pp. 1-8 ,2015.

PLAGIARISM CERTIFICATE

SSS

ORIGINALITY REPORT

18%	6%	17%	5%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Sivasubramani, S.. "Hybrid DE-SQP algorithm for non-convex short term hydrothermal scheduling problem", Energy Conversion and Management, 201101 Publication	1%
2	www.ijsrp.org Internet Source	1%
3	Submitted to Universiti Teknikal Malaysia Melaka Student Paper	1%
4	Kumar, S.. "Efficient real coded genetic algorithm to solve the non-convex hydrothermal scheduling problem", International Journal of Electrical Power and Energy Systems, 200712 Publication	1%
5	V. L. Paucar. "Long Term Hydrothermal Scheduling Linear Programming Model for Large Scale Power Systems", 2007 Large Engineering Systems Conference on Power	1%